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Environmental analysis of soilless tomato production in a high-tech greenhouse

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ABSTRACT

Soilless farming systems are currently considered a viable production technique reducing environmental impacts due to use of chemical factors, soil and water This study analysed the first high-tech hydroponic greenhouse in Southern Italy, using a Life Cycle Assessment approach. The environmental performances of equipped with automated systems for monitoring the growth environment (high-tech) and soil based without automation of climate and lighting (low-tech) greenhouses were compared. The analysis of high-tech greenhouse was based on primary data from field surveys. For low-tech greenhouse, secondary data from literature were used. The system boundary was from 'cradle-to-farm-gate', the functional unit 1 ha of cultivated area. Soil-based cultivation had the highest overall environmental impacts primarily attributable to consumption of fossil fuel and the fertilisers. The results showed that in the high-tech greenhouse, the use of renewable energy and soilless closed-loop cultivation system electronically controlled and managed, significantly reduced the environmental burden. Results suggest solution for the expansion of greenhouse farming improving their environmental performances by renewable energy and closed-loop systems. This study regarding an advanced and almost unique reality is suitable to be reapplied in any context vocated to greenhouses vegetable farming with the foresight to appropriately complement it by economic and social assessments.

1. Introduction

According to FAO forecasts, the global growing population of 9.9 billion by 2050 will require twice as much water and land to produce food. Furthermore, agriculture should take into account the challenges due to changing climatic conditions and the incidence of biotic stresses (Raza et al., 2019; Teshome et al., 2020). Competition for natural resources and the pressure on the environment of farming activities rise to the need to develop strategies favouring a shift towards less impactful farming methods.

The Sustainable Development Goals state that to be sustainable, agriculture requires major improvements in resource efficiency, mitigation of negative effects on the environment and guarantee of global food security.

Protected cultivation has spread significantly in recent decades as its controlled environment provides a means of facing adverse weather events. This cultivation system allows year-round production, higher yields and more efficient use of natural resources and agronomic inputs (Padmanabhan et al., 2016; Singh et al., 2008). However, several studies report that greenhouse cultivation is associated to environmental impacts mainly due to the large consumption of energy for heating and lighting (Ntinas et al., 2017a; Omer, 2016; Paris et al., 2022a). Heating and cooling of greenhouses positively influences yields (Soussi et al., 2022); however, the use of electricity for microclimate conditioning and lighting of greenhouses is mostly dependent on fossil sources, resulting in considerable greenhouse gas emissions (GHG) (Paris et al., 2022b). According to the literature, energy consumption increases significantly where temperatures are colder and the weather is generally cloudy, as in northern European countries (Acosta-Silva et al., 2019; Gorjian et al., 2021). The need to reduce GHG from fossil fuels sets the goal of accelerating the transition to clean energy to achieve international climate targets.

The limitations of this farming system highlight the need for suitable technologies to address the environmental footprint of farms. The

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choices of the growers regarding the production techniques utilised have a long-term impact on environmental quality and natural resources availability; therefore, polluting production activities make the transition to more environmentally friendly cultivation systems indispensable.

In recent years, increasing attention has been paid to so-called high-tech greenhouses. These greenhouses have emerged in response to the need to increase yields by efficiently using resources such as water, fertilisers and energy (Moons et al., 2022). Modern greenhouses are equipped with various technological devices, such as fertigation sensors (Canaj et al., 2021), supplementary lighting (Palmitessa et al., 2021), software for microclimate control (Nicolosi et al., 2017) and photovoltaic systems for electricity generation (Liantas et al., 2023).

The challenge for modern and sustainable greenhouses is to optimize input management, such as water, fertilisers, pesticides and energy. Soilless cultivation systems (SCS) are applied in most high-tech greenhouses (Gruda et al., 2019). SCS is a modern greenhouse cultivation technology, that represents an example of innovative production process (Savvas and Gruda, 2018). SCS does not use soil for cultivation but includes hydroponic and substrate-based cultivation. Hydroponic cultivation involves a liquid medium such as the Floating System (floating hydroponics) and Nutrient Film Technique (NFT) in which the plant root is immersed directly into the nutrient solution; substrate-based cultivation is a system that uses various inert organic (e.g., coconut fibre) or inorganic (e.g., rockwool or perlite) substrates. In addition SCS offer the great advantage to prevent the proliferation of soil pathogens, strongly affecting greenhouses, (Gonnella and Renna, 2021a), as soil is replaced by inert substrates free of pests and diseases due to their production process (Raviv et al., 2019).

The continuing transition to soilless cultivation is also due to the possibility of improving system performance through better control of several crucial factors. Soilless greenhouse cultivation is characterised using sophisticated structures and equipment that allow for greater efficiency in the use of inputs resources in production processes. The fertigation can be precisely controlled by a decision support system based on sensors that detect the real needs of the plants, and the closed-loop system allows drainage to be recovered and reused several times in the same production cycle. These technologies make efficient use of inputs and limit losses into the environment (Bacci et al., 2005; Massa et al., 2020a; Putra and Yuliando, 2015).

The increasing attention to environmental concerns related to food supply chains, requires the need for evaluating the different production technologies. There are an increasing number of technical innovations that can be used in greenhouses to increase productivity; however, their effects on natural resources and environmental impacts have to be carefully evaluated and considered. In this multifaceted framework, it is crucial that each technological innovation was accurately evaluate regarding to its own environmental performances and impacts. For this purpose, efficient and shared analysis tools and methodologies are needed and Life Cycle Assessment (LCA) is currently widely recognized and applied by the scientific community. The importance of the production stage in the Life Cycle Assessment (LCA) (De Boni et al., 2022a) of vegetable products draws attention on a careful assessment of efficiency of the farming systems and inputs; an urgent consideration should be devoted to environmental impacts reduction strategies of greenhouses cultivation.

The aim of this study was to evaluate and compare, through a LCA analysis, the environmental sustainability of two different greenhouse production systems for tomatoes: 1) soilless cultivation in a high-tech glasshouse; 2) soil-based cultivation in a low-tech greenhouse. LCA was used to quantify the energy demand, resources consumption and pollutant emissions of technological improvements of the greenhouse production system. Among horticultural crops, tomato has been selected as a representative crop for the study as it represents the most widespread greenhouse crop. Thus, growing tomatoes in greenhouse in considered the most efficient method to produce quality tomatoes while saving water resources, whereas open-field tomato cultivation is hampered by high incidence of pests and diseases, and is extremely sensitive to heat and water shortage stress (Amoako Ofori et al., 2022).

Insights from this research may contribute to improve the sustainability of crop productions because it quantifies precisely all the environmental impacts due to the different input and technologies involved in the tomato cultivation. It may be of particular interest of practitioner interested in optimising input consumption. That may reduce costs and may allow to boast an environmental quality certification to enhance its product. Policy makers may be particularly interested in the results and methodology used to calibrate support tools to foster the sustainability of specific companies and products in accordance with the European Green Deal guidelines, that under the United Nations Sustainable Development Goals (SDGs), were used as targets to assess the sustainability of production systems.

To address the environmental issues involved in greenhouse systems, sustainable agricultural practices using technological solutions are required. Soilless cultivation in high-tech greenhouses is a possible pathway to sustainable intensification. In high-tech greenhouses, management practices and environmental performance can be improved through the adoption of solutions that reduce dependence on natural resources and fossil fuels and improve production yields.

Considering the environmental impacts caused by agriculture and the scarcity of natural resources, more sustainable practices and technologies are needed. In this LCA study, a benchmark was used to show how soilless cultivation system in high-tech greenhouse can be used to produce vegetables with a more sustainable use of resources and energy, mitigating the environmental impacts of low-tech greenhouses.

1.1. Literature review

The development of smart greenhouses is crucial to achieve sustainable agricultural production.

Intensive greenhouse production allows production efficiency; however, it involves several environmental risks. The main one is represented by the emissions related to the considerable amount of electricity needed for temperature control and artificial lighting (Gołasa et al., 2021; Mahdavian and Wattanapongsakorn, 2017).

Reducing energy use and carbon neutrality are the most important global environmental goals in response to the climate emergency (Feng, 2022). Recent studies have provided important information on several innovations in protected greenhouse cultivation. Various researchers reported that the use of renewable energy improved carbon footprint by 24% (Chel and Kaushik, 2011a; Ntinas et al., 2020). Gorjian et al. (2021) and Ntinas et al. (2017b) have investigated the use of natural gas and solar energy in greenhouses in Southern Europe, the results suggest that up to 60% of the carbon footprint can be reduced through renewable energy. In greenhouses, electricity is also used for supplementary light to extend the growing season and increase yields in seasons with low levels of solar radiation (Paucek et al., 2020a). Recently, high-pressure sodium (HPS) lamps have been replaced by light-emitting diodes (LEDs). Recent technological advances have made high-intensity LED lamps more attractive as lighting sources as they save energy by being more efficient in converting electricity into light (Katzin et al., 2021a).

Regarding energy use in greenhouse sector, there is great potential in reducing GHG through the energy transition towards renewables; however, few studies exist examining the use of renewable energy in greenhouse production (Paris et al., 2022b). Moreover, some research results suggest that the adoption of renewable energy is hindered by the high cost of the initial investment (Acosta-Silva et al., 2019). Therefore, policies should take into account the need for subsidies to encourage farmers to use renewable energy. Each sector must consider how to respond and the use of renewable energy in greenhouses is a field that has been hardly investigated so far. Since in protected cultivation systems the use of electricity plays a dominant role, renewable energy source is a possible solution for reducing GHG emissions from electricity consumption and achieving the UN Sustainable Development Goals.

Soilless cultivation systems, applied in high-tech greenhouses, is a cultivation method that can ensure food safety, thanks to the high yields and products quality (Gruda, 2009; Lykogianni et al., 2023; Malik et al., 2018). Higher tomato yields have been observed in high-tech greenhouses in Spain and the Netherlands, mainly due to the use of supplementary light (Zhou et al., 2021). According to Torrellas et al. (2012c), the recycling of nutrient solution through a closed-loop system in soilless cultivation results in significant water savings compared to low-tech systems.

A study compared greenhouse soil cultivation in Germany with hydroponic cultivation in Greece (Ntinas et al., 2017b). The authors stated that soilless cultivation resulted in significant water savings, 458.4 L m^{-2} and 216.1 L m^{-2} respectively. Other studies have shown that switching to a closed-loop system in soilless cultivation substantially reduces nitrate pollution of water resources, moreover the recycling of the nutrient solution optimises water and fertiliser use (Gartmann et al., 2023; Massa et al., 2010). Fertigation sensors and the closed-loop system allow optimal use of water and fertilisers, reducing their negative impacts on the environment (Pardossi et al., 2009). Considering the need for increasing automation and reduce pollution, the adoption of these techniques appears to be an evolution of protected crops.

Scientific findings provide evidence for optimising production processes, which is useful for improving knowledge for decision-makers and stakeholders.

Reducing emissions from food production is one of the greatest global challenges, so particular attention should be paid to potential strategies for improving the sustainability of greenhouse crop production. To respond to the growing world-wide food demand and the need for sustainable production processes, these high-tech greenhouses must be constructed quickly and in quantity (Alvarado et al., 2020a).

In the literature, there are few studies conducted on soilless production in high-tech greenhouses, especially in Mediterranean regions where they are not yet widespread (Incrocci et al., 2020; Bakker et al., 2008)). Most Mediterranean greenhouses are still low-tech with plastic coverings and no climate monitoring systems (Antón et al., 2007; Cellura et al., 2012a) in which vegetable production takes place in soil (Incrocci et al., 2020; Thompson et al., 2020). In these regions, heated greenhouses and the adoption of technological innovations are still limited due to the higher costs of technological facilities and the lack of knowledge of growers about the potential benefits (Blanco et al., 2022; Castilla et al., 2004). Therefore, most studies on performance and environmental impacts have focused on unheated low-tech greenhouses (Alvarado et al., 2020b; Khapte et al., 2022; Passam et al., 2001; Rojas-Rishor et al., 2022; Tuzel et al., 2017).

Considering that the several published studies on high-tech greenhouses mainly cover the areas of Northern Europe, Asia and the United States (Blanco et al., 2022), a study in the Mediterranean area, such as Italy, could be useful for stakeholders and policy makers to know the progress of greenhouse cultivation and the environmental implications.

Technologies for greenhouse sector are continually developing and currently there is little data on these in Italy. To our knowledge, there are no detailed analyses of high-tech greenhouse production systems. Furthermore, few studies have compared the environmental performance of low-tech and high-tech greenhouses.

Thus, this study discusses the environmental performance of relevant developments of a high-tech greenhouse in cultivation techniques (soilless), fertirrigation management (closed-loop system for recirculation, automated sensors), electricity-saving systems (photovoltaic panels, LED light). The objective of this research was to provide scientific evidence useful to transfer information to growers and policy makers. The results may be useful to improve the level of knowledge about the potential advantages of increasing the technological level of greenhouses and to outline strategies to encourage their diffusion.

This study addresses the environmental sustainability of a high-tech hydroponic greenhouse in Italy. For comparison with the performance of a low-tech greenhouse, the analysis draws on literature studies in four Mediterranean regions. However, the general conclusions are applicable to other regions worldwide.

2. Materials and methods

A reference point is needed to assess the environmental performance of a technologically improved greenhouse management system. Therefore, the environmental impact of two greenhouse tomato production techniques was evaluated by modelling two scenarios with two different technological levels, called high-tech greenhouse and low-tech greenhouse. For the production scenario in a high-tech greenhouse, primary data collection was conducted through a direct interview with the owners of a production company located in Monopoli (BA), (40.9027253 N,17.3277492 E), in the region of Apulia, southern Italy (reference year 2022). During the survey, greenhouse growers and managers described their operations and quantified material and energy inputs for the production process.

Specifically, it is an innovative semi-closed commercial greenhouse with photovoltaic panels for energy production and a closed-loop system for nutrient solution management. Tomatoes are grown on rockwool substrate using precision sensors for fertigation and supplemental LED light. The greenhouse was considered as a case study as it is representative of high-tech agricultural practices. Moreover, it should be underlined that for the high-tech greenhouse scenario, it was possible to use data from a single farm as it is not yet widespread in Italy, but it can be considered a pilot firm in Apulia region.

For the comparison with the low-tech greenhouse, data from the literature were used. The studies in the literature were selected according to the following criteria: (i) tomato production in greenhouses, (ii) southern European regions, (iii) low-tech greenhouses with soil cultivation. Since energy consumption between greenhouses is strongly influenced by climate, case studies conducted in Mediterranean basin were selected. Moreover, a limited number of studies were used for modelling the low-tech greenhouse production system in order to improve data consistency. From the reviewed publications, the inventory data of four studies were chosen and average values were used as representative data to be applied in the analysis of tomato production in a low-tech greenhouse. The four selected representative case studies concern the cultivation of tomatoes on soil in low-tech greenhouses in four Mediterranean regions: Italy, Spain, Albania and France (Boulard et al., 2011a; Canaj et al., 2020; Cellura et al., 2012b; Torrellas et al., 2012a).

Two representative production systems were modelled and evaluated starting from data collected both in field surveys and in desk analyses: (1) soilless cultivation in high-tech glasshouse with steel structure, (2) soil-based cultivation in low-tech greenhouse with plastic covering and structure in steel.

In the high-tech glasshouse, plants are grown on rockwool substrate, the most used in heated greenhouses. Irrigation is managed using high-precision irrigation sensors, which detect the real water needs of the plants, and a closed-loop system, in which excess nutrient solution is recovered and recirculated after a process of filtration, correction and disinfection. Concerning the energy inputs, the farm is powered by solar photovoltaic energy and a cogeneration plant that uses natural gas. Moreover, the plants are grown with supplemental LED lighting as a solution to ensure year-round productivity (Palmitessa et al., 2020a; Paucek et al., 2020b).

For the low-tech greenhouse production, the tomatoes are planted on soil, tillage involves ploughing and levelling, fertirrigation is via a drip system and there is no heating system.

Table 1 summarises an average of the input-output data of the two production systems.

LCA is a methodology to systematically assess the environmental performance of a product or service system throughout its life cycle (Alhashim et al., 2021; De Boni et al., 2022b; Muralikrishna and

Table 1
Main characteristics of the greenhouse systems considered.

Short description	High-tech glasshouse Soilless system	Low-tech plastic house Soil-based system
Structure	Steel–glass	Steel–polyethylene
Substrate	Rockwool	Soil
Plant density (stems m^{-2})	4.73	2.5
Lighting-Heating	Yes	No
Energy consumption (kWh ha^{-1})	1,310,070	10,979
Natural gas consumption (m^3 ha^{-1})	267,216	
Diesel (kg ha^{-1})	–	15,000
Irrigation and fertilisation	Drip irrigation-closed cycle	Drip irrigation
Total water inputs (m^3 ha^{-1})	3,750	8,300
Nutrient inputs (kg ha^{-1})		
N-fertiliser	1,768	935
P-fertiliser	589	312
K-fertiliser	3,284	1,736
Other fertilisers	3,397	1,796
Pesticides (kg ha^{-1})	23.00	23.00
Weed control	No	Plastic mulch
Yields (kg ha^{-1})	250,000	166,000

Manickam, 2017; Roy et al., 2009). The analysis considers all stages of the life cycle, from the extraction of raw materials to the production phase and disposal. Through the compilation of inputs and outputs in the life cycle inventory and the assessment of potential environmental impacts, LCA a powerful tool for interpretation of disparity among different phases of production processes.

In the agricultural sector, LCA is mainly used to assess the environmental issues of agricultural activities. The results of this methodology allow more environmentally friendly agricultural practices to be identified to support decision-making processes (Torres Pineda et al., 2021).

The LCA study was performed in conformity with ISO 14040 standards (ISO, 2006), aiming to assess the environmental impact of tomato production in order to identify the environmental hotspots and suggest improvements for increasing sustainability of the production system.

The representative greenhouses were the primary source of data, while the secondary data for the background processes were obtained from the Ecoinvent database (Frischknecht et al., 2005). The impact assessment was performed using the software Simapro 7.3., the evaluation methods used were EPD 2008 (Environmental Product Declarations) and Eco-indicator 99. The EPD is based on the ISO 14025 standard to conduct a type III environmental declaration (Del Borghi et al., 2020). Type III labels are based on life cycle assessment and report multiple environmental impacts (Hospido et al., 2022). Other authors have recognized EPDs as one of the most important environmental impact assessment systems, because they are based on a common methodology and because their transparency contributes to the comparability of different declarations (Lauri et al., 2020; Rangelov et al., 2021). Furthermore, with EPDs it appears that overestimation of potential environmental impacts can be avoided (Del Rosario et al., 2021). We focused on five impact categories that investigated the main potential environmental impacts: Global Warming Potential with a timeline of 100 years (GWP) in kg CO_2 eq., Ozone layer Depletion (OLD) in kg CFC-11 eq., Eutrophication (EU) in kg PO_4 eq., Acidification (AC) in kg SO_2 eq., and Non-renewable, fossil (NRF) in MJ (Nicolo' et al., 2017).

Eco-indicator 99 is an environmental impact assessment method that enables impact categories (midpoints) to be aggregated into three damage categories (endpoints) called eco-indicators: human health, ecosystem quality and resources (Goedkoop and Spriensma, 2001). The main advantage is that it is possible to obtain a single environmental score through the weighting procedure (i.e. eco-indicator). Therefore, the methodology of Eco-indicator 99 simplifies the interpretation of LCA results by limiting the number of impacts to be assessed. Damage to human health is expressed in disability-adjusted life year (DALY) and includes six impact categories: carcinogens, respiratory organics and inorganics, climate change, radiation, ozone layer. Damage to ecosystem quality, expressed in potentially disappeared fraction (PDF)*m^2*year, refers to the loss of species over a certain area, during a certain time. This eco-indicator aggregates three impact categories: ecotoxicity, acidification/eutrophication, and land use. Damage to resources is measured in the surplus energy needed for future extractions of minerals and fossil fuels (MJ surplus); the impact categories included are minerals and fossil fuels.

All resources utilization and emissions were assigned to a functional unit of 1 ha of harvested land; the study set the system boundaries from raw material extraction to the farm gate. Since the goal was to improve production techniques, the system boundaries included the main agricultural operations: pest management, fertilisation, irrigation, soil tillage, as well as energy consumption. The background processes included: the extraction of raw materials and the production of pesticides, fertilisers, fossil fuel, electricity and natural gas (Fig. 1).

The contribution of infrastructure to environmental impact (construction, maintenance and disposal) was not included in the analysis because, due to its generally long lifespan, it may be considered insignificant versus that of the other inputs (Torres Pineda et al., 2021).

The high-tech greenhouse was intended as representative of the more advanced cultivation technologies for the improvement of Mediterranean greenhouses. Several alternatives that could be applied to improve the environmental performance of low-tech greenhouses were analysed, such as the use of renewable energy, hydroponic cultivation and recirculation of the nutrient solution.

3. Results

3.1. Life cycle impact assessment

The most relevant aspects focused on are the reduction of the use of fossil fuels, the application of water and fertilisers and the recycling of the nutrient solution. Comparison of the two systems showed that soilless cultivation in the high-tech greenhouse is more environmentally friendly than cultivation on soil in the low-tech greenhouse.

In the high-tech greenhouse, electricity is used for temperature control, supplemental lighting and nutrient circulation, therefore it is more energy intensive (1,310,070 kWh ha^{-1}) than the low-tech greenhouse (10,979 kWh ha^{-1}) (Table 1), which reduces the sustainability of this system. However, it also depends on the sources of energy production.

The use of renewable energy in the Apulian greenhouse resulted in negative values of GWP and AC (-2.15 kg CO_2 eq and -0.011 kg SO_2 eq, respectively) (Table 2), which means that the greenhouse gases carbon dioxide (CO_2) and sulphur dioxide (SO_2) are sequestered from the atmosphere during the life cycle. These results confirm that environmental performances may be improved through the use of renewable energy systems for regulation of greenhouse habitat (Acosta-Silva et al., 2019). Furthermore, LED lights are more energy efficient than HPS lights (Katzin et al., 2021b), offering potential to reduce overall energy consumption.

These results are confirmed by a study conducted in a high-tech multi-tunnel greenhouse in Almeria, Spain (Torrellas et al., 2012b). The analysis showed that with 40% renewable energy used in the electricity generation, the environmental loads can be reduced of up to 32%. Furthermore, achieving higher yields of 25 kg m^{-2}, as in our case, by increasing the efficiency of production systems leads to a 34% reduction in inputs and environmental impacts.

Natural gas, for the heating system, is a major burden in all impact categories. The greatest burden is in terms of NRF (35%), GWP (32%) and OLD (32%) due to the emissions of CO_2 and nitrous oxide (N_2O) from combustion, as well as methane (CH_4) emitted during production. Results for heated greenhouses in France (Boulard et al., 2011a) confirm

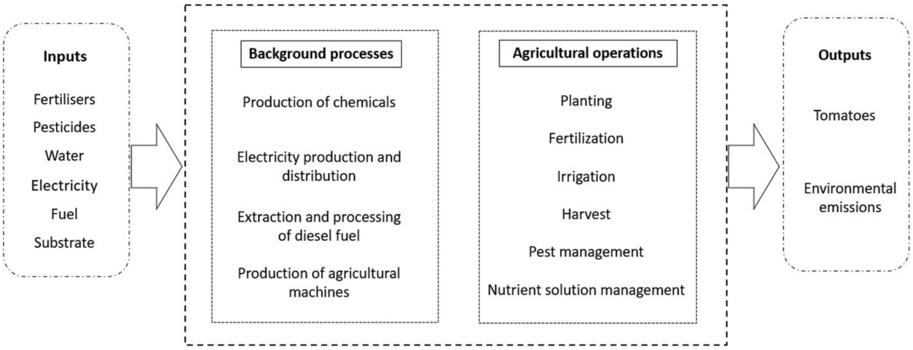

Fig. 1. System boundaries.

Table 2
Results of LCA analysis related to 1 ha of cultivated area (EPD, 2008).

Impact Category	Unit	High-tech glasshouse Soilless system	Low-tech plastic house Soil-based system
Global warming (GW)	kg CO_2 eq	−2.15	0.48
Ozone layer depletion (OLD)	kg CFC-11 eq	$66.8*10^{-8}$	$4.04*10^{-8}$
Photochemical oxidation (PO)	kg C_2H_4 eq	$8.58*10^{-4}$	$3.20*10^{-4}$
Acidification (AC)	kg SO_2 eq	$-11.0*10^{-3}$	$1.81*10^{-3}$
Eutrophication (EU)	kg PO_4^{3-}eq	$4.03*10^{-4}$	$13.0*10^{-4}$
Non-renewable, fossil (NRF)	MJ	13.6	16.4

that around 90% of the total impact is due to the use of non-renewable fossil energy for heating greenhouses. Natural gas provided 85% of the NRF impact category and caused 80% of the total GWP.

Fertilisation had the highest environmental impact on the OLD (52%) and PO (43%) categories, that are higher for soilless cultivation than for soil based. The higher consumption of fertilisers is justified by the higher planting density (4.73 stems m^{-2}) than soil-based cultivation (2.5 stems m^{-2}). The emission of acidifying compounds from fertiliser manufacturing was the main process causing the impacts. On the other hand, recycling the nutrient solution results in lower losses of fertilisers to the environment (Giuffrida et al., 2003); closed loop system significantly reduced EU by 69% compared to the soil-based system (0.0004 against 0.0013 kg PO_4 eq). This is also confirmed by comparing the results obtained in greenhouses in Spain (Anton et al., 2005). The study found a 40% reduction in eutrophication impact in transition from soil-based to soilless tomato crop.

Concerning the substrate used, rockwool production caused an environmental impact mainly determined by acidifying emissions of nitrogen oxides (NO_x), with a 10% contribution to the impact category AC. Moreover, the inert substrate does not contain soilborne pathogens, which reduces the need for pesticides.

It is evident that the low-tech system presents a highest impact for most categories. The results showed that fertilisers and electricity were major contributors to all environmental impact categories. In particular, fertiliser production caused 85% of the 0.0003 kg of C_2H_4 eq (PO) and 64% of the 0.002 kg of SO_4 eq (AC). The main contributing emissions were SO_2, NO_x and ammonia (NH_3) (Brentrup et al., 2004). Nitrogen leaching and the emission of phosphorus to soil (assuming 20% of the input) resulted in EU with an incidence of about 53%.

The case studies on unheated greenhouses in the Mediterranean regions report that in low-tech greenhouses, the management of fertilisation is often not optimal, leading to an excessive use of inputs. The results identified the use of fertilisers as the main contributor to most impact categories. In particular, fertilisation contributed significantly to EU, from about 25% to 51%, and GWP, from 30% to 45%, impact categories.

Electricity consumption, used to pump water for fertigation, contributed mainly to NRF (43%), that is almost twice the value of the high-tech greenhouse, GWP (36%) and OLD (36%), due to the emission of GHGs: CO_2, CH_4, and N_2O. This is coherent with the other LCA studies on low-tech greenhouses confirming that energy for irrigation is the second main factor contributing to environmental footprint. environmental.

The insights of this study indicated that it is possible to achieve improvements in the production system and at once lower environmental impacts with greenhouse optimisation. The LCA results showed that the switch to renewable energy and a closed-loop system can significantly reduce the environmental impacts of soilless cultivation in high-tech greenhouses.

In an effort to increase understanding of the two different production systems, a further comparative analysis was carried out using the Eco-Indicator 99 environmental assessment method. The results are shown in Table 3 and Fig. 2.

Soilless cultivation in the high-tech greenhouse generated a positive performance regarding damage to human health, 190% less damage with respect to the low-tech greenhouse. The negative endpoint category score ($-4.7*10^{-5}$ DALY) indicates an avoided environmental impact. This is due to the use of renewable solar energy that avoids the emission of inorganic compounds (respiratory inorganics) and greenhouse gases (climate change, radiation). This result confirms the importance of the transition to renewable energy in agri-food systems (FAO, 2021).

Regarding the ecosystem quality and resources indicators, high-tech greenhouse showed relatively higher damage values, 1.2 times and 1.8 times greater than low-tech greenhouses. For ecosystem damage, the major contribution arises from the ecotoxicity impact category. Fertiliser production was the process with the greatest impact, due to

Table 3
LCA results from damage assessment (Eco-Indicator 99).

Midpoint Impact Category	Endpoint Damage Category	Unit	High-tech glasshouse Soilless system	Low-tech plastic house Soil-based system
Carcinogens, Respiratory organics, Respiratory inorganics, Climate change, Radiation, Ozone layer	Human Health	DALY	$-4.7*10^{-5}$	$5.19*10^{-5}$
Ecotoxicity, Acidification/ Eutrophication, Land use	Ecosystem Quality	PDF*m^2*yr	$4.39*10^{-6}$	$3.5*10^{-6}$
Minerals, Fossil fuels	Resources	MJ surplus	$2.62*10^{-4}$	$1.46*10^{-4}$

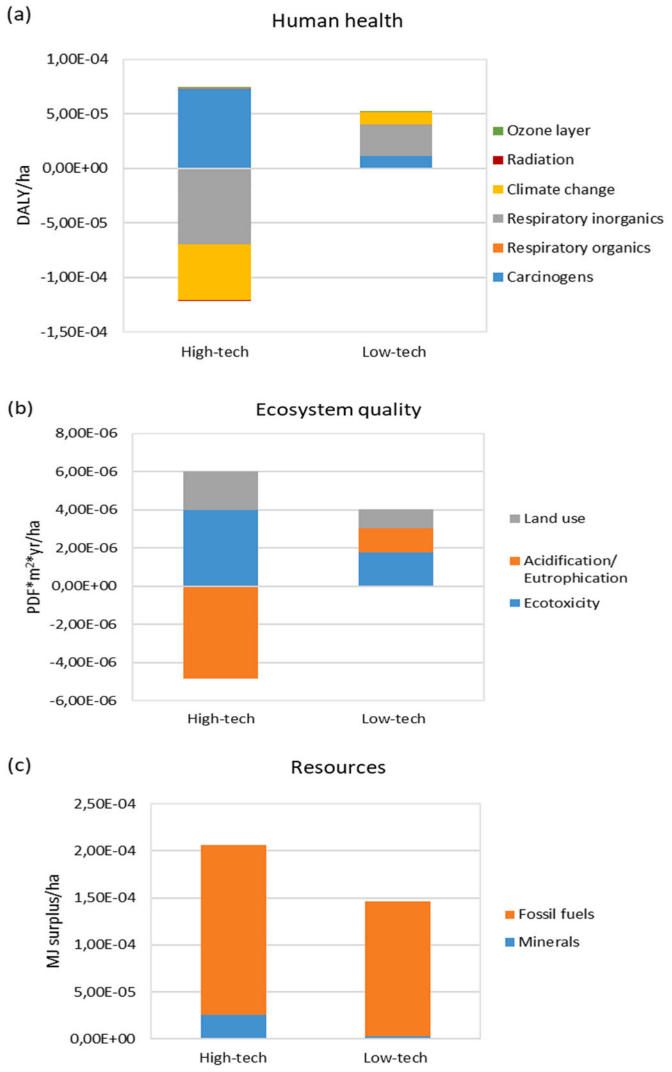

Fig. 2. Comparison of the contribution of midpoint categories to endpoint impact categories by Eco-Indicator 99 method: human health (a); ecosystem quality (b); resources (c).

emissions of nitrogen oxides. Therefore, ecotoxicity for high-tech greenhouse is higher in comparison to low-tech one due to the greater use of nutrients. For the low-tech greenhouse, acidification/eutrophication was the second most important cause of damage to ecosystem quality, with 31% of the impact. This was dominated by non-renewable energy consumption and the emission of nitrogen and phosphate compounds. On the other hand, the same category generated an avoided impact in the high-tech greenhouse (−409%), attributed to the adoption of renewable energy, which avoids the emission of acidifying compounds into the air, and the closed-loop system that avoids the emission of the eutrophicating compounds into the water.

The resources category was influenced by fossil resources depletion. In high-tech greenhouse, approximately 90% of the impact is due to the use of natural gas for greenhouse heating and the production and transport of fertilisers. In low-tech, the input that was identified to contribute the most is non-renewable energy for fertigation (80%).

Damage analysis at the endpoint level showed slightly higher environmental impacts for the ecosystem quality and resources categories of the high-tech greenhouse; however, these are offset by the positive environmental performance (avoided impact) in the acidification/eutrophication midpoint impact category and human health endpoint damage. Moreover, it should be underlined that the yield is 1.5 times higher for the soilless technique in a high-tech greenhouse.

Fig. 2 shows the contribution of the midpoint impact categories on the three endpoint categories.

3.2. *Scenario sensitivity analysis*

A scenario sensitivity analysis was performed for LCA results of the high-tech greenhouse, considering the variability of electricity consumption and fresh tomato yield, as those are the most important input in heated greenhouses and output, respectively. For the analysis, the One-At-a-Time (OAT) method was applied (Pianosi et al., 2016); the influence of reduction and increase was evaluated by assigning each parameter a range of variation between −10% and +10%, according to the specifications of the Apulian high-tech greenhouse technicians. Stochastic modelling was performed to estimate the probability of variation with a number of 100 simulations. From the probabilistic approach, the highest probability levels were selected, −9%, +3%, +10% for the energy requirement and −4%, +5% for the yield (Fig. 3).

The results in Table 4 show that the 10% increase in energy consumption is the variation that most influences the LCA results. The worsening of environmental performance is due to the dependence on the electricity grid to satisfy the increased energy demand not met by photovoltaic panels. In detail, the negative variations in GW and AC show that higher energy requirement, satisfied by fossil fuels, reduces the positive effect on avoided pollutant emissions of the base case (photovoltaic energy only). The sensitivity analysis highlighted that the use of renewable energies sources is determinant for the viability of greenhouse production systems. Otherwise, the −9% reduction in electricity utilization would increase GHG emissions savings by +1.5% and +1.2% for GW and AC respectively. Yield variations have proportional influences on environmental loads, so negative yield variations negatively affect environmental performance. In general, the average variations showed that the varied parameters did not significantly affect the relative results, demonstrating the viability of the results and the robustness of the model.

4. Discussion

Energy consumption and associated emissions depend on the greenhouse type and the source used. The most innovative element of Apulian high-tech greenhouse lies in the energy approach. The results of this study showed that the use of photovoltaic panels allowed large savings in terms of energy consumption and greenhouse gas emissions. The findings of the literature confirm that the environmental loads can be reduced considerably with renewables sources reducing CO_2 emissions (Achour et al., 2021; Chel and Kaushik, 2011b; Nicolosi et al., 2017). In addition, as reported by Palmitessa et al. (2020b), to be more energy efficient, LED lights offer stable output on an annual basis and the increase in output could mitigate environmental impacts per unit of product.

The eutrophication potential, mainly due to nitrate leaching, depends on fertilisation management. In the soil-based system, the absence of fertigation sensors and recirculation system means that the crop is always fed with fresh solution delivered more than the actual needs of the plants. Excess solution leads to nutrient leaching and consequent pollution of water bodies (Bres and Politycka, 2016).

In the high-tech greenhouse analysed fertigation sensors and the closed-loop system reduce excessive fertiliser use, moreover, not using the soil prevents nutrient leaching and the loss of irrigation water through gravity. These results are in accordance with those of other studies (Gonnella and Renna, 2021b; Massa et al., 2020b), which reported an improved input use efficacy in soilless cultivation with closed-loop systems. Other authors stated that sensors and micro-irrigation, at reduced flow rates, save water by optimising distribution in proportion to the absorption capacity of the plants (Fan et al., 2020; Nikolaou et al., 2019). According to Pardossi et al. (2009) Pardossi, the high-water efficiency makes closed-loop systems

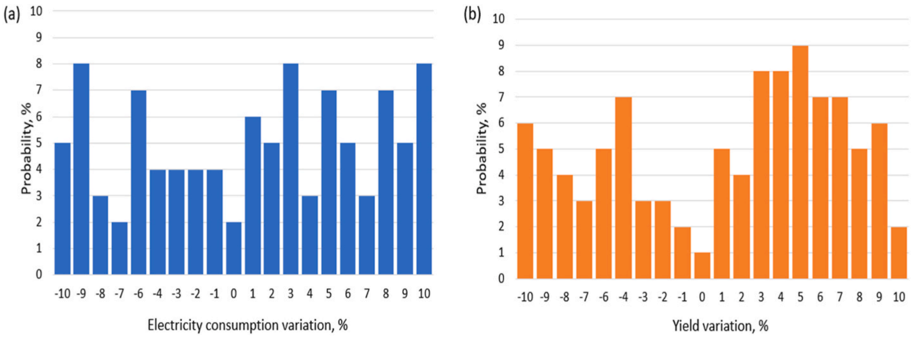

Fig. 3. Probability distribution of: (a) percentage variation in energy consumption; (b) percentage variation in yield.

Table 4
OAT sensitivity analysis.

Impact categories	Variation				
	Electricity −9%	Electricity +3%	Electricity +10%	Yield −4%	Yield +5%
GW (kg CO_2 eq)	+1.5%	−4.8%	−15.8%	+4%	−5%
OLD (kg CFC-11 eq)	−1.5%	+1.8%	+6.0%	+4%	−5%
PO (kg C_2H_4 eq)	−5.1%	+5.4%	+18.1%	+4%	−5%
AC (kg SO_2 eq)	+1.2%	−3.7%	−12.5%	+4%	−5%
EU (kg PO_4^{3-} eq)	−9.0%	+8.3%	+27.8%	+4%	−5%
NRF (MJ)	−3.8%	+10.4%	+34.6%	+4%	−5%
Average variation	−2.8%	+2.9%	+9.7%	+4%	−5%

interesting for areas with a climate with low water availability.

An important negative impact derives from the waste of rockwool substrate used in soilless technique. The use of rockwool is criticised by the problem of landfilling, which is responsible for significant pollutant emissions. However, some studies report that sustainability can be improved through recycling, for example by mixing it with peat to create a potting substrate (Boulard et al., 2011b; Bussell and Mckennie, 2004a). Currently, very few studies have evaluated the possibility of composting rock wool, which is mainly hampered by the presence of plastic. A study showed that after a grinding and drying process, plastic residues can be separated from rock wool, which can be reused again as a substrate or for the production of bricks (Bussell and Mckennie, 2004b). Therefore, further research is needed to increase the sustainability of soilless cultivation from a circular economy perspective.

The results of this study are in line with previous studies which showed that high-tech greenhouses and hydroponic growing techniques can reduce the environmental impact of greenhouse horticulture (Gruda et al., 2019; Koukounaras, 2020; Pomoni et al., 2022; Van Tuyll et al., 2022). However, the literature review revealed that there are economic, governmental and technological barriers to renewable energies adoption. The high initial investment required, the difficulty in obtaining funding and the low availability of skilled technicians are the main factors affecting the renewable energy sector (Omer, 2016; Seetharaman et al., 2019). Similar obstacles have been encountered for the development of soilless cultivation and high-tech greenhouses, which to date represent a small percentage compared to low-tech greenhouses. The biggest challenge for entrepreneurs is the high initial investment cost for the construction and operation of the greenhouse (Rahman and Alam, 2023; Velazquez-Gonzalez et al., 2022). In addition, there are difficulties in finding proper know-how and technical support for control systems and software management (Azizoglu et al., 2021; Kavga et al., 2018).

In our view, considering the various obstacles, political decisions will be crucial for the development and diffusion of state-of-the-art production techniques and renewable energies. Governments and public bodies should ensure adequate subsidies to support expensive technologies, promote training programmes for competent technicians, and support research to improve the efficiency of production techniques and renewable technologies.

We want to emphasise that to compare the performance of the Apulian high-tech greenhouse with a low-tech one, we modelled the low-technology scenario on data from literature studies on greenhouse tomato production in Mediterranean regions. The authors of the selected studies affirm that the inventory data are representative of greenhouse tomato cultivation in the country. Therefore, we acknowledge that the comparison is not absolute because management practices in greenhouses vary according to their regional location.

Although the reference system was representative, the quantitative part of our study was limited in terms of the sample size of smart greenhouses; unfortunately, the adoption of high-tech innovations is not widely spread in Apulian greenhouses. The analysis of the environmental sustainability of more high-tech greenhouses in the study area could improve the reliability of the results. Therefore, we hope that in future research, following the diffusion of high-tech greenhouses, a larger sample can be considered to provide a more representative analysis.

5. Conclusions

The transition to sustainable agriculture requires the development of new techniques and management practices that are efficient in terms of water, nutrients and energy. It is therefore a matter of implementing a process of technological innovation in greenhouse cultivation, aimed at reducing environmental impact and standardising production systems, as far as quality and quantity.

The main aim of this study was to investigate the environmental performance of cherry tomato cultivation in Italy's first high-tech hydroponic greenhouse using life cycle analysis methodology. The Apulian high-tech greenhouse was intended as representative of the more advanced cultivation technologies for the improvement of Mediterranean greenhouses. Through a comparison with the environmental performance of the low-tech greenhouse scenario, this study provided an understanding of possible technological and production innovations that can be used to reduce the environmental impacts of greenhouse production.

By means of application of LCA it has been achieved the definition of the main environmental burdens and the evaluation of possible alternative reduction methods. The results of the comparison of the two greenhouse cultivation systems showed that electricity and fertigation are the main hotspots in greenhouse cultivation. This LCA study showed that the switch to renewable energy and a closed-loop system is crucial to improve the environmental sustainability of the greenhouse sector. The results obtained showed that the use of renewable energy in the high-tech was of great importance. Photovoltaic panels generated considerable avoided impacts on global warming and acidification potential, −2.15 kg CO_2 eq and −0.011 kg SO_2 eq, respectively. Moreover, the use of supplementary LED light results in higher yields in the high-tech greenhouse, 25 kg m^{-2} compared to 16 kg m^{-2} for the low-tech greenhouse.

In soilless cultivation, recycling the nutrient solution results in lower fertilisers losses to the environment. In fact, the closed loop system significantly reduced the eutrophication potential by 69% compared to the soil-based system (0.0004 vs. 0.0013 kg PO_4 eq).

The sensitivity analysis highlighted that the use of renewable energies sources is determinant to improve the sustainability of greenhouse production systems. The analysis also showed that the higher yields achieved in soilless cultivation in high-tech greenhouses reduce the overall environmental load. High-technology greenhouses offer the opportunity to improve yields while reducing environmental impact using energy-efficient and water-saving technologies. In this study, it was shown that a high-tech greenhouse can be environmentally sustainable with the use of renewable energy, fertigation sensors and a closed-loop system.

However, nowadays, high-tech greenhouses are not widespread in some Mediterranean regions such as Italy, which are dominated by unheated greenhouses with reduced technological equipment. Technological advances require considerable investment by the agricultural entrepreneurs. Therefore, economic feasibility is another important aspect to consider. Consequently, the analysis will be integrated with the assessment of the economic sustainability of soilless cultivation in high-tech greenhouse. Future research will deal with monitoring of performances and practicability of this innovative technology over time.

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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.

Data availability

Data will be made available on request.

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