Chapter 22
Adopting Life Cycle Assessment for Various Greenhouse Typologies in Multiple Cropping Environment in Australia

Ana Evangelista, Yi-Chen Lan, Zhonghua Chen, Vivian W. Y. Tam, and Rina Datt

Abstract Over the last decades, dramatic population growth worldwide has been directly reflecting in food security. United Nations (UN) projects a world population will increase more than one billion people within the next years, reaching 8.5 billion in 2030. With this anticipated scenario, agricultural industry is experiencing monumental pressures and challenges in adopting and utilising cutting-edge technologies for both open field and controlled agriculture aiming for a sustainable and profitable food production per unit of area of plantation. This study focuses on the controlled agriculture or commonly referring to “greenhouses”, which is broadly categorised under three main typologies: (1) low, (2) medium, and (3) high technologies. In general, adopting new materials lead to an increase for both durability and cost of greenhouse structures. Australian horticulture industry has set ambitious and new export targets that would lift export earnings by hundreds of millions of dollars annually. Australian conditions are very different to those that prevail under the northern European climate of the Netherlands, where technologies, associated management systems and accumulated experience were first developed. The study aims to investigate the environmental impacts of a common high technology greenhouse configuration in Australia, which encompasses various infrastructural and production components such as greenhouse structures, soilless cultivation systems, irrigation/fertigation systems, heating/cooling systems, and relevant production applications. The methodology is based on a critical literature review identifying the knowledge gap in Australia, as many studies have been focusing on individual crops in the northern hemisphere. Gaps in life cycle assessment applied to a variety of crops and in high technology greenhouses incorporating green components were identified.

A. Evangelista · V. W. Y. Tam
School of Computing, Engineering and Mathematics, Western Sydney University, Sydney, Australia

Y.-C. Lan (✉) · R. Datt
School of Business, Western Sydney University, Sydney, Australia
e-mail: y.lan@westernsydney.edu.au

Z. Chen
School of Science and Health, Western Sydney University, Sydney, Australia

Y. Kishita et al. (eds.), *EcoDesign and Sustainability II*, Sustainable Production, Life Cycle Engineering and Management, https://doi.org/10.1007/978-981-15-6775-9_22

Keywords Greenhouses technology · Life-cycle assessment · Resource sustainability · Environmental impacts

22.1 Introduction

Despite the human population growth, the agriculture sector is required to produce food, fibre, and biomass energy products under limited resources while reducing related environmental impacts. Caffrey and Veal (2013) cited the main influences from the agricultural segment to the environmental impacts are the land-use change, greenhouse gas (GHG) emissions, eutrophication, eco-toxicity, and human health impacts.

Alternatively, to the open field cultivation, greenhouses appear like an indoor environment suitable to produce a wide range of vegetables or flowers within a controlled condition reducing the risks related to pests, diseases and severe weather. Aiming to target food scarcity in disadvantaged regions, it arises as an important alternative for more sustainable and efficient crop production (Ingram et al. 2017; Jadhav and Rosentrater 2017). The sustainability theme and the social concern about climate change have been increasing within a wide range of industry globally (Wang et al. 2018; Golzar et al. 2018; Santonicola et al. 2018; Shamshiri et al. 2018). In this direction, life cycle assessment (LCA) is an important methodology to quantify greenhouse gas emissions and to assess a wide range environmental impacts of harvest production methods including greenhouse horticulture (Bos et al. 2008; Bartzas et al. 2015, 2017; Goglio et al. 2018).

The DPI NSW (2018) presents some definitions, for example, the glasshouse is the term used when the covering material is glass, and 'greenhouse' or 'polyhouse' denotes the use of plastic coats. Additionally, 'shade house' or 'screen house when the material is interlaced to permit sunlight, moisture and air to pass through the structure and reach the crops. In Australia majority of the industry in currently relies on low technology structures and the most usual are the Tunnel houses, or "igloos" (less than 3-m height) without vertical walls and lack of ventilation. This type of greenhouse is for seasonal and normally operates during the warmer months. Another typology is the medium level greenhouse, characterised by vertical walls, roof and/or sidewall ventilation and clad with either single or double coating plastic film or glass (Department of Primary Industry 2018).

Considering the three typologies, the most innovative is the high technology greenhouse. Burchi et al. (2018) reported a clear definition: "high tech greenhouse is designed to manage, in a controlled and efficient way, different types of crops with different cultivation needs". The high-tech term arises from the greenhouse automation including sensors, data acquisition and analysis via the computational system to optimise crop management, resulting in more accurate information to control the crop environment inputs and outputs, such as impacts to air, water and soil.

This study aims to review the life cycle assessment (LCA) applications within greenhouse crop production in different countries highlighting that Australia is distinctly different in terms of climate, water resources and solar radiation. Additionally, identifying gaps in the literature under the topic of LCA applied to greenhouses including suitable sustainable strategies for protected crop production.

22.2 Methodology

The strategy used in the literature review relies on the Scopus Elsevier Database as the main source for search trustable publications.

Initial search with keywords such as "Life Cycle Assessment" and "Greenhouses" in Title and Abstract fields, limited to English language and Subject Areas including Environmental Science, Agricultural and Biological Sciences, retrieved 756 documents published since 1996 (see Fig. 22.1).

To identify and visualise the most cited keywords and important terms network, VOS viewer software was adopted regarding the simple integration with the Scopus Elsevier Database. Figure 22.2 shows the keywords retrieved from 138 documents close related to LCA greenhouses and published in relevant sources, such as Acta Horticultura, Journal of Cleaner Production, Renewable and Sustainable Energy Reviews and International Journal of Life Cycle Assessment, which was in-depth analysed and discussed in this study.

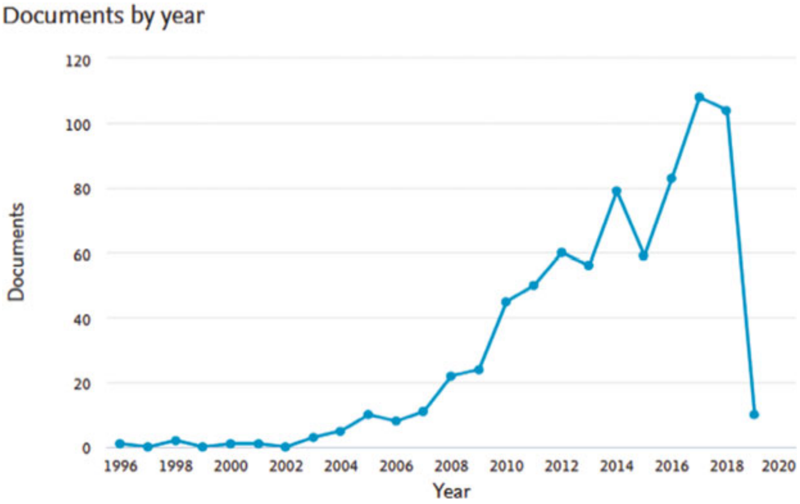

Fig. 22.1 Timeline for the publication's retrieval with the total of 756 references

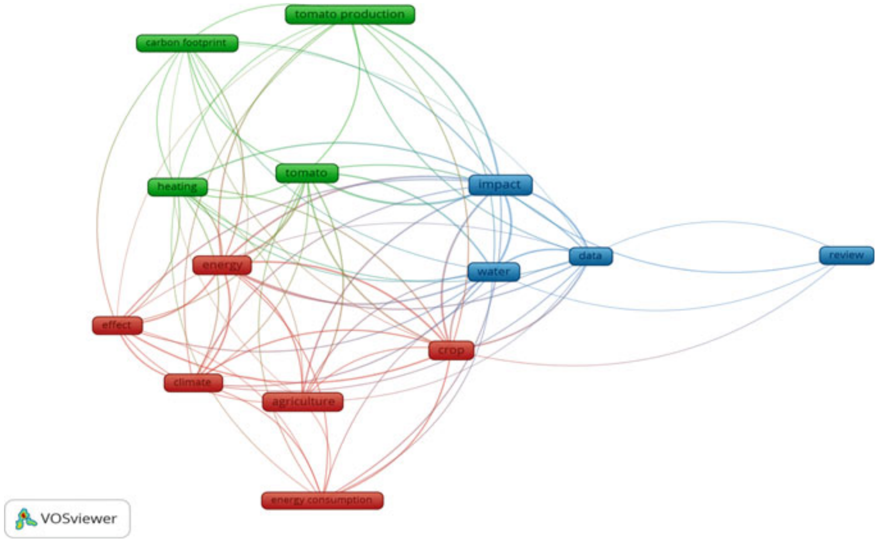

Fig. 22.2 LCA, greenhouse and crop keywords

22.3 Greenhouse Configurations

22.3.1 General Typology

Worldwide is well established that greenhouses are suitable for food production during the entire year. In general, different regions require specific equipment and structure according to the type of crop and construction materials availability (Teitel et al. 2012).

According to Badgery (1999), “a greenhouse should have efficient light transmission, adequate height, enough strength to carry the wind load and sufficient air volume and ventilation to avoid temperature extremes”. The shape of the structure influences the greenhouse concerning the quantity of light transmitted and natural ventilation, internal space, structural materials, condensation run-off, cooling and heating.

It is worth to note the research conducted by Page et al. (2011) comparing different types of greenhouses typology in Australia. The authors reported that the average tomato products of 60 tons ha − 1160 tons ha − 1340 tons ha − 1, and 570 tons ha − 1 in open field, low technology greenhouse, medium technology greenhouse and high technology greenhouse, respectively.

The advantages of the modern or high-tech greenhouse are the live acquisition of important data: such as room temperature, humidity, light, carbon dioxide, electric conductivity to measure the strength of nutrients solution, pH and plant temperature. For example, specific sensors are installed for weighing gutter for crop transpiration and chlorophyll fluorescence for photosynthesis. (Hemming et al. 2017).

Following other industries trend, automation of greenhouses has had supplied by modern enterprises, such as Priva and Hortimax allowing productivity increments combined with sustainable management of water, energy and nutrients.

22.3.2 High-Tech Greenhouse Structure

In general, heights of the roof and sidewall in a high-tech greenhouse are 8 m and 4 m respectively, and both will have ventilation mechanisms. Usually, the building materials selected for cladding are plastic film, polycarbonate or glass (Teitel et al. 2012). Some researches, Valera et al. (2017) analysing greenhouses productivity combined with economic performance, depicted the fact of crop management developed on advanced structures does not certainly result in direct increases of these factors. The outcomes showed that the natural ventilation led to higher yield than other climate control systems, at minimum cost.

22.4 Life Cycle Assessment (LCA)

The LCA methodology is based on ISO 14,040 and 14,044 guidelines covering: Goal and Scope aiming to identifies the functional equivalent, system boundary and the set of building materials, Life Cycle Inventory's (LCI) main challenge is the difficulty of collecting reliable and applicable data. In Life Cycle Impact Assessment (LCIA), the quantities of materials, energy consumption, and input data are collected using the environmental impacts indicators. The fourth step is Interpretation to the evaluate the results obtained from LCI and LCIA (UNEP Setac 2009).

During the last years, a variety of software on LCA methodology have been used to simplify the analysis for products and systems, such as SimaPro, GaBi, TEAM and Open LCA. Aiming to provide relevant information about environmental impacts evaluation, this paper illustrates the classification of different midpoint indicators that lead to endpoint categories, as shown in Table 22.1.

According to Cellura et al. (2012), LCA could be used as a decision support tool by three distinct groups:

(a) Product Producers: to improve the environmental performance of a production system;
(b) Product Consumers: to guide purchasing decisions; and
(c) Policy-makers: to inform and direct long-term strategies.

Protected cultivation presents high productivity and high efficiency of most resource usage. Conversely, higher demand and use of water, energy, fertiliser and pesticides result in environmental impacts, such as N-leaching, GWP and energy consumption (Stanghellini and Montero 2012).

Table 22.1 Environmental impacts that lead to human health, ecosystem quality and natural resource (European Commission—Joint Research Centre—Institute for Environment and Sustainability (EC-JRC) 2010)

Midpoint indicators	Endpoint area of protection
Climate change	Human health/ Ecosystem quality
Ozone depletion	Human health
Ionising radiation	Human health
Photochemical ozone formation	Human health/ Ecosystem quality
Particulate matter formation	Human health
Acidification	Ecosystem quality
Eutrophication	Ecosystem quality
Toxicity	Ecosystem quality
Land use	Human health/ Ecosystem quality
Consumptive water use	Human health/ Ecosystem quality
Resource depletion—fossil fuels	Natural resources
Resource depletion – minerals	Natural resources

The environmental impact of greenhouse production for different crops has been published in literature through LCA approaches (Russo and Scarascia Mugnozza 2005a; Russo et al. 2008; Liang et al. 2019; Pons et al. 2015; Dias et al. 2017; Sanjuan-Delmás et al. 2018). According to Perez et al. (2018), several researchers had examined the intensive production of tomatoes in areas with different technological systems in countries such as Switzerland, the Netherlands, Turkey, France or Spain. However, it is important to note that these findings apply to the northeast hemisphere climate characteristics. Nevertheless, a few studies report the state of the art of southern hemisphere, specifically in the context of this study, environmental impacts applied to greenhouse production in Australia (Nordey et al. 2017).

22.4.1 Goal and Scope

This section covers the aims for carrying out, the functional units, the system boundary, reference flows, limitation, data requirements and allocation procedures under ISO 14,044 Goal and Scope. Table 22.2 presents the commonly used functional unit and system boundary. Despite other crops, such as capsicum, cucumber, melon, and eggplant, tomatoes are the most studied product worldwide.

Table 22.2 Examples of functional unit and system boundary

Functional unit	System boundary	References
1 kg of table tomatoes	Typology of greenhouse materials	Russo and Scarascia Mugnozza (2005b)
1 kg of fresh tomato	Cradle to farm gate and included all the direct farming	Page et al. (2012)
1000 kg of vegetables, including the packaging (tomatoes, cherry tomatoes, peppers, melons and zucchinis)	Production and delivery of construction materials for the greenhouses, as well as the production and delivery of chemicals (fertilisers, manures and pesticides), energy resources (diesel) and water	Cellura et al. (2012)
1 tonne of tomatoes	raw material extraction to the farm gate, including material waste disposal	Torrellas et al. (2013)
1 kg of fresh tomato	N/A	Page et al. (2014)
1 kg of packaged tomatoes	cradle-to-gate	Dias et al. (2017)
653 kg of tomatoes	HPS system is replaced by an overhead LED system—incandescent lights are replaced with an LED system	Zhang et al. (2017)
1 kg of fresh tomatoes	Cradle to regional distribution centre approach	Pérez Neira et al. (2018)
11.4-cm begonia plant in a 12-plant shuttle tray	6.6 plants on each square meter of a concrete floor and plants were irrigated using an overhead, traveling boom	Ingram et al. (2018)
1 t of tomato	cradle-to-farm gate	Liang et al. (2019)

22.4.2 Life Cycle Inventory (LCI)

The second phase of LCA is Life Cycle Inventory (LCI) where the information on building materials, energy and emissions are computed (UNEP Setac 2009). In summary, quantified inputs and outputs of a crop production system are included in the whole lifecycle of the greenhouse.

Table 22.3 shows a wide range of inputs considered to the analysis of environmental impacts presented in the literature. It is worth to highlight that the lifespan of the greenhouse materials depends on both intrinsic (materials composition) and extrinsic factors (environmental conditions and use of chemicals).

Table 22.3 Illustration of inputs and life cycle stages

Type of Data/Inputs	Life span	References
Building materials + Energy consumption	Life of structure 10 years	Russo and Scarascia Mugnozza (2005b)
Fertilisers, pesti- cides, electricity and fuel use, water use, rainwater harvesting if any, and typical yields	N/A	Page et al. (2012)
Construction materials,, production and delivery of chemicals (fertilisers, manures and pesticides), energy resources (diesel) and water	Pavilion structures have a life-span of 10 years, while foundations last 30 years	Cellura et al. (2012)
Greenhouse dimensions and agricultural operations, such as crop period, crop density and volume of substrate per bag; as well as water, fertiliser, pesticide, electricity and fuel consumption	The life-span of the greenhouse was estimated as 15 years	Torrellas et al. (2012a)
Fertilisers, fuel, electricity, water requirement, pesticides/and the greenhouse construction	N/A	Page et al. (2014)
Various types of technologies materials and management systems	Lifespan of 25 years	Dias et al. (2017)
Consumption of electricity	N/A	Zhang et al. (2017)
Record of all input products, equipment use, and other activities	N/A	Ingram et al. (2017)
Energy Consumption	N/A	Pérez Neira et al. (2018)
Greenhouse construction materials	10 years in the case of wood and bamboo and 20 years in the case of most other more durable material	Liang et al. (2019)

22.4.3 Life Cycle Impact Assessment (LCIA)

The LCIA includes the calculations, considering quantities of building materials, energy consumption, and emissions to provide the environment impacts results. illustrates the most adopted indicators including abiotic depletion (AD), acidification (AC), eutrophication (EP), global warming potential (GWP), ozone layer depletion (OD), carbon footprint (CF) water footprint (WF), nitrogen footprint (NF), human toxicity (HT) and photochemical oxidation (PO) (Table 22.4).

Table 22.4 Usual impact category and LCIA methods

Method	Indicators	References
CML 2 of 2000	AD, GWP100 OD, HT AP TE, PO, AP, EP	Russo and Scarascia Mugnozza (2005b)
IPCC and Water footprint—methodology by Ridoutt and Pfister (2010)	*CF, WF*	Page et al. (2012)
CML2001 v.2.04	AD, AAP, EP, GWP, POP, Energy use, WF	Cellura et al. (2012)
CML2001 v.2.04	AD, AAP, EUP, GWP, PO, CED, water	Torrellas et al. (2012a)
IPCC	*CF, Energy use, WF*	Page et al. (2014)
TRACI	WF, GWP, OD, EP, Smog, AC,	Dias et al. (2017)
EPA TRACI, CED	GWP, AC, OD, EP Energy use, ecotoxicity	Zhang et al. (2017)
IPCC	*GWP*	Ingram et al. (2017)
CED	Energy use	Pérez Neira et al. (2018)
eBalance v3.0—NF calculations	NF	Liang et al. (2019)

22.4.4 Interpretation

This phase leads to conclusions and recommendations, shows the environmental issues magnitude, and generates appropriate decisions (UNEP Setac 2009). In this study, assessing the case studies retrieved from the most recent literature, word class research groups show that the whole life cycle analysis (typology and crop management) of modern greenhouses are strongly based on embodied energy and operational energy. Regarding this, the LCA of greenhouses main targets presented herein, are building materials, heating system and lighting systems. It does not mean, that other important impacts such eutrophication, water footprint or acidification are less significant. On the contrary, it points the relevance to show the current demand for new studies in order to broadly cover and expand the impact analysis.

(a) Building Materials

Cellura et al. (2012) reported that construction materials, greenhouse maintenance and product packing contribute considerably to the environmental impacts, for example, CO_2 emission. In order to mitigate this impact, eco-friendly raw materials should be selected.

Investigating different types of the materials, Castellano et al. (2008) found that "the presence of glass in the steel structure with aluminium window frames is the main reason for the higher emissions compared to the other greenhouses due to the quantity of metal and energy required to produce it". The authors' findings indicated that the greenhouse in wood proved to be the most eco-compatible.

Similar findings were reported by Torrellas (2012b) demonstrating that the materials used to construct the structure have a significant influence on the impact categories, for example: abiotic depletion (50%), global warming (37%), photochemical oxidation (54%) and cumulative energy demand (50%), due to the large amount of steel in the frame and plastic in the covering and floor.

Recently, the impact of building materials on nitrogen emission (NF), was reported by Liang (2019). In China, from 2004 onwards, the construction materials, largely because of the use of steel, but also brick and low-density polyethylene (LDPE), have been the second most important contributor to the total NF.

(b) Heating systems

Dias et al. (2017) presented a GWP of 3.2 kg CO2e/kg of packaged tomatoes, within the range of values (0.24 to 5.1 kg CO2e/kg of tomatoes) published in other studies for a variety of technologies (Table 22.5). It is important to observe that the fuel combustion for the heating system (in this case: natural gas and bunker fuel) accounted for 50–85% of the total impact for ozone depletion, global warming, smog, acidification, and respiratory effects.

In Iran, Khoshnevisan et al. (2014), to evaluate the heating system (natural gas), reported that GWP to produce one kg of cucumber and tomato was 0.244 kg and 0.129.39 kg CO2e respectively.

Perez et al. (2018) compared heated (multi-tunnel greenhouses) and unheated tomatoes production, cited that the annual energy output from tomato cultivation in Almeria (Spain) is estimated to be 246.4 × 103 MJ ha − 1, corresponding to 62.1–37.9% of heated and unheated tomatoes, respectively. Energy (gas, diesel and electricity) (67.7%) and infrastructure (18.5%) are the main factors influencing energy

Table 22.5 Influence of heat system on GWP

Country	GWP kg CO_{2e}/FU	Heating System	References
Spain	0.24	Unheated	Almeida et al. 2014)
France	0.51	Unheated	Boulard et al. 2011)
Hungary	0.53	Thermal water	Russo and Scarascia Mugnozza 2005b)
Italy	0.74	N/A	Cellura et al. 2012)
Australia	*1.7*	*Coal*	Page et al. 2012)
Australia	*1.9*	*Natural gas, coal*	Page et al. 2012)
Netherland	2.0	Combined heat and power	Torrellas et al. 2013)
France	2.0	Natural gas, oil	Boulard et al. 2011)
Northern Italy	2.3	Natural gas	Torrellas et al. 2013)
Canada	2.3	Natural gas	Dias et al. 2017)
Hungary	5.1	Natural gas	Torrellas et al. 2013)

Adapted from Dias et al. (2017)

demand of the heated tomato production, but infrastructure (43.3%) and fertilisation and crop protection measures (25.3%) are the main factors of unheated tomatoes.

It is well known that Australia has the highest average solar radiation/m^2 of any continent in the world. To investigate renewable sources, Page et al. (2014) reported the outcomes of the energy demand of greenhouses. The energy obtained from coal and natural gas were substituted by equivalent MJ through electricity generation in photovoltaic systems for the medium and high technology systems. Regarding this new scenario and the production of one kg of tomato, the carbon emissions from energy sources used in artificial heating reduced from 1.4 to 0.31 kg CO2e and from 1.57 to 0.4 kg CO2e, respectively for medium and high technology. However, more energy is required for cooling rather than heating purpose in Australia. Further research should be carried out in this aspect.

(c) Lightning system

Innovative and sustainable lighting systems are important components of modern greenhouses. Aiming to investigate sustainable alternatives, Zhang and Zaho (2015) (Zhang et al. 2017) compared different light systems, such as high-pressure sodium (HPS), LED and incandescent lights. It is worth to note that the use and consumption of electricity is the largest contributor among all the groups. One exception is the incandescent compared to 18WLED due to the copper component of LED, making it the largest contributor to carcinogenic category. The authors found that LED adoption can result in a net 40% reduction in categories such as global warming potential or cumulative energy demand.

22.5 Summary

From the global scenario in the agricultural sector, it is extensively required new strategies such as sustainable approaches, sustainable materials practices and renewable energy systems to reduce energy and water consumption, GHG emissions, and other environmental impacts of greenhouses crop production.

In Australia, protected cropping is one of the relevant growing areas of food production with almost 30% of all farmers' production in some form of a soilless horticulture system. Recent research, Tingey et al. (2018) reported significant investments and expansion of protected cropping systems concentrated in temperate regions. However, 58% of the total production of high-value vegetables (i.e. tomato, capsicum, cucumber, melon, and eggplant) are supplied from an open field growing region in QLD, WA and NT in the tropics of Australia characterised by climate variability and extreme weather conditions (Tingey, et al. 2018). In this way, more initiatives to research greenhouse crop production and environmental impact in less favourable regions are needed. Page et al. (2012) brought attention to the combination of cropping system and seasoning. The results indicated that in season, low technology greenhouse presents the lowest carbon footprint and overall damage scores at the endpoint level when compared to med and high-tech systems.

It is important to notice that the natural gas, one of the most used energy sources, had been utilised by both cooling and heating systems resulting in significant effects on the environmental burdens. Under this circumstance, it is recommendable to use modern technologies to improve energy use efficiency via automated systems. In Australia, solar energy is an alternative to renewable energy to reduce the usage of natural gas in cooling/heating systems.

Further studies should be considered about the new technologies and design of high technology greenhouses. It is important to evaluate the building components that will be affecting the plant growth, for example, heating/cooling system, lights, site, space and growing media. These components could be designed by adopting the building information modelling (BIM), as a useful platform to gather information on both infrastructure (greenhouse structure) and energy systems.

In terms of the environmental impact analysis considering high tech greenhouse, it is possible to observe that the significant number of publications are focused on Energy demand showing sustainable alternatives to mitigate CO2 emission and/or GWP. However, further studies are needed to evaluate other impacts pertinent to the agriculture industry, mainly water scarcity, and eutrophication in a controlled environment production.

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