Journal of Cleaner Production 534 (2025) 146920

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Life cycle assessment of open and closed hydroponic systems for vegetable (tomato and cucumber) production in arid lands

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HIGHLIGHTS

- Closed hydroponic systems reduced environmental impacts by 8–11 % compared to open ones.
- Integrating solar energy helps reduce greenhouse gas emissions and mitigate the depletion of fossil fuels.
- Life cycle assessment confirmed closed hydroponics as a climate-smart farming solution.
- A trade-off between the environmental and the economic benefits of hydroponic systems exists.
- Long-term environmental benefits exceed short-term economic benefits, especially for closed hydroponic systems.

ARTICLE INFO

Keywords:
Open hydroponics systems
Closed hydroponics systems
Tomato and cucumber production
Arid land
Life cycle assessment (LCA)
Renewable energy

ABSTRACT

This study employs a life cycle assessment (LCA) approach to compare the environmental impacts of open hydroponic systems (OHS) and closed hydroponic systems (CHS) across 35 farms in Abu Dhabi, United Arab Emirates. Using SimaPro© software and ReCiPe methodology, the analysis highlights substantial reductions in greenhouse gas emissions, energy consumption, and water usage in CHS compared to OHS. The LCA analysis is augmented with economic analysis. CHS showed marked advantages across key environmental indicators, including reductions in abiotic depletion (11 %), global warming potential (9 %), and eutrophication potential (8 %). Additionally, endpoint analysis indicated that CHS significantly improved outcomes for human health, ecosystems, and resource conservation by limiting nutrient leaching, chemical runoff, and pollution. Reusing nutrient solutions in the CHS contributed to enhanced water and energy efficiency, addressing critical challenges of water scarcity and high energy costs in arid regions. Furthermore, CHS reduced health-related impacts, such as respiratory conditions, by lowering emissions of pollutants. The study also identified solar energy as a sustainable alternative to fossil fuels, further decreasing environmental impacts when integrated with CHS. While initial investments in CHS are higher, their long-term benefits, including biodiversity conservation and reduced ecological footprints, make them a promising solution for sustainable agriculture. These findings support policymakers, engineers, and farmers adopting hydroponics to enhance food security and sustainability in arid environments. This study evaluates tomato and cucumber production's economic and environmental performance under open and closed hydroponic systems in the UAE. Using farm-level data and life cycle assessment, we calculate net returns and global warming potential (GWP) per kilogram for each crop-system combination. Eco-efficiency, defined as net return per unit of GWP, is used to assess climate-smart profitability. Results show that cucumber in CHS yields the highest economic and eco-efficiency, while CHS offers lower GWP and better environmental performance for tomatoes. Sensitivity analysis results emphasize the importance of material selection in a sustainable greenhouse design.

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https://doi.org/10.1016/j.jclepro.2025.146920
Received 29 January 2025; Received in revised form 2 June 2025; Accepted 23 October 2025
Available online 18 November 2025
0959-6526/

1. Introduction

The global population is projected to increase from approximately 8 billion today to 8.5 billion by 2030 and 9.7 billion by 2050 (United Nations, 2015). This growth and rising income levels, shifting dietary preferences, and escalating demand for diverse diets have substantially strained global food systems. These challenges are further compounded by the limited availability and productivity of critical resources, such as water, energy, and arable land, which vary significantly across regions and production systems (Ranganathan et al., 2018). Further, given the adverse impacts of climate change, particularly in arid and semi-arid regions where water scarcity and soil degradation are prevalent, the need for adopting sustainable agricultural practices has attained paramount importance. In particular, the Arabian Peninsula, including the United Arab Emirates (UAE), clearly showcases the challenges confronted under such environmental conditions. In these regions, agriculture consumes 78 % of the total water consumption, predominantly from non-renewable groundwater. resources (Odhiambo, 2017; "The State of Food and Agriculture, 2020,"). The resulting overexploitation of these resources has led to declining water tables and increased salinity, exacerbating water scarcity and undermining agricultural sustainability (Elhadj, 2004).

Alternatively, hydroponic farming has become an attractive, sustainable agricultural strategy in water-scarce regions, as it eliminates the need for soil and optimizes water use. The UAE, characterized by arid conditions and increasingly affected by climate change, has been working to enhance its agricultural sector. To this end, it has embraced sustainable and climate-smart farming practices, focusing on optimal land management and improving local product quality. One such initiative is the "Zaarie" program, which provides farmers with investment grants and interest-free loans to promote the economic and environmental advantages of hydroponic farming systems. These systems, specifically for vegetable production, increase the supply of fresh, locally grown food, reducing reliance on imports. This increased local supply lowers average food prices, contributing to food security. According to previous studies, hydroponic farming systems may save up to 90 % of water usage compared to conventional agricultural practices, making them particularly effective in arid areas with limited water resources (Sousa et al., 2024). Moreover, closed hydroponic systems (CHS) recycle nutrient solutions and are more resource-efficient. However, they require higher water quality and initial investment to establish than those required by open hydroponic systems (OHS), which are less efficient and generate more waste (Maucieri et al., 2019). Despite these benefits, hydroponic systems are energy-intensive because they rely on artificial lighting, water pumps, and climate control. Additionally, the environmental impacts of these energy demands vary significantly depending on the energy source used – Fig. 1. For instance, studies by Romeo et al. (2018) and Martin and Molin (2019) highlighted the potential of renewable energy sources, such as solar and wind power, to mitigate the carbon footprint of hydroponic systems.

Since the 1960s, life cycle assessment (LCA) has been utilized for assessing the environmental effects of agricultural systems, providing a "cradle-to-grave" analysis of resource use, emissions, and waste generation, thereby offering valuable insights into the sustainability of production systems (Roy et al., 2009; Cellura et al., 2012). Specifically, in the case of hydroponics, LCA studies have revealed significant environmental benefits such as reduced water use and emissions, while identifying significant trade-offs such as high energy consumption and material requirements. (Li et al., 2018). Region-specific LCA studies have further underscored the adaptability of hydroponic systems to diverse climatic conditions. For example, it was found that hydroponic tomato production in Iran resulted in an 11 % reduction in environmental impacts compared to traditional greenhouses (Mofatteh et al., 2024).

Adopting hydroponics in arid regions confronts hurdles such as high setup costs and energy requirements, and insufficient technical skills. Further, poor water quality, often characterized by high salinity, poses additional problems and requires advanced treatment systems to maintain optimal performance (Nadeem et al., 2024). However, adopting innovative approaches such as integrating renewable energy, enhancing nutrient cycling, and improving waste management practices can largely contribute to overcoming these challenges and enhancing hydroponic systems' sustainability (Farvardin et al., 2024; Sisodia et al., 2021). While Life Cycle Assessment (LCA) provides a robust framework for evaluating these trade-offs by quantifying the environmental impacts of hydroponic systems across their life cycles, few studies have explicitly focused on arid regions, where challenges such as high salinity, extreme heat, and limited access to renewable energy significantly influence the environmental performance of these systems (Farvardin et al., 2024; Nadeem et al., 2024). Therefore, we addressed this knowledge gap by analyzing hydroponic systems tailored for arid conditions to gain insights into adopting sustainable farming practices in water-scarce environments. This study offers great potential for influencing global food security and environmental sustainability. As arid regions are particularly vulnerable to climate change, developing resource-efficient agricultural systems is essential to enhance resilience and reduce reliance on food imports, consistent with the UN Sustainable Development Goals of Zero Hunger (SDG 2), Clean Water and Sanitation (SDG 6), and Climate

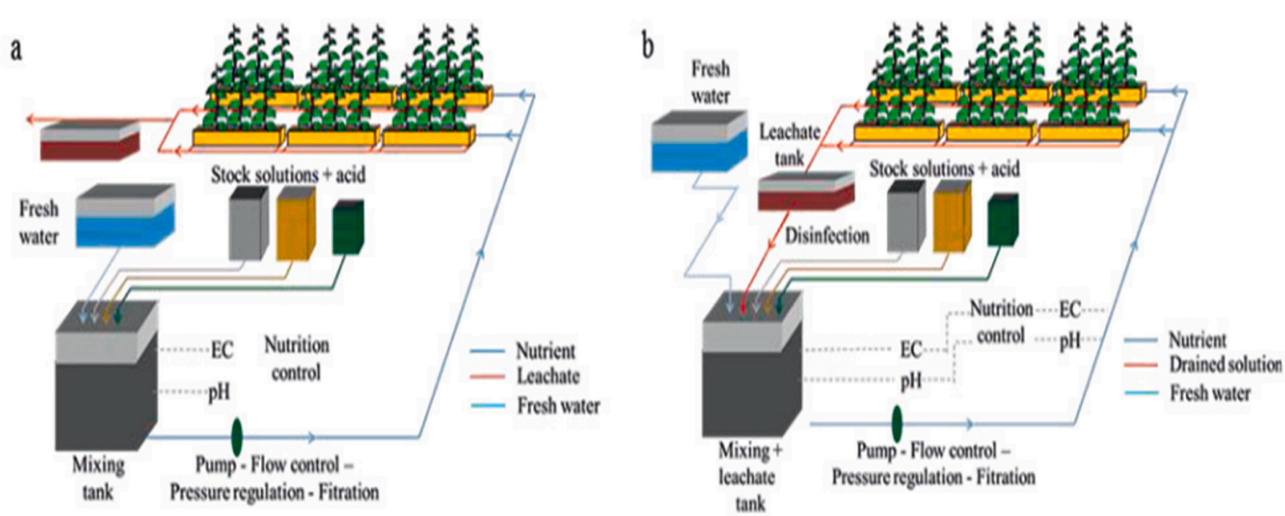

Fig. 1. (a) OHS and (b) CHS (source: Putra and Yuliando, 2015).

Action (SDG 13). Moreover, the findings reported herein are of great significance for policymakers, agricultural engineers, and decision-makers, who can assist in implementing sustainable practices in response to the current pressing environmental and societal challenges.

2. Methodology

2.1. Aims and scope

This study aimed to identify the environmental impacts of OHS and CHS in the UAE, a region with typical arid land conditions. Particularly, the study aimed to (1) establish a basis for assessing the environmental impact of vegetable production in a controlled environment under arid climatic conditions and (2) determine the most sustainable vegetable cultivation option with the least environmental impact. An attributional cradle-to-gate LCA was used to calculate the annual environmental footprint of tomato and cucumber production per unit weight. The functional unit is defined as 1 kg of marketable vegetable produced.

The system boundaries for the LCA study on the hydroponic systems are defined as "cradle-to-gate." This includes all processes and inputs involved from the initial production of materials to the point where vegetables are ready for distribution. Key inputs within the system boundaries are raw materials, greenhouse structures (including frames, coverings, and foundations), auxiliary equipment (such as irrigation systems, substrates, and electricity), hydroponic nutrient solutions, and energy supply. Outputs considered include the production of vegetables (tomatoes and cucumbers) and emissions into air, water, and soil. The LCA excludes processes beyond the gate, including composting and recycling of waste materials, transportation of inputs, and distribution and transportation of the final output. These exclusions are based on limited data availability and their relatively marginal contribution to on-site environmental impacts in preliminary assessments.

2.2. Life cycle inventory

Hydroponic production systems were divided into multiple stages for inventory analysis to facilitate the examination and interpretation of the results: greenhouse construction, auxiliary equipment, and hydroponic nutrient solutions. Fig. 2 shows a flow diagram of the production system, and all procedures included in the flow diagram adhered to the parameters established for the purpose and scope of the study.

The life cycle inventory (LCI) for OHS and CHS highlights the resources and outputs involved in vegetable production. OHS uses 4761 m^2 of land compared to 5062 m^2 in CHS, with growing substrates like rock wool requiring 10,712 kg and 11,390 kg, respectively (see Table S1). Greenhouse structures include materials such as galvanized steel pipes and sheets, high-density polyethylene, and concrete, sourced and calculated per area based on the guidelines offered by Almarzooqi (2018). Table 1 illustrates that CHS demand more water (16,412 m^3 for irrigation and 46,824,000 kg for cooling, compared to 12,000 m^3 and 38,083,000 kg in OHS) and consumes additional energy for operations and desalination due to advanced nutrient and water recycling processes. Nutrient inputs, including nitrogen, phosphorus, potassium, and trace elements like zinc and boron, are also slightly higher in CHS to support their efficient recycling mechanisms. Despite these increased inputs, CHS yields higher vegetable output, producing 257 tons annually compared to 214 tons in OHS (Almarzooqi, 2018; ADFSC Hydroponic

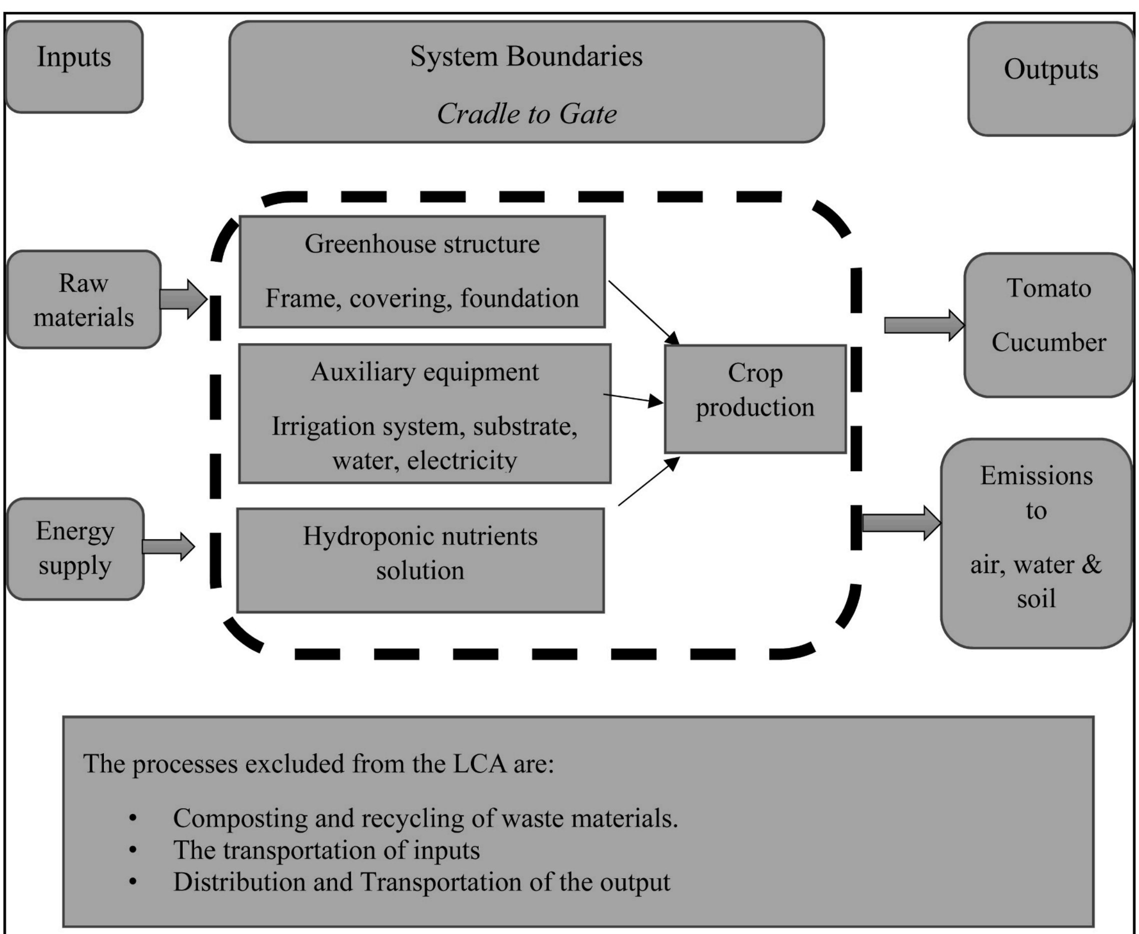

Fig. 2. System boundaries 'cradle-to-gate' of the hydroponic production systems.

Table 1
LCI for OHS and CHS based on annual output per kilogram.

Input	Unit	OHS	CHS
Land	m^2	4761	5062
Hydroponic nutrient solution	kg	2063	1736
Hydroponic greenhouse structure	kg	1,445,183	1,536,656
Substrate (Rockwool)	kg	10,712	11,390
Seedlings	Plant	42,849	45,558
Irrigation water	m^3	12,000	16,412
Water for the cooling system	kg	38,083,000	46,824,000
Energy consumption	kWh	4,825,637	5,131,201
Energy for water desalination	kWh	1,171,950	1,479,706
Outputs			
Vegetable	ton	214	257

Manual).

2.3. Impact assessment

A comparative analysis of OHS and CHS was performed using Simapro 9.4.0 ® software, which combines the allocation at the point of replacement database with many LCI datasets, such as Ecoinvent v3.7. A list of all the LCI datasets used in the analysis is included in the Supplementary Material (Supplementary S1). The midpoint and endpoint methods, which are characterization models offering indications at several levels, are routinely used by life-cycle impact assessment (LCIA) consultants. The endpoint method evaluates how the environment affects resources, ecosystems, and human health under areas of production (AoP). In turn, the midpoint method evaluates the environmental impacts along the entire cause-and-effect chain, from substance release or resource consumption to the endpoint. This ReCiPe analysis is a favored LCIA method for LCA research because it compares midpoint and endpoint methods by distilling information from inventories into a single score. The approach yields detailed halfway findings; however, the endpoint results are simple. Furthermore, ReCiPe is particularly beneficial for obtaining endpoint findings because it includes additional damage information (ILCD, 2011). This study examined endpoint-level data to determine the environmental effects and damage caused by two hydroponic systems, with an emphasis on the natural environment, human health, and natural resources (Keyes et al., 2015; Vinyes et al., 2015). The H perspective, which is a consensus model, was used to evaluate the environmental effects of both OHS and CHS. The H viewpoint was selected because its superiority corresponds to the scope of this study. The attributional life cycle assessment (ALCA) technique, which uses a reason-and-outcome chain approach, was used to investigate the shift in environmental conditions and resource flow caused by functional unit modifications. Key-effect categories included acidification, global warming, human toxicity, abiotic depletion, and eutrophication (Table 2).

In this study, the LCA is augmented by performing an economic analysis, which involves calculating the net return by subtracting operational and fixed costs from revenue for each of the four options: CHS-tomato, CHS-cucumber, OHS-tomato, and OHS-cucumber. The options are then ranked from highest to lowest net revenue for average farms in each of these alternatives.

Table 2
Selected impact categories, their abbreviations, and the measurement units.

Impact categories	Abbreviation	Unit
Abiotic depletion	AD	kg Sb eq
Abiotic depletion (fossil fuels)	AD(FF)	MJ
Global warming (GWP100a)	GWP	kg CO_2 eq
Ozone layer depletion	OLD	kg CFC-11 eq
Human toxicity	HT	kg 1,4-DB eq
Freshwater aquatic ecotoxicity	FE	kg 1,4-DB eq
Marine aquatic ecotoxicity	ME	kg 1,4-DB eq
Terrestrial ecotoxicity	TE	kg 1,4-DB eq
Photochemical oxidation	PO	kg C_2H_4 eq
Acidification	AC	kg SO_2 eq
Eutrophication	EP	kg PO_4 eq

Furthermore, this study conducted a sensitivity analysis in life cycle assessment (LCA), which is a method used to evaluate how changes in input assumptions or parameters impact the results of an LCA study. This analysis helps identify which variables have the most significant influence on the outcome, thereby providing insight into the robustness and reliability of the results.

3. Results

3.1. Environmental impact of hydroponic systems

LCA comprehensively evaluates the environmental impacts of a product or process by examining various impact categories, each addressing a specific aspect of environmental sustainability. Specifically, abiotic depletion focuses on reducing non-renewable resources, including minerals measured in kg antimony equivalents (kg Sb eq) and fossil fuels assessed in terms of MJ or kg oil equivalents (Salas et al., 2016). Meanwhile, the global warming potential (GWP) category measures the impact of greenhouse gas (GHG) emissions on climate change over a 100-year horizon and is expressed as kg CO_2 equivalents (kg CO_2 eq). In turn, the ozone layer depletion (OLD) category evaluates substances such as chlorofluorocarbons (CFCs), which cause a thinning of the ozone layer, measured in kg CFC-11 equivalents (kg CFC-11 eq) (Salas et al., 2016). Finally, the human toxicity category assesses the potential health impacts of carcinogenic and non-carcinogenic chemical emissions in kg 1,4-dichlorobenzene equivalents (kg 1,4-DB eq).

In addition to the aforementioned, LCA encompasses the following ecotoxicity categories: freshwater aquatic, marine aquatic, and terrestrial ecotoxicities, which measure the harmful effects of chemical emissions on freshwater, marine, and terrestrial ecosystems, all expressed in kg 1,4-DB equivalents. Meanwhile, photochemical oxidation potential, related to smog formation from nitrogen oxides (NOx) and volatile organic compounds (VOCs), is assessed in kg ethylene equivalents (kg C2H4 equivalents). In turn, acidification potential evaluates the emissions that contribute to the acidification of soil and water, often resulting in acid rain, and is measured in kg sulfur dioxide equivalents (kg SO_2 eq). Finally, eutrophication potential examines the impact of nutrient emissions, such as nitrogen and phosphorus, on water-body over-enrichment, leading to oxygen depletion and harm to aquatic life, and is expressed in kg phosphate equivalents (kg PO_4 eq).

By analyzing these impact categories, LCA offers a holistic view of environmental impacts, guiding sustainable decision-making to mitigate resource depletion, combat climate change, and protect ecosystems and human health (Lopes et al., 2018; Chen et al., 2020).

3.2. Environmental impact of OHS

Fig. 3 illustrates the environmental impacts of the various components and processes within OHS, highlighting the multifaceted nature of its environmental footprint. In the abiotic depletion category, materials such as galvanized steel and high-density polyethylene used in greenhouse structures were the primary contributors, indicating a significant impact of construction materials on mineral resource depletion. Electricity for cooling, pumping, and desalination processes emerged as the dominant factor in the abiotic depletion of fossil fuels, reflecting the substantial energy demands of the system. Similarly, in the global warming-potential category, electricity used in cooling, pumping, and desalination accounted for the most significant GHG emissions, with additional contributions from high-density polyethylene, galvanized steel, and concrete.

Ozone layer depletion was primarily driven by electricity usage across various processes, which underscores the environmental costs of

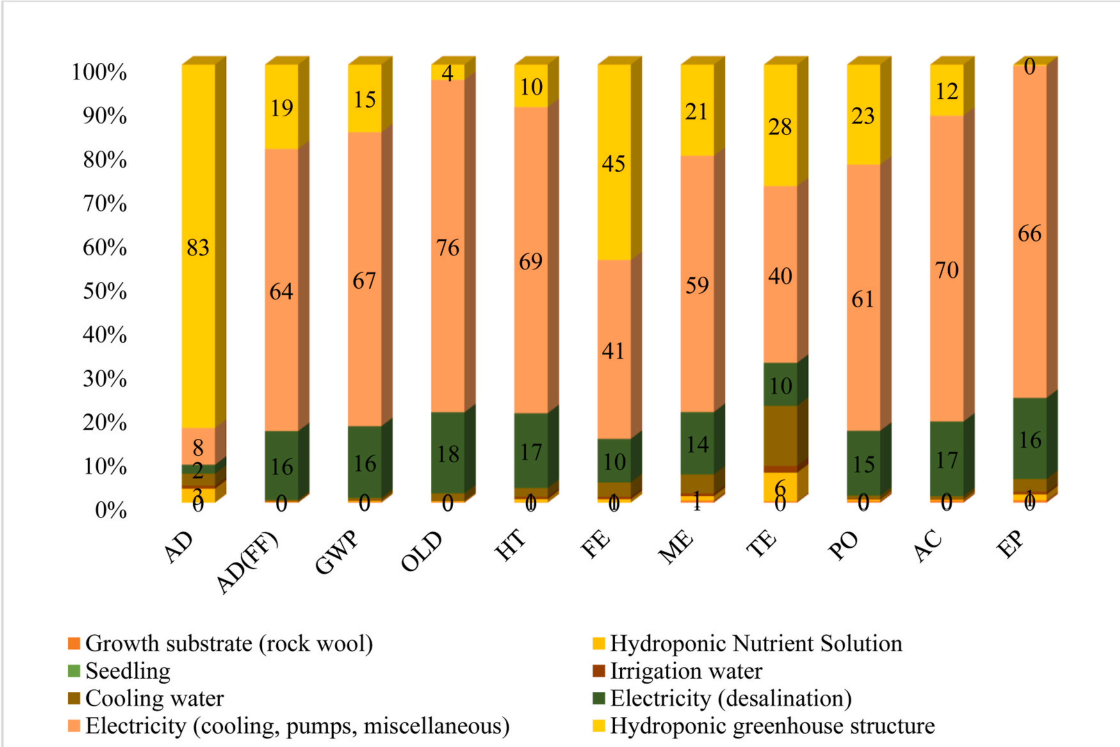

Fig. 3. Environmental impact categories for the various components and processes in OHS.

energy consumption. In the human toxicity category, electricity for cooling and desalination, as well as materials such as high-density polyethylene and concrete, were the main contributors, highlighting the health risks associated with the use of energy and materials. In turn, freshwater and marine aquatic ecotoxicities were significantly affected by galvanized steel sheets, electricity usage, and high-density

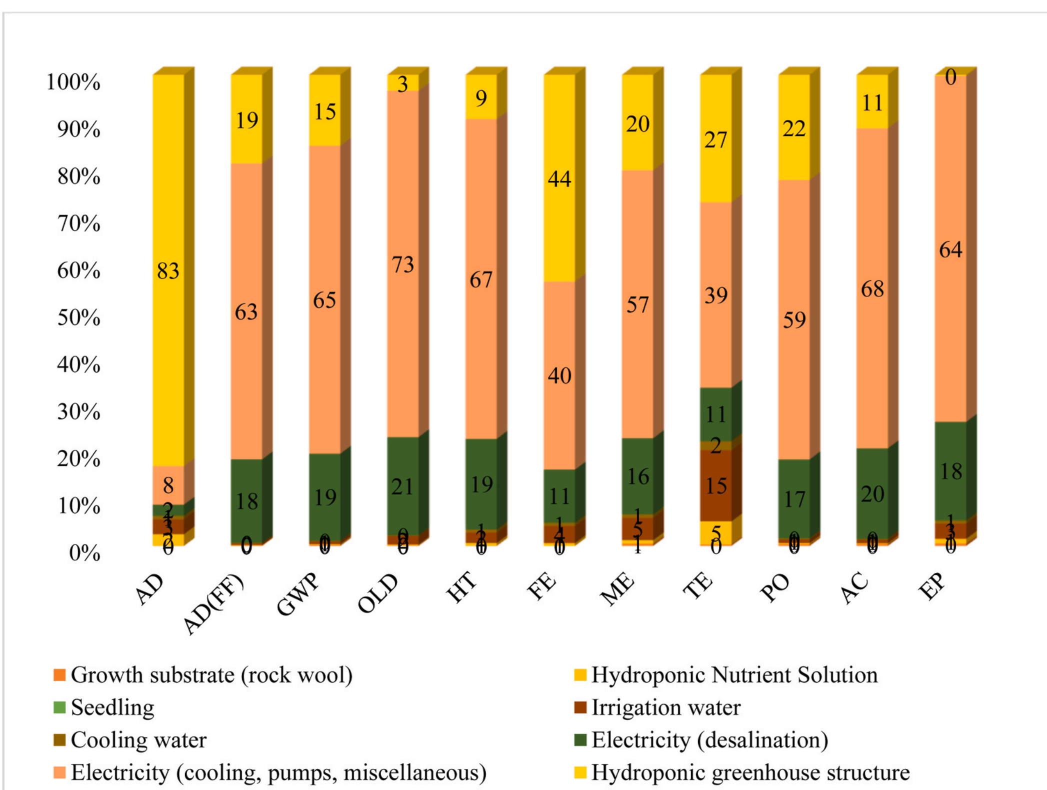

Fig. 4. Environmental impact categories for the components and processes in CHS.

polyethylene, with additional impacts from water used for cooling and irrigation. Moreover, electricity for cooling, water usage, and materials such as concrete and galvanized steel were the primary contributors to terrestrial ecotoxicity, with some impacts from hydroponic nutrient solutions.

Electricity for cooling and desalination mainly influenced photochemical oxidation and acidification, along with contributions from high-density polyethylene and galvanized steel sheets. Notably, the eutrophication category exhibited a negative impact from galvanized steel, which mitigated the nutrient enrichment effects, whereas electricity usage made a positive contribution. These findings underscore the complex interplay between energy and material inputs across different environmental-impact categories, emphasizing the need for targeted strategies to mitigate these effects in open hydroponic systems.

3.3. Environmental impact of CHS

Fig. 4 highlights the environmental impact categories associated with the components and processes of CHS, revealing similarities with the OHS, as well as significant differences. A key distinction was the significant contribution of irrigation water across all environmental impact categories, which can be attributed to the large cultivation areas in the CHS. As in the OHS, abiotic depletion is primarily driven by galvanized steel in greenhouse structures, although the relative contribution was slightly altered. Abiotic depletion of fossil fuels and global warming potential (GWP-100a) continue to have substantial impacts on electricity use, specifically for cooling, pumping, and desalination, owing to the UAE's heavy reliance on natural gas for power generation.

Electricity use dominated most impact categories, including ozone layer depletion, reflecting its significant environmental footprint. This reliance on natural gas as an energy source aligns with the UAE's strategy of reducing its carbon footprint while meeting its growing energy demands. However, fossil fuel dependence continued to contribute to greenhouse gas (GHG) emissions, highlighting the need for improved energy efficiency and greater adoption of renewable energy sources to reduce environmental impacts. Interestingly, the galvanized steel sheets in greenhouse structures negatively contributed to eutrophication and human toxicity, suggesting potential environmental benefits in specific contexts.

Table 3
Life cycle impact indicators in OHS and CHS (per unit weight basis).

Impact categories	Unit	OHS	CHS	Increase in the OHS compared to the CHS
Abiotic depletion	kg Sb eq	1.04E-05	9.24E-06	11 %
Abiotic depletion (fossil fuels)	MJ	4.35E+02	3.97E+02	9 %
Global warming (GWP100a)	kg CO_2 eq	2.38E+01	2.17E+01	9 %
Ozone layer depletion	kg CFC-11 eq	1.76E-06	1.62E-06	8 %
Human toxicity	kg 1,4-DB eq	2.37E+00	2.17E+00	8 %
Freshwater aquatic ecotoxicity	kg 1,4-DB eq	1.42E+00	1.29E+00	9 %
Marine aquatic ecotoxicity	kg 1,4-DB eq	3.62E+03	3.31E+03	9 %
Terrestrial ecotoxicity	kg 1,4-DB eq	5.95E-03	5.43E-03	9 %
Photochemical oxidation	kg C_2H_4 eq	4.66E-03	4.24E-03	9 %
Acidification	kg SO_2 eq	9.45E-02	8.64E-02	9 %
Eutrophication	kg PO_4 eq	7.41E-03	6.81E-03	8 %

3.4. Comparison of environmental impact between OHS and CHS

A comparative analysis (Table 3) revealed that CHS are more environmentally friendly than OHS across all categories. For instance, abiotic depletion increased by 11 % in OHS, indicating greater consumption of non-renewable mineral resources. Similarly, the abiotic depletion of fossil fuels increased by 9 %, reflecting higher energy use. Global warming potential and ozone layer depletion also increased by 9 % and 8 %, respectively, suggesting higher greenhouse gas (GHG) emissions and a greater impact on the ozone layer in OHS. Meanwhile, toxicity-related categories, such as human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, and terrestrial ecotoxicity, each exhibited a 9 % increase, highlighting a more pronounced harm to human health and ecosystems by OHS. Other categories, including photochemical oxidation, acidification, and eutrophication, showed similar increases.

Overall, these findings underscore the environmental advantages of CHS, with reduced impacts ranging from 8 % to 11 % across all categories, compared with OHS. These insights emphasize the importance of CHS in optimizing resource use efficiency and minimizing the environmental footprint of sustainable agriculture.

3.5. Environmental impacts of tomato and cucumber production

In addition to the above environmental impacts of hydroponic systems *per se*, this study evaluated the environmental impact of tomato and cucumber production in OHS and CHS. The results summarized in Table 4 revealed significant differences in the environmental impacts between the two systems. CHS showed lower environmental impacts across most categories than those shown by OHS. For example, the global warming potential (GWP100a) of tomatoes was reduced by nearly half, from 61.811 kg CO_2 eq in OHS to 31.370 kg CO_2 eq in CHS. Similarly, GWP100a of cucumbers decreased from 18.489 in OHS to 17.036 kg CO_2 eq in CHS. Moreover, CHS showed notable reductions in marine aquatic ecotoxicity (4815.840 kg 1,4-DB eq for tomatoes and 2630.714 kg 1,4-DB eq for cucumbers) compared to OHS. Other categories, such as abiotic depletion of fossil fuels, human toxicity, and acidification, also showed marked reductions in CHS for both crops,

Table 4
Life cycle impact indicators for tomato and cucumber in OHS and CHS (on a per unit weight basis).

Impact categories	Unit	Tomato		Cucumber	
		OHS	CHS	OHS	CHS
Abiotic depletion	kg Sb eq	0.000	0.000	0.000	0.000
Abiotic depletion (fossil fuels)	MJ	1100.477	572.620	327.008	310.201
Global warming (GWP100a)	kg CO_2 eq	61.811	31.370	18.489	17.036
Ozone layer depletion	kg CFC-11 eq	0.000	0.000	0.000	0.000
Human toxicity	kg 1,4-DB eq	5.378	3.166	1.741	1.728
Freshwater aquatic ecotoxicity	kg 1,4-DB eq	4.644	1.848	1.174	0.997
Marine aquatic ecotoxicity	kg 1,4-DB eq	11895.500	4815.840	3276.725	2630.714
Terrestrial ecotoxicity	kg 1,4-DB eq	0.039	0.008	0.009	0.004
Photochemical oxidation	kg C_2H_4 eq	0.015	0.006	0.004	0.003
Acidification	kg SO_2 eq	0.228	0.125	0.071	0.068
Eutrophication	kg PO_4 eq	0.015	0.010	0.005	0.005

relative to those corresponding to OHS.

3.6. Endpoint approach (damage assessment)

The endpoint approach in LCA provides a comprehensive perspective on the broader environmental consequences of hydroponic vegetable production systems. This method aggregates impacts into three overarching damage categories: ecosystem quality, human health, and resource depletion. By comparing OHS and CHS using this framework, clear trade-offs emerge between environmental sustainability and production practices.

Ecosystem damage, measured as potential species loss over time (species·yr), was markedly lower in CHS. The primary reason is enhanced control over nutrient cycles and water usage, which significantly reduces chemical runoff and nutrient leaching into surrounding environments. Such improvements reduce the risk of eutrophication and biodiversity loss. As shown in Fig. 5, OHS consistently exhibit higher ecosystem-related impacts, particularly in water discharge and nutrient management processes. Moreover, the dendrogram in Fig. S3 reveals that ecosystem-related categories cluster more closely with OHS, highlighting their larger ecological footprint. In contrast, the separation of CHS in the dendrogram underscores their reduced impact and greater environmental compatibility.

Resource depletion, assessed in terms of increased costs for future resource extraction (USD2020), was also substantially lower in CHS. These systems benefit from recirculated water and nutrient solutions, which reduce the need for continuous resource input. The efficient use of fertilizers and electricity through advanced control systems and reuse strategies helps curb raw material consumption. Fig. 5 illustrates that OHS incur higher resource depletion impacts, especially from energy-intensive processes. Additionally, Fig. S3 groups resource-intensive categories with OHS, supporting their greater reliance on depletable inputs. These findings underscore the advantage of CHS in conserving both materials and economic resources.

Human health impacts, expressed in disability-adjusted life years (DALY), followed a similar trend. CHS demonstrated significantly lower health-related impacts, primarily due to reduced emissions of harmful substances such as nitrates, agrochemicals, and greenhouse gases. Improved input control and enclosed operations in closed systems mitigate pollutant release to air and water, reducing risks of respiratory and cardiovascular diseases. Fig. 5 shows elevated human health damage in OHS, primarily from electricity use and chemical inputs. In parallel, Fig. S3 groups these human health-related impacts within the OHS cluster, reinforcing the comparative health burden posed by conventional practices.

Collectively, these endpoint results confirm the environmental superiority of CHS. By reducing damage across ecosystems, resources, and human health, they present a more sustainable alternative for intensive vegetable production, critical in resource-constrained and ecologically sensitive regions.

3.7. Scenario analysis: comparison between natural gas and solar energy

Fig. 6 compares the environmental impacts of using natural gas and solar energy for electricity generation in OHS and CHS. The impacts were divided into two categories for each energy source: electricity used for desalination and electricity used for cooling, pumping, and miscellaneous purposes. The results across several environmental-impact categories indicated that, for both systems, solar energy had a lower impact than natural gas in the categories of abiotic depletion (fossil fuels) and global warming potential (GWP100), reflecting the cleaner nature of solar energy in terms of carbon emissions and resource depletion. Solar energy consistently showed a slightly higher ozone layer-depletion impact than natural gas, which may be attributed to the production or maintenance of solar panels. In all scenarios, human toxicity, marine aquatic toxicity, and terrestrial ecotoxicity were higher for natural gas than for solar energy. This indicates that natural gas contributes more to these categories, likely due to fuel combustion emissions and

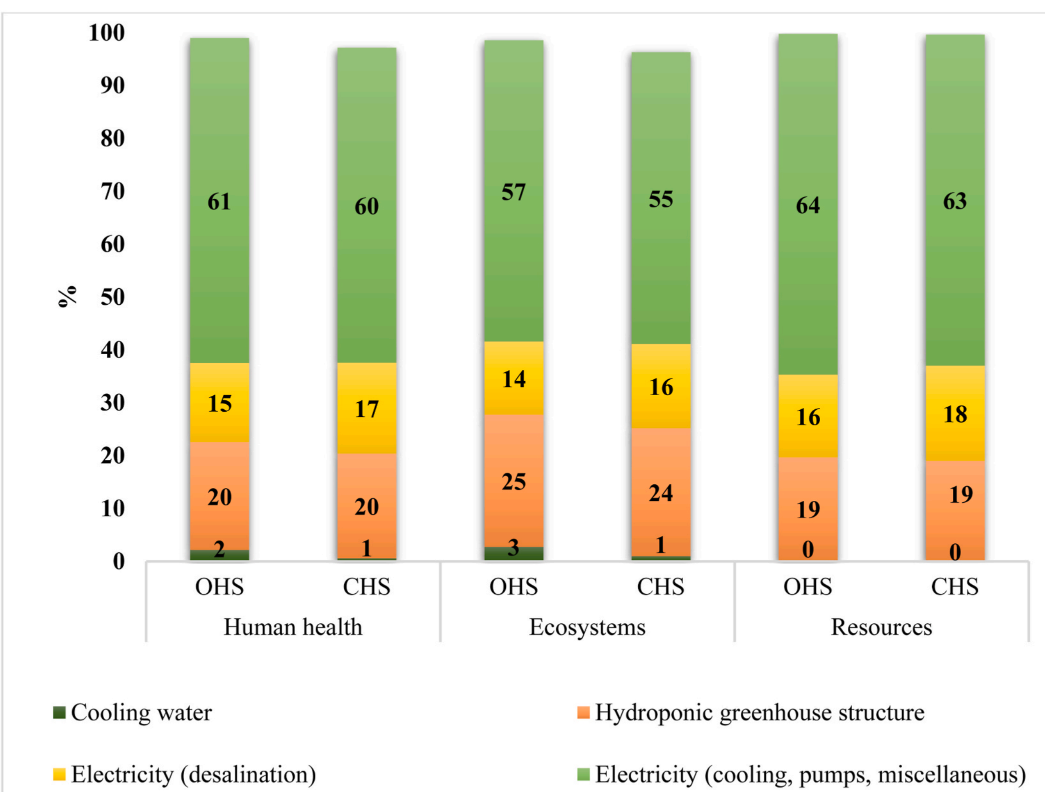

Fig. 5. Environmental impacts of the annual production of a vegetable crop (kg) for OHS and CHS, based on the ReCiPe endpoints method.

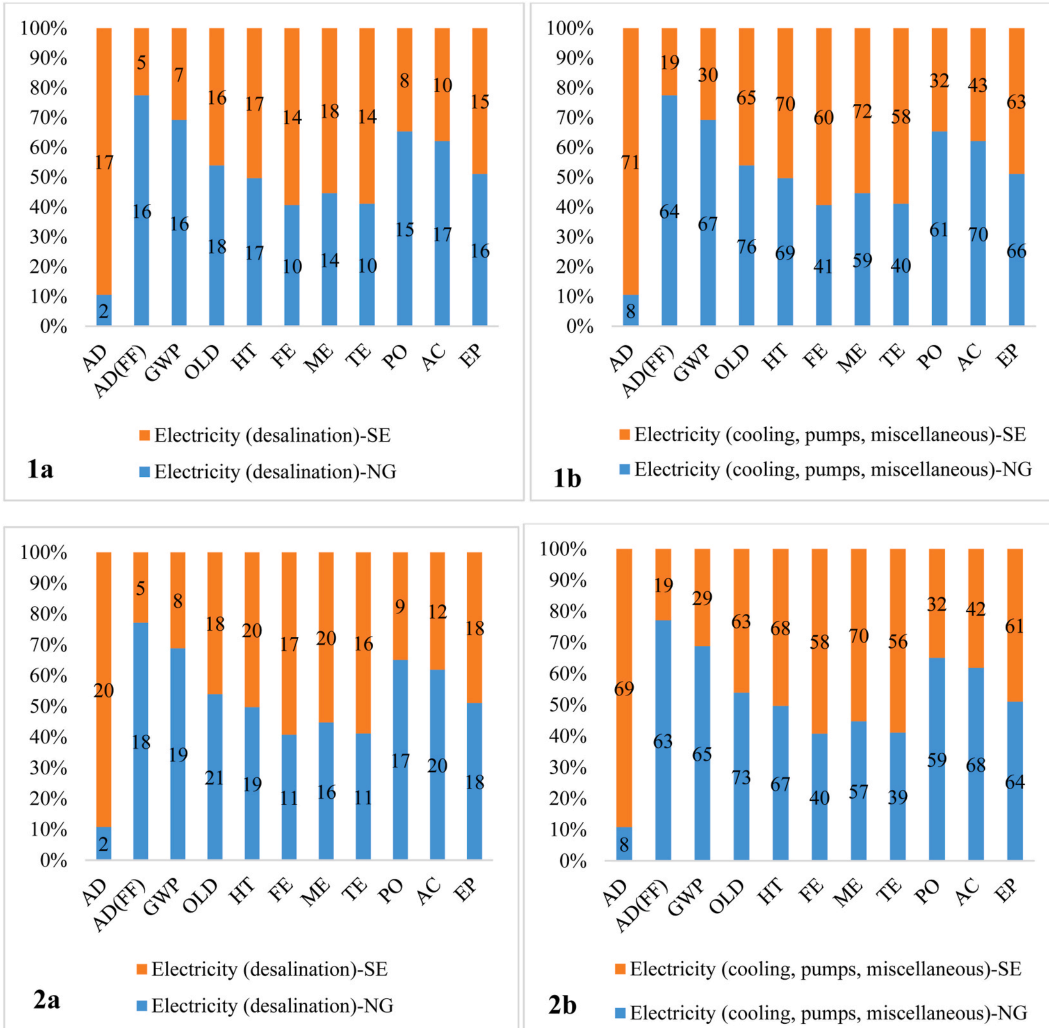

Fig. 6. Environmental impacts of using natural gas (NG) and solar energy (SE) for electricity generation in two hydroponic systems: OHS (1) and CHS (2). The impacts are divided into two categories for each energy source: electricity used for desalination (a) and electricity used for cooling, pumping, and miscellaneous purposes (b).

byproducts. Meanwhile, freshwater aquatic toxicity and eutrophication showed mixed trends; however, these were generally higher for natural gas. Solar energy consistently demonstrated lower impacts on photochemical oxidation and acidification than natural gas across all scenarios, further supporting its environmental advantages. Across all impact categories, CHS tended to have slightly lower overall impacts than those caused by OHS. This could be due to the increased water and nutrient efficiency in CHS. Electricity used for desalination has a smaller impact than cooling, pumps, and miscellaneous uses in natural gas and solar energy scenarios. These findings highlight that the operational side of hydroponic systems (cooling and pumping) has a larger environmental footprint than desalination (see Supplementary Tables S2 and S3) (see Fig. 7).

3.8. Economic analysis

The economic performance results in Table 5 reveal that cucumber production is more profitable than tomato production in both OHS and CHS. Cucumber production in OHS yields a higher net return, attributed to higher production volumes and relatively lower fixed costs per kilogram produced. While CHS incurs higher operational expenses, such as increased labor and greenhouse maintenance, it maintains competitive margins for cucumber production. In contrast, tomato production appears less economically attractive per kilogram, driven by lower sales volumes and higher fixed costs. Nonetheless, CHS offers modest economic performance improvements compared to OHS.

Average revenue, operational and fixed costs, gross margin, and net return for tomato and cucumber farms under open and closed hydroponic systems in the UAE. Net return is calculated as gross margin minus fixed costs, and all values are based on aggregated farm-level data.

Per-kilogram economic indicators and GWP-based eco-efficiency by system and crop were also conducted. The eco-efficiency analysis in Table 6 provides further insights by integrating the economic and environmental dimensions. Cucumber grown in OHS demonstrates the highest eco-efficiency, suggesting it delivers the most climate-smart economic return (0.08 AED/kg CO_2-eq). Although CHS marginally reduces the GWP for cucumber, the slightly lower net return diminishes their overall eco-efficiency. For tomato production, the CHS significantly reduces GWP per kg (31.37 vs. 61.81 kg CO_2-eq), enhancing its eco-efficiency despite a modest reduction in net return. This suggests that CHS could play a pivotal role in reducing the climate footprint of tomato production.

Eco-efficiency is calculated as the ratio of the net return per kilogram to the global warming potential (GWP) per kilogram (kg CO_2-eq). This metric expresses the climate-smart profitability of each crop-system combination.

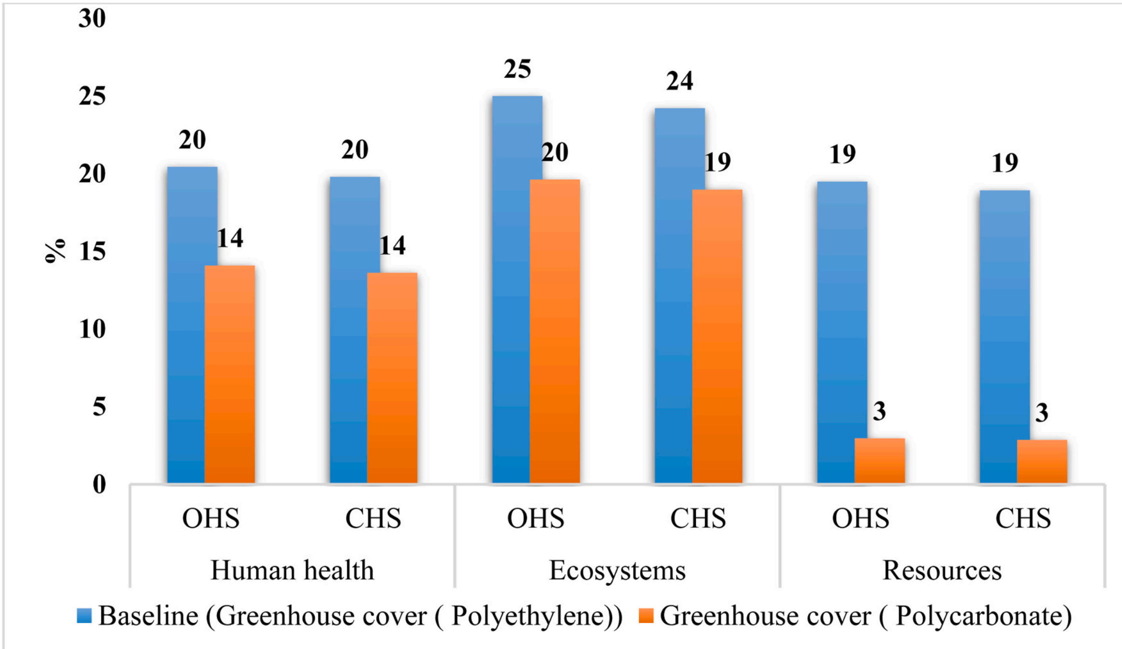

Fig. 7. Sensitivity analysis comparing polycarbonate use instead of polyethylene as greenhouse covering materials across ReCiPe 2016 endpoint categories (human health, ecosystem quality, and resource scarcity) for OHS and CHS.

Table 5
Economic performance per crop and hydroponic systems (AED).

	Cucumber (OHS)	Cucumber (CHS)	Tomato (OHS)	Tomato (CHS)
Quantity sold (kg)	246,333	229,167	86,111	80,000
Price per kg (AED)	2	2	3	3
Revenue	563,533	504,146	258,333	240,000
Operational Cost				
1 Electricity	32,516	24,064	21,753	17,632
2 Nutrient purchase	6938	4981	3507	2857
3 Cost of protection	1848	2054	1342	973
4 Seed	4065	3667	2401	7298
5 Diesel	6216	6323	4120	2392
6 Fuel	7536	6811	4320	5828
7 Labor	69,440	90,229	55,200	51,703
8 Maintenance for the greenhouse	3945	4750	1008	1975
9 - Maintenance of the irrigation system	9517	3511	2972	1459
Total operation cost	142,021	146,387	96,623	92,115
Gross margin	421,513	357,758	161,710	147,885
Fixed cost	66,667	66,667	66,667	66,667
Net return	354,846	291,091	95,043	81,218
Net return per kg	**1.44**	**1.27**	**1.10**	**1.02**

3.9. Sensitivity analysis

This study's sensitivity analysis is divided into two segments: sensitivity analysis on the material used in the structure (e.g., using polycarbonate instead of polyethylene) and sensitivity analysis based on reducing energy consumption by 20 %, 30 %, and 40 % from the base level of consumption.

3.9.1. Impact of greenhouse cover material on environmental performance of hydroponic systems

A material-based sensitivity analysis was conducted to evaluate the effect of using polycarbonate instead of polyethylene for greenhouse coverings in hydroponic production. Although more durable, polycarbonate showed mixed environmental outcomes across the ReCiPe 2016 endpoint categories. Switching to polycarbonate resulted in lower ecosystem impact for both systems due to reduced material replacement frequency. However, increased production energy for polycarbonate led to slightly higher resource use impacts in CHS. Human health impacts were minimally affected. The net benefit depended on the system type and crop cycle length (see Fig. 7).

3.9.2. Reduced energy consumption scenarios using endpoint categories

A multi-impact sensitivity analysis was conducted to evaluate the environmental performance of hydroponic systems under clean electricity transition scenarios aligned with the UAE Energy Strategy 2050; Using ReCiPe 2016 endpoint categories, we analyzed the influence of increasing clean energy shares (20 %, 30 %, 40 %) on human health, ecosystem quality, and resource use. The results show meaningful reductions across all categories, particularly in energy-intensive crop production systems.

CHS exhibited the most substantial improvements across all impact categories as the clean electricity share increased. For instance, human health impacts (DALY) in CHS declined by approximately 18 % when

Table 6
Eco-efficiency analysis of tomato and cucumber production in OHS and CHS.

System Type	Vegetable Type	Revenue (AED/kg)	Total operation cost (AED/kg)	Gross margin (AED/kg)	Fixed cost (AED/kg)	Net return (AED/kg)	Global warming (GWP100a) CO_2-eq)	Eco-efficiency (AED/GWP)
OHS	Cucumber	2.29	0.58	1.71	0.27	1.44	18.49	0.08
CHS	Cucumber	2.20	0.64	1.56	0.29	1.27	17.04	0.07
OHS	Tomatoes	3.00	1.12	1.88	0.77	1.10	61.81	0.02
CHS	Tomatoes	3.00	1.15	1.85	0.83	1.02	31.37	0.03

transitioning from 20 % to 40 % clean energy. Similarly, resource scarcity (USD2013) was reduced by around 15 %, and ecosystem quality impacts (species.yr) improved by nearly 12 %. These reductions are attributed to the energy-intensive nature of CHS, which benefits more from low-carbon electricity sources.

OHS, while less reliant on electricity, also showed meaningful gains. The human health impacts of these systems declined by 9 % between the scenarios. Ecosystem quality improved by approximately 6 %, and resource scarcity decreased by nearly 5 %. Overall, the transition from 20 % to 40 % clean electricity resulted in impact reductions ranging from 5 % to 18 %, depending on the crop and system type. These findings highlight the substantial environmental benefits of aligning hydroponic agriculture with national energy decarbonization goals (see Table 7).

Sensitivity analysis of hydroponic tomato and cucumber production under OHS and CHS across three electricity scenarios (20 %, 30 %, 40 % clean energy). Results are presented for ReCiPe 2016 endpoint categories: Human health (DALY), ecosystem quality (species.yr), and resource scarcity (USD, 2013).

4. Discussion

The results summarized herein confirm that CHS are more sustainable than OHS because of their more efficient use of resources. CHS significantly reduced abiotic depletion (fossil fuels), global warming potential (GWP), and nutrient runoff. These findings echo those of Wimmerova et al. (2022) and Abd-Elmoniem et al. (2006), who reported improved resource use efficiency and lower environmental pollution in CHS. However, the higher initial investment costs for CHS (Sisodia et al., 2021), despite their long-term benefits, such as biodiversity conservation and reduced health risks, can be a barrier to adoption.

Hydroponic systems such as the nutrient film technique (NFT) and deep-water culture (DWC) use up to 90 % less water than traditional soil-based agriculture, making them ideal for water-scarce regions. As previously reported, CHS enhances water and nutrient efficiency, reducing pollution and nutrient losses. (Abd-Elmoniem et al., 2006; Rufí-Salís et al., 2020). Although these systems show outstanding performance concerning water conservation, their energy demands remain a significant challenge, as noted by Wimmerova et al. (2022 and Farvardin et al. (2024).

This study identified solar energy as the most sustainable energy source for hydroponic systems, offering significant reductions in global warming potential (GWP), abiotic depletion, and toxicity impacts. However, the marginally higher ozone depletion potential during the production and recycling of solar energy needs to be addressed. These results align with those reported by Romeo et al. (2018b), which emphasized the importance of renewable energy integration for reducing the carbon footprint of controlled environment-agriculture systems. In contrast, while reliable and supported by the existing infrastructure, natural gas demonstrated higher impacts across most environmental categories. This finding suggests that a transition to solar energy is the optimal long-term strategy, supporting the conclusions of Tewolde et al. (2016) and Farvardin et al. (2024). Combining solar energy with controlled hydroponic systems (CHS) is the most sustainable approach because it reduces environmental impacts across key categories. Similar conclusions were drawn by Saha (2021), who highlighted the synergistic benefits of combining resource-efficient systems with renewable energy sources.

Despite the environmental advantages of hydroponic systems, some challenges persist. In particular, energy intensity is a primary concern, as the heating, lighting, and operational demands of these systems can offset the environmental benefits. As highlighted by Chen et al. (2020) and Naseer et al. (2022), integrating renewable energy and energy-efficient lighting, such as LEDs, is essential for reducing ecological impacts. Furthermore, economic barriers, including high initial costs, severely hinder broader adoption. However, government subsidies and supportive policies, as suggested by Sisodia et al. (2021), can make these systems viable, particularly in urban and arid regions.

Future advancements should focus on scaling CHS through technological innovation, improving energy management, and utilizing reclaimed water. As noted by Nadeem et al. (2024)Integrating hydroponic systems into urban infrastructure can enhance local food production, reduce dependency on imports, and improve food security.

This study highlights several strategies for making hydroponic greenhouse cultivation more sustainable. Key recommendations include integrating renewable energy sources, such as solar panels and wind turbines, into power operations alongside energy-efficient technologies, including LED lighting, advanced climate control, and automation. These measures align with the findings of Casey et al. (2022) and Sousa et al. (2024), which highlights the significance of renewable energy in mitigating the environmental impact of controlled-environment agriculture. Optimizing greenhouse design and insulation further minimizes heating and cooling demands, resonating with Chen et al. (2020), who noted that infrastructure improvements can enhance the overall efficiency of greenhouse agriculture. Water management remains critical, and this study recommends implementing wastewater treatment and recycling systems to reuse water for irrigation or cooling. Additionally, smart sensors and data analytics can be utilized to optimize water use. Similar findings were reported by Putra and Yuliando (2015) and Rufí-Salís et al. (2020), who highlighted the potential of CHS for minimizing water consumption and nutrient losses. Additionally, using renewable, recyclable, or biodegradable materials in greenhouse structures aligns with the goals of sustainable agricultural development. (Sánchez-Zarco and Ponce-Ortega, 2023).

This dual analysis underscores the trade-off between economic return and environmental impact. Cucumber under OHS offers the best short-term profitability and eco-efficiency. However, CHS shows environmental advantages for tomato cultivation, highlighting their potential role in climate-resilient horticulture.

The choice of greenhouse cover material can significantly influence life cycle impacts, especially in controlled-environment agriculture. Polycarbonate, with its higher initial embodied energy, offers long-term benefits in terms of durability and insulation. The material trade-off may favor polycarbonate for systems with extended use or perennial crops. However, for short-term or lower-tech systems, polyethylene remains a viable option.

Table 7
Sensitivity of ReCiPe endpoint impact categories to clean energy scenarios.

Endpoint Categories	System Type	Electricity (desalination)							Electricity (cooling, pumps, miscellaneous)						
		Baseline	20 %	% Change	30 %	% Change	40 %	% Change	Baseline	20 %	% Change	30 %	% Change	40 %	% Change
Human health	OHS	15	14	5 %	13	16 %	12	23 %	61	59	5 %	52	16 %	48	23 %
	CHS	17	16	9 %	14	16 %	13	23 %	60	54	9 %	50	16 %	46	23 %
Ecosystems	OHS	14	13	5 %	12	17 %	11	24 %	57	54	5 %	47	17 %	43	24 %
	CHS	16	15	8 %	13	17 %	12	24 %	55	51	8 %	46	17 %	42	24 %
Resources	OHS	16	15	3 %	14	9 %	13	14 %	64	63	3 %	58	9 %	56	14 %
	CHS	18	17	3 %	16	9 %	16	14 %	63	60	3 %	57	9 %	54	14 %

Hydroponic systems, especially closed types, are sensitive to upstream energy sources. Transitioning to cleaner electricity reduced impacts in all ReCiPe endpoint categories, reinforcing the climate-policy-agriculture linkage. Human health and resource depletion were the most responsive categories, indicating potential co-benefits from decarbonizing the energy mix. These results highlight the need for integrated planning between the energy and agriculture sectors to maximize environmental efficiency.

5. Conclusions

Hydroponic systems represent a sustainable alternative to traditional agriculture, offering significant benefits in terms of water use efficiency and land conservation. When integrated with renewable energy solutions, they become even more environmentally friendly, aligning with global efforts toward sustainable food production. However, their high energy demands present a critical challenge, highlighting the importance of significant advancements in energy-efficient technologies and supportive policies to mitigate their impacts.

This study highlights the environmental and economic advantages of CHS, particularly when combined with renewable energy sources. These systems exhibit superior performance in reducing emissions, preserving ecosystems, and conserving resources, reinforcing their potential for addressing global sustainability challenges and food security. These findings also align with previous research, underscoring the importance of innovations in energy efficiency, water management, and material sustainability to minimize the environmental footprint of hydroponic farming.

Although closed systems showed clear environmental benefits, their higher initial investment costs and operational complexity remain critical barriers to widespread adoption. Further research is needed to optimize the cost-benefit ratios and ensure these systems are accessible and economically viable. Strategic investments and ongoing assessments, such as life cycle assessments (LCAs), can provide valuable insights into improving the sustainability of hydroponic practices.

Continuous innovation, collaborative stakeholder efforts, and supportive policies are crucial for unlocking the full potential of hydroponic farming. By addressing these challenges, hydroponics can play a pivotal role in transitioning to a more sustainable and resilient global food system. Hydroponic systems promise to conserve natural resources and contribute to food security in arid regions, such as the UAE. Furthermore, a comparison between Controlled Environment Systems (CHS) and Open-Field Systems (OHS) using Life Cycle Assessment (LCA) analysis showed that CHS requires a higher initial investment; however, this type of system reduces the negative environmental impacts of agricultural production under controlled environments. OHS are economically superior for cucumber production, while CHS are environmentally advantageous for tomato cultivation. The eco-efficiency framework reveals important trade-offs between profitability and environmental impact, guiding crop-system decisions in sustainable agriculture. These insights support policy and farm-level strategies for climate-smart horticulture in arid regions.

Economic analysis showed that, based on net return, the options are ranked in order from most preferred to least preferred: 1) Cucumber Open, 2) Cucumber closed, 3) Tomato open, 4) Tomato closed. This appears to be different from environmental preferences, showing the presence of a trade-off between the environmental and the economic benefits of CHS and OHS under the two different crops. The trade-off is evident: this ranking differs from the LCA ranking.

Material sensitivity analysis reveals that greenhouse design choices, such as cover type, are critical in environmental performance. Polycarbonate presents a promising option for reducing maintenance and long-term ecosystem impacts; however, its selection should be context-specific, balancing durability, upfront costs, and operational lifespan.

Using endpoint categories in sensitivity analysis provides a comprehensive view of how clean energy policies affect food production systems. The UAE's progress toward cleaner electricity can significantly enhance the environmental performance of hydroponics, especially for closed-loop operations. This underscores the role of cross-sectoral synergies in achieving sustainable food systems.

CRediT authorship contribution statement

Eihab Fathelrahman: Writing – review & editing, Resources, Funding acquisition, Validation, Project administration, Conceptualization, Supervision, Methodology. **Raeda Osman:** Visualization, Formal analysis, Writing – review & editing, Methodology, Data curation, Writing – original draft, Investigation, Conceptualization. **Sabeera Haris:** Writing – original draft, Methodology, Conceptualization, Visualization, Investigation, Software, Formal analysis. **Munjed Maraqa:** Supervision, Writing – original draft, Software, Validation, Conceptualization **Tamrat Gebiso:** Writing – review & editing, Data curation, Validation, Formal analysis. **Berhanu Degefa:** Investigation, Data curation **Elke Neumann:** Funding acquisition, Project administration. **Dana Hoag:** Validation, Conceptualization, Writing – review & editing.

Funding

This research is supported by ASPIRE, the technology program management pillar of Abu Dhabi's Advanced Technology Research Council (ATRC), via the ASPIRE Research Institute for Food Security in the Drylands (grant number 21R097) in collaboration with the United Arab Emirates University (UAEU). Moreover, it is partially funded by the National Water and Energy Centre at the United Arab Emirates University for the data collection (Fund Code 31R223).

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Eihab Fathelrahman reports financial support was provided by ASPIRE UAE. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors acknowledge the contribution of the director of the ASPIRE Research Institute for Food Security in the Drylands project, Musammil Naluparappattil, and the Academic Programs Research Management Team of Aspire for their support.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.146920.

Data availability

Data will be made available on request.

References

Abd-Elmoniem, E.M., Abdrabbo, M.A.A., Farag, A.A., Medany, M., 2006. Hydroponics for food production: Comparison of open and closed systems on yield and consumption of water and nutrient. https://www.researchgate.net/publication/274710318.

ADFSC. Hydroponic Manual. Abu Dhabi Farmers' Services Centre Technical Development Section, Protected Agriculture Unit.

Almarzooqi, M.R., 2018. Life Cycle Assessment of Conventional, Organic Green-House and Hydroponic Tomato Cultivation Systems in Abu Dhabi. UAE.

Casey, L., Freeman, B., Francis, K., Brychkova, G., McKeown, P., Spillane, C., Bezrukov, A., Zaworotko, M., Styles, D., 2022. Comparative environmental footprints of lettuce supplied by hydroponic controlled-environment agriculture and

field-based supply chains. J. Clean. Prod. 369. https://doi.org/10.1016/j.jclepro.2022.133214.
Cellura, M., Ardente, F., Longo, S., 2012. From the LCA of food products to the environmental assessment of protected crops districts: a case-study in the south of Italy. J. Environ. Manag. 93 (1), 194–208. https://doi.org/10.1016/j.jenvman.2011.08.019.
Chen, P., Zhu, G., Kim, H.J., Brown, P.B., Huang, J.Y., 2020. Comparative life cycle assessment of aquaponics and hydroponics in the Midwestern United States. J. Clean. Prod. 275. https://doi.org/10.1016/j.jclepro.2020.122888.
Elhadj, E., 2004. Camels don't fly, deserts don't bloom: an assessment of Saudi Arabia's experiment in desert agriculture. Occas. Pap. 48 (6).
Farvardin, M., Taki, M., Gorjian, S., Shabani, E., Sosa-Savedra, J.C., 2024. Assessing the physical and environmental aspects of greenhouse cultivation: a comprehensive review of conventional and hydroponic methods. Sustainability 16 (3). https://doi.org/10.3390/su16031273.
International Reference Life Cycle Data System (ILCD) Handbook General Guide for Life Cycle Assessment: Provisions and Action Steps, 2011. Publications Office.
Keyes, S., Tyedmers, P., Beazley, K., 2015. Evaluating the environmental impacts of conventional and organic apple production in Nova Scotia, Canada, through life cycle assessment. J. Clean. Prod. 104, 40–51. https://doi.org/10.1016/j.jclepro.2015.05.037.
Li, L., Wu, W., Giller, P., O'Halloran, J., Liang, L., Peng, P., Zhao, G., 2018. Life cycle assessment of a highly diverse vegetable multi-cropping system in Fengqiu County, China. Sustainability 10 (4). https://doi.org/10.3390/su10040983.
Lopes, J., Medeiros, D.L., Kiperstok, A., 2018. Combining cleaner production and life cycle assessment for reducing the environmental impacts of irrigated carrot production in Brazilian semi-arid region. J. Clean. Prod. 170, 924–939. https://doi.org/10.1016/j.jclepro.2017.08.198.
Martin, M., Molin, E., 2019. Environmental assessment of an urban vertical hydroponic farming system in Sweden. Sustainability 11 (15). https://doi.org/10.3390/su11154124.
Maucieri, C., Nicoletto, C., van Os, E., Anseeuw, D., Van Havermaet, R., Junge, R., 2019. Hydroponic technologies. In: Aquaponics Food Production Systems: Combined Aquaculture and Hydroponic Production Technologies for the Future. Springer International Publishing, pp. 77–110. https://doi.org/10.1007/978-3-030-15943-6_4.
Mofatteh, S., Khanali, M., Akram, A., Afshar, M., 2024. Progressing environmental sustainability in hydroponic greenhouse systems: embracing circular bioeconomy through compost and biochar pathways. J. Clean. Prod. 475. https://doi.org/10.1016/j.jclepro.2024.143600.
Nadeem, A., Tariq, M.A.U.R., Sarwar, K., Iqbal, M., Ahmad, K., Ahmed, K., 2024. Assessing the environmental impacts of reclaimed and conventional water in hydroponics based on a life cycle assessment approach. Water Supply 24 (8), 2765–2780. https://doi.org/10.2166/ws.2024.160.
Naseer, M., Persson, T., Hjelkrem, A.G.R., Ruoff, P., Verheul, M.J., 2022. Life cycle assessment of tomato production for different production strategies in Norway. J. Clean. Prod. 372. https://doi.org/10.1016/j.jclepro.2022.133659.
Odhiambo, G.O., 2017. Water scarcity in the Arabian Peninsula and socio-economic implications. Appl. Water Sci. 7 (5), 2479–2492. https://doi.org/10.1007/s13201-016-0440-1.
Putra, P.A., Yuliando, H., 2015. Soilless culture System to support water use efficiency and product quality: a review. Agric. Sci. Proced. 3, 283–288. https://doi.org/10.1016/j.aaspro.2015.01.054.
Ranganathan, J., Waite, R., Searchinger, T., Hanson, C., 2018. How to Sustainably Feed 10 Billion People by 2050, p. 21. *Charts*.
Romeo, D., Vea, E.B., Thomsen, M., 2018a. Environmental impacts of urban hydroponics in Europe: a case study in Lyon. Proced. CIRP 69, 540–545. https://doi.org/10.1016/j.procir.2017.11.048.
Romeo, D., Vea, E.B., Thomsen, M., 2018b. Environmental impacts of urban hydroponics in Europe: a case study in Lyon. Proced. CIRP 69, 540–545. https://doi.org/10.1016/j.procir.2017.11.048.
Roy, P., Nei, D., Orikasa, T., Xu, Q., Okadome, H., Nakamura, N., Shiina, T., 2009. A review of life cycle assessment (LCA) on some food products. J. Food Eng. 90 (1), 1–10. https://doi.org/10.1016/j.jfoodeng.2008.06.016.
Rufí-Salís, M., Petit-Boix, A., Villalba, G., Sanjuan-Delmás, D., Parada, F., Ercilla-Montserrat, M., Arcas-Pilz, V., Muñoz-Liesa, J., Rieradevall, J., Gabarrell, X., 2020. Recirculating water and nutrients in urban agriculture: an opportunity towards environmental sustainability and water use efficiency? J. Clean. Prod. 261. https://doi.org/10.1016/j.jclepro.2020.121213.
Saha, G., 2021. Technological influences on monitoring and automation of the hydroponics system. In: 3rd IEEE International Virtual Conference on Innovations in Power and Advanced Computing Technologies, i-PACT 2021. https://doi.org/10.1109/i-PACT52855.2021.9696519.
Salas, D.A., Ramirez, A.D., Rodríguez, C.R., Petroche, D.M., Boero, A.J., Duque-Rivera, J., 2016. Environmental impacts, life cycle assessment and potential improvement measures for cement production: A literature review. J. Clean. Prod. 113, 114–122. https://doi.org/10.1016/j.jclepro.2015.11.078.
Sánchez-Zarco, X.G., Ponce-Ortega, J.M., 2023. Water-energy-food-ecosystem nexus: an optimization approach incorporating life cycle, security and sustainability assessment. J. Clean. Prod. 414. https://doi.org/10.1016/j.jclepro.2023.137534.
Sisodia, G.S., Alshamsi, R., Sergi, B.S., 2021. Business valuation strategy for new hydroponic farm development – a proposal towards sustainable agriculture development in United Arab Emirates. Br. Food J. 123 (4), 1560–1577. https://doi.org/10.1108/BFJ-06-2020-0557.
Sousa, R. de, Bragança, L., da Silva, M.V., Oliveira, R.S., 2024. Challenges and solutions for sustainable food systems: the potential of home hydroponics. Sustainability 16 (Issue 2). https://doi.org/10.3390/su16020817. Multidisciplinary Digital Publishing Institute (MDPI).
Tewolde, F.T., Takagaki, M., Oshio, T., Maruo, T., Kozai, T., Kikuchi, Y., 2016. Environmental impact of tomato production under different hydroponic systems. Acta Hortic. 1112, 467–471. https://doi.org/10.17660/ActaHortic.2016.1112.63.
The State of Food and Agriculture, 2020. In: The State of Food and Agriculture 2020. FAO. https://doi.org/10.4060/cb1447en, 2020.
United Nations, 2015. Transforming our World: the 2030 Agenda for Sustainable Development.
Vinyes, E., Gasol, C.M., Asin, L., Alegre, S., Muñoz, P., 2015. Life cycle assessment of multi-year peach production. J. Clean. Prod. 104, 68–79. https://doi.org/10.1016/j.jclepro.2015.05.041.
Wimmerova, L., Keken, Z., Solcova, O., Bartos, L., Spacilova, M., 2022. A comparative LCA of Aeroponic, hydroponic, and soil cultivations of bioactive substance producing plants. Sustainability 14 (4). https://doi.org/10.3390/su14042421.