

# Towards more sustainable greenhouse production

**Dianfan Zhou**



## **Propositions**

- 1.** It is crucial to consider transboundary effects across industries and administrative regions in sustainability assessment of a given system.  
(this thesis)
- 2.** Farmers' choices reflect the opportunities and challenges in achieving sustainability.  
(this thesis)
- 3.** Knowledge sharing by stakeholders is key to facilitate sound policy making.
- 4.** Although norms, values and jargon are integral and important parts of the scientific process, they also impede broader scientific communication.
- 5.** It is important to tread carefully between working independently and succumbing to self-doubt.
- 6.** Carbon emissions are not the sole concern impacting our current and future lives.

Propositions belonging to the thesis, entitled

Towards more sustainable greenhouse production

Dianfan Zhou

Wageningen, 3 June 2024

# **Towards more sustainable greenhouse production**

**Dianfan Zhou**

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# Towards more sustainable greenhouse production

**Dianfan Zhou**

## **Thesis**

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# **CHAPTER 1**

## **General introduction**

Dianfan Zhou

## 1.1. Background

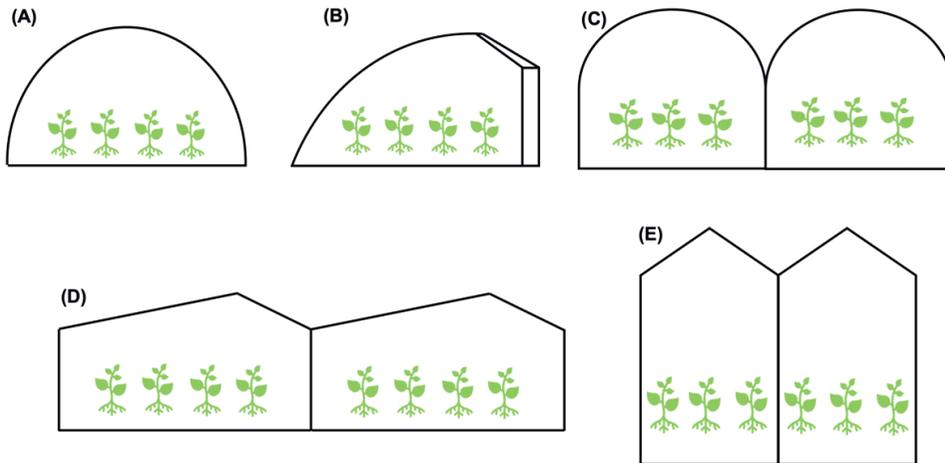
### ***Importance of greenhouse horticulture in sustainable intensification***

We must increase food production within its current footprint, while minimising environmental impacts and maintaining the stability of ecosystems (e.g. biodiversity) (Tilman *et al.*, 2011; Willett *et al.*, 2019). Many studies have discussed key trajectories towards sustainable intensification in food production, such as improving efficiencies in resource use (Tilman *et al.*, 2011; Springmann *et al.*, 2018; Cassman and Grassini, 2020), and applying advanced fertilisation and irrigation (Struik and Kuyper, 2014; Jägermeyr *et al.*, 2016). These commonly underline that adopting innovative technology is a crucial step for achieving sustainable food production (Struik *et al.*, 2014). Greenhouses contain some of the most advanced technologies used for food production, differing considerably from conventional field production of food. The adoption of greenhouse production systems not only represents a step-change in productivity, but it also enables much greater diversity of crops to be grown. Further, the high-tech, soilless cultivation in greenhouses makes it possible to use land unsuitable for open-field production. This unique feature provides opportunities to alleviate the pressure on demands in arable land, and to strategically place vegetable production sites near major consumption centres and transport routes and thus potentially reduce the greenhouse gas (GHG) emissions due to transportation. Nowadays, greenhouse horticulture is seen as a promising avenue of contributing to sustainable intensification for food production (Aznar-Sánchez *et al.*, 2020).

### ***Overview of greenhouse production***

In recent decades, greenhouses have shown success in providing affordable, year-round fresh produce with high and consistent quality while using resources in an efficient way (Marcelis *et al.*, 2019). There is a spectrum of greenhouse types that can be classified either based on the greenhouse shape (Figure 1.1) and covering material (plastic or glass), or on the level of technology adopted (ranging from unheated to automatic climate control). According to an estimation by Cuesta Roble Consulting (2019), the world greenhouse area (including permanent and semi-permanent structures) had reached 5.6 million ha by 2018. It was estimated that ca. 90% of greenhouse production area was covered by plastics with large contributions from Southern Europe (especially Spain) and China. Tomato is the most common crop in greenhouse cultivation worldwide in terms of production area (Marcelis *et al.*, 2019). According to the non-exhaustive data compiled by Marcelis and Heuvelink (2019), Europe has the largest area of greenhouse production,

estimated at 178,000–210,000 ha, which is followed by Asia (ca. 180,000 ha). In some countries or regions, such as the Netherlands and Southeast Spain (e.g. Almeria), greenhouse horticulture plays an important socio-economical role (Galdeano-Gómez *et al.*, 2017; Van Grinsven *et al.*, 2019). Apart from conventional greenhouse cultivation, greenhouses with organic cultivation are attracting investment and research interest in response to the increasing demand for organic products due to their perceived environmental benefits and high profitability (Marcelis and Heuvelink, 2019).



**Figure 1.1.** Shapes of common greenhouse frames: (A) single plastic tunnel; (B) Chinese solar greenhouse with North wall; (C) gutter-connect multi-span plastic house; (D) Spanish Parral-type plastic house; (E) Dutch Venlo-type greenhouse.

## 1.2. Problem definition

### *Greenhouse production and environment*

Greenhouses have proved to be a good solution for intensification of horticultural production, but their impacts on the environment and ecosystems pose challenges to meet sustainability requirements demanded by the public. Additionally, perceptions of greenhouse production from conventional growers and consumers include that it represents unnatural cultivation, and this combined with concerns around the use of fossil fuels for greenhouse heating, has increased attention on the sustainability performance of greenhouse systems (Bremmera *et al.*, 2008; Gan *et al.*, 2022). The overall environmental sustainability of greenhouse production greatly depends on the type of greenhouse (e.g. level of climate control, covering material), type of cultivation (e.g. soil-based or soilless) and crop management. This is mainly influenced by local climate and market conditions (Torrellas *et al.*, 2012b). For example, in Northern Europe or Canada, where the climate is

temperate or cold, additional heating is essential in greenhouse production for ensuring sufficient plant growth when temperature is low, or even for plant survival in winter times. Consequently, consumption of fossil fuels for greenhouse heating has been identified as the biggest contribution to GHG emissions in relation to greenhouse production systems (e.g. CO<sub>2</sub>, NO<sub>x</sub>) (Torrellas *et al.*, 2012b; Dias *et al.*, 2017), which drives climate change (IPCC, 2007). In the Netherlands, GHG emissions from greenhouse horticulture represent 25% of the GHG emissions of the total agricultural sector (Van Grinsven *et al.*, 2019). Hence, building carbon neutral greenhouses would make a major contribution towards GHG mitigation in colder regions. Conversely, in China and Spain, unheated, soil-based plastic greenhouses are extensively used, resulting in large amounts of plastic waste “flowing” into the environment and ecosystems (Sayadi-Gmada *et al.*, 2019; Zhang *et al.*, 2020; Castillo-Díaz *et al.*, 2021). Moreover, excessive use of synthetic fertiliser and irrigation water has led to considerable pollution of ecosystems, and aggravated local freshwater scarcity (Min *et al.*, 2012; Bai *et al.*, 2020; Incrocci *et al.*, 2020).

The complexity of greenhouse production systems, in terms of raw materials used for greenhouse infrastructure, resource inputs and technology adoption, makes it more complex to evaluate their sustainability, compared to traditional open-field production. For instance, a comprehensive understanding of the environmental performance of greenhouse production requires considerations of the impacts embedded in various stages, ranging from pre-greenhouse-production (e.g. manufacture of greenhouse infrastructure) to post-greenhouse production (e.g. waste disposal) (Table 1.1). Life cycle assessment (LCA) has been commonly applied in the environmental assessments of greenhouse production. While LCA studies have been conducted on several greenhouse production systems in Asia and European countries, there are limited studies in non-traditional greenhouse production regions such as Australia (Roggeveen, 2010; Page *et al.*, 2011, 2012, 2014).

**Table 1.1.** Potential environmental impacts and their associated causes of greenhouse production systems at different stages. Adapted from Plumiers *et al.* (2000) and Torrellas *et al.* (2012b).

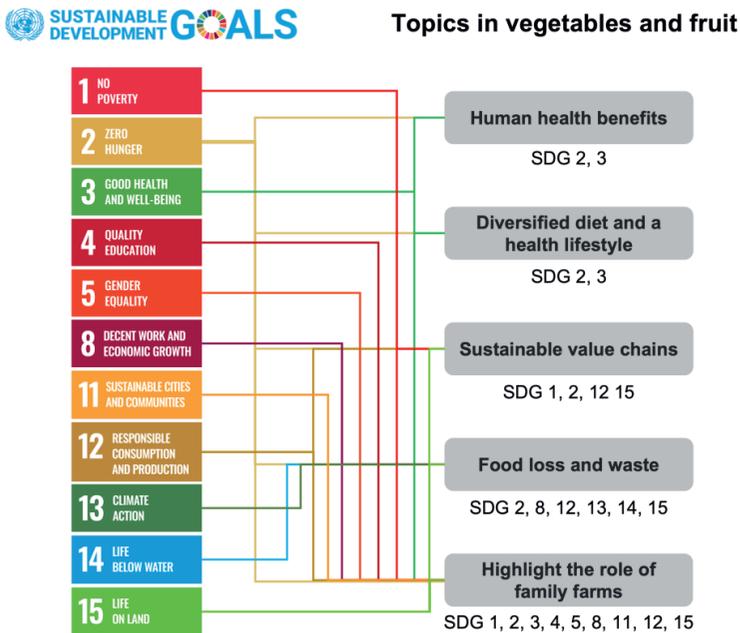
Stage	Inputs and activities	Main causes of environmental impacts	Potential environmental impacts
<b>Pre-production</b>	Manufacturing and production of materials for greenhouse infrastructure*, fertiliser, pesticides, seedlings, growing medium, electricity generation etc.	GHG <sup>1</sup> emissions, air pollutants, depletion of freshwater and heavy metals etc.	Climate change, abiotic depletion, air acidification, eutrophication, ecotoxicity, human health etc.
<b>During production</b>	Combustion of fossil fuels*  Use of synthetic fertiliser  Use of synthetic pesticides	GHG emissions, SO <sub>2</sub> <sup>2</sup> and small particulate matters  Nutrients losses, e.g. N <sub>2</sub> O <sup>3</sup> , NO <sub>3</sub> <sup>-4</sup> , PO <sub>4</sub> <sup>3-5</sup>  Chemical residues	Depletion of non-renewable energy climate change, air acidification, photochemical oxidation and respiratory effects  Climate change, eutrophication in aquatic systems  Ecotoxicity, human toxicity and biodiversity losses
<b>Post-production</b>	Irrigation  Greenhouse infrastructure*  Waste generation and its disposal pathways (landfill, incineration, compost and recycling)	Depletion of freshwater  —  Non-yield biomass, non-degradable solid waste, heavy metals, GHG emissions, nitrogen losses	Freshwater scarcity  Land occupation and biodiversity losses  Eutrophication, climate change, photochemical oxidation, human toxicity, terrestrial ecotoxicity
<b>Throughout whole greenhouse production system</b>	Transportations	Emissions of GHG, SO <sub>2</sub> and small particulate matters	Depletion of non-renewable energy climate change, air acidification, photochemical oxidation and respiratory effects

\* Asterisk denote that inputs or/and activities are specific or more pronounced for greenhouse production; <sup>1</sup> GHG = Greenhouse gas; <sup>2</sup> SO<sub>2</sub> = Sulphur dioxide; <sup>3</sup> N<sub>2</sub>O = Nitrous oxide;

<sup>4</sup> NO<sub>3</sub><sup>-</sup> = Nitrate; <sup>5</sup> PO<sub>4</sub><sup>3-</sup> = Phosphate.

## ***Sustainable development and greenhouse production systems***

Transformation of agri-food production must underpin sustainable development (SD) and is essential for the wellbeing of current and future generations (World Commission on Environment and Development, 1987). Despite no universal definition of SD, it is widely accepted that achieving SD requires harmonisation of three intrinsically linked dimensions: environmental compatibility, economic feasibility and social acceptance (United Nations, 2015). Within the Sustainable Development Goals (SDGs) proposed by the United Nations (2015), the FAO has identified that the consumption and production of vegetables and fruits specifically relates to 11 SDGs out of a total of 17 SDGs (Figure 1.2), pointing to a vital role of vegetables and fruit in achieving a sustainable world (Food and Agriculture Organisation, 2020). The widespread adoption by all UN members of SDGs makes it a valuable framework to consider a broader view of the sustainability of greenhouse production systems. In order to understand and monitor progress towards SD, metrics and methods must be developed for measuring SD. In the agri-food sector, a number of tools have been developed mostly for staple food such as maize, wheat and rice, to assess SD from both single and multiple aspects of environmental, economic and social dimensions (Schader *et al.*, 2014; Arulnathan *et al.*, 2020). However, there is still a lack of approaches covering integrated assessment of multi-dimensional aspects of SD for greenhouse production.



**Figure 1.2.** Sustainable Development Goals in relation to the production and consumption of vegetables and fruit. Adapted from Food and Agriculture Organization of the United Nations (2020).

The focus of sustainable development of food production has predominantly centred on environmental sustainability. This is particularly so for greenhouse production. Tomato, which is a commonly grown crop in global greenhouse cultivation, serves as an ideal case study for in-depth analyses of environmental sustainability within greenhouse production systems (Aznar-Sánchez *et al.*, 2020). Measurements based on field experiments (e.g. nitrogen leaching in soils) and life cycle assessment (LCA) are two main methods used in greenhouse studies to respectively assess specific environmental issues such as nutrient losses and freshwater use (Brentrup *et al.*, 2000; Hosono *et al.*, 2006; Grewal *et al.*, 2011; Yoshihara *et al.*, 2016; Llorach-Massana *et al.*, 2017; Martinez-Mate *et al.*, 2018; Liang *et al.*, 2019a), and a range of potential environmental impacts, such as climate change (GHG emissions), air and water pollution (Page *et al.*, 2012; Torrellas *et al.*, 2012b; Dias *et al.*, 2017; Golzar *et al.*, 2019; Naderi *et al.*, 2019). LCA is a tool to quantitatively assess the potential environmental impacts of a product, process or activity throughout its life cycle (Guinée, 2001). LCA has been extensively used to understand the environmental dimension of sustainability and explore solutions for mitigating identified environmental issues in greenhouse production (Pineda *et al.*, 2021). The prevalent environmental issues associated with greenhouse production include nutrient losses (Qasim *et al.*, 2021),

excess irrigation (Grewal *et al.*, 2011; Martinez-Mate *et al.*, 2018), GHG emissions caused by the use of fossil fuels for greenhouse heating (Gruda *et al.*, 2019), and non-degradable waste generation (Sayadi-Gmada *et al.*, 2019).

Given growing economic and social importance, and aggravating environmental issues, greenhouse production systems deserve more attention considering their sustainable performance. To address this, tailored approaches or tools are needed for greenhouse production systems to measure and monitor the progress towards SD, considering simultaneously environmental limits, economic benefits and social acceptance.

### 1.3. Thesis aims

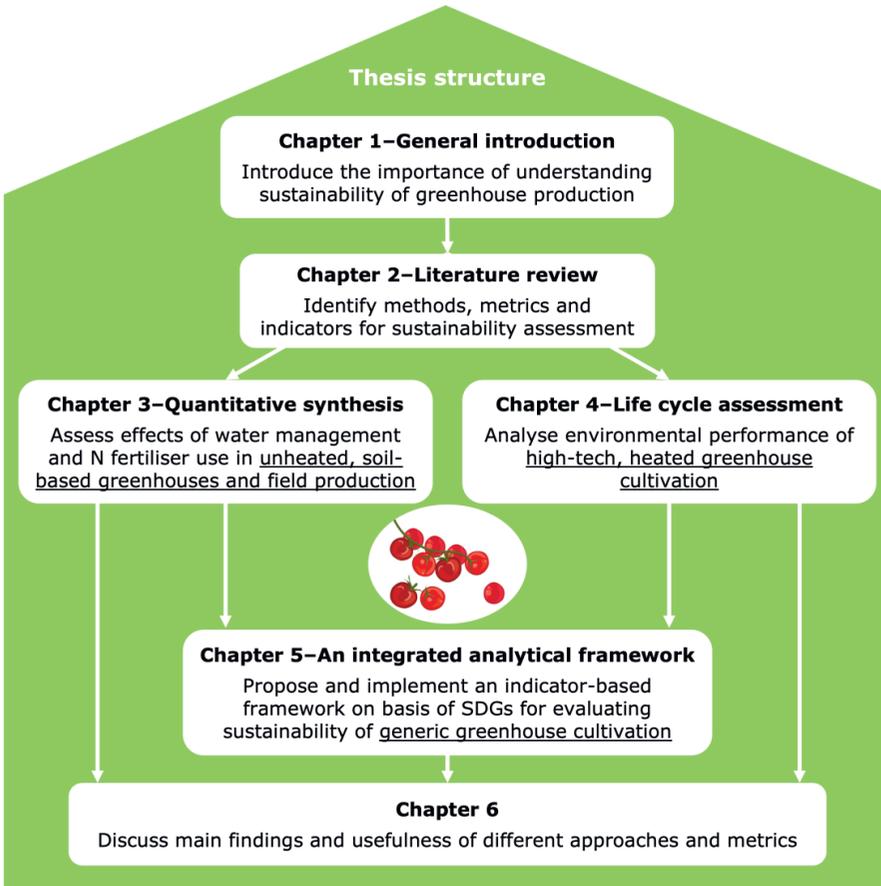
The overall aim of this thesis is to assess the environmental sustainability of nitrogen, water and energy use and analyse its impacts (direct and indirect) on economic and social dimensions of various greenhouse production systems using tomato as a case study. The ultimate aim is to foster the transformation of greenhouse production systems towards greater sustainability. The geographical context of this work includes mature greenhouse industries in Asia (e.g. China and India) and Europe (e.g. the Netherlands, Spain), and relatively young industries (e.g. Australia). Additionally, the level of technology (from low to high) adopted in the greenhouses and different types of cultivation (conventional and organic) are considered. Tomato was chosen as an example of greenhouse production due to its importance in terms of production, cultivation area and the availability of data. Moreover, major greenhouse crops such as sweet peppers and cucumber have a very similar type of production system, markets, ways of consumption (Alsanius *et al.*, 2019) and maybe sustainability performance. To achieve the overall aim, the research objectives are four-fold:

1. Review scientific literature to identify suitable approaches, in terms of methods, frameworks, indicators and metrics, for assessing the sustainability of greenhouse production systems (Chapter 2);
2. Assess the efficiencies of water and nitrogen (N) fertiliser use of greenhouse production systems in comparison to conventional field production at a global scale (Chapter 3);
3. Evaluate the environmental sustainability of greenhouse tomato production systems from a life-cycle analysis perspective (Chapter 4);

4. Propose and implement a framework of monitoring sustainability of greenhouse production systems based on the SDGs (Chapter 5).

## 1.4. Thesis outline

This thesis contains an introductory chapter (this chapter), followed by four research chapters and a general discussion (Chapter 6) as graphically displayed in Figure 1.3.



**Figure 1.3.** Conceptual diagram of the thesis structure.

**Chapter 2** reviews the literature on suitable methods and frameworks, indicators and metrics for evaluating sustainability of greenhouse production systems. Resource use efficiency, life cycle assessment and SDGs were identified as providing key information that considers environmental sustainability and resource use while provides insights in potential impacts on economic and social aspects for achieving sustainable greenhouse production.

**Chapter 3** evaluates the effects of water and nitrogen (N) fertiliser use and the interaction between water and N on tomato yield, water use efficiency (WUE) and N fertiliser use efficiency (NUE) in greenhouse (primarily soil-based) and field production systems through compiling baseline data of tomato yield, water management and N fertiliser use and their efficiencies at a global scale. Effects of water management were assessed through three aspects: total water input, mulching, and deficit and excess irrigation (a ratio of total water input to crop evapotranspiration).

**Chapter 4** assesses the potential environmental impacts of small-scale, commercial tomato greenhouse production systems in Australia through an LCA. This case study helped growers understand how their choices on greenhouse practices (e.g. use of wood biomass for greenhouse heating, use of coco coir as substrate) influenced the overall environmental sustainability of their production systems. Moreover, this study provided insights on how well the young greenhouse industry reflects the environmental issues identified from mature industries in Europe and North America and identified major environmental burdens (e.g. freshwater scarcity) in the greenhouse industry in Australia.

**Chapter 5** builds on the previous two chapters by incorporating adapted and simplified indicators used in the quantitative synthesis and LCA analysis. Through the lens of the SDGs, I propose a framework for the sustainability assessment of four different greenhouse production systems representing high-technology (the Netherlands), low-technology (Spain), each combined with two methods of cultivation (conventional and organic). Through implementing the framework, trade-offs and synergies can be identified in aid of decision making towards attaining different aspects of sustainability in greenhouse production.

**Chapter 6** synthesises the main findings of these study, by discussing the commonalities and differences between different approaches. Furthermore, the feasibility and usefulness of different methods, and their benefits and shortfalls for various potential users are discussed. Finally, I suggest possible pathways for facilitating the sustainable development of greenhouse production systems.

# **CHAPTER 2**

## **Approaches for assessing the sustainability of greenhouse production**

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## Abstract

The increasing demand for year-round fresh produce has stimulated the growth of greenhouse horticultural production worldwide. At the same time, public and political attention regarding the sustainability of greenhouse production systems has increased. The aims of this review were to identify suitable methods and frameworks, indicators and metrics for examining sustainability of greenhouse production, and to explore their potential usefulness in covering environmental, economic, and social dimensions of sustainability.

Contextualisation is needed for approaches assessing the sustainability of greenhouse production systems, particularly considering the higher complexity in inputs and outputs of greenhouse cultivation compared to field production. Nutrients, irrigation, energy, plant protection products (pesticides) and waste are the most critical sustainability themes identified in greenhouse production systems, impacting environmental, economic and social dimensions of sustainability. Management of nutrients and irrigation have transboundary negative impacts on our environment and ecosystems (across air, soil and water systems). Most greenhouse studies have focused on the environmental aspects of sustainability rather than on economic or social components. Resource use efficiency (RUE) and approaches based on life cycle thinking (LCT) have been extensively used for indicating sustainability of greenhouse systems. There is a need for system approaches considering multiple dimensions and their interconnections in order to provide a comprehensive understanding of greenhouse systems. Given the multidimensional nature, the Sustainable Development Goals (SDGs) of the United Nations were identified as suitable guidelines for proposing an analytical framework for sustainability assessment of greenhouse production systems. Metrics on the basis of RUE and LCT are considered as suitable indicators for constructing an analytical framework based on the SDGs.

**Key words:** Greenhouse production; Indicators and metrics; Methods and frameworks; Multiple dimensions; Sustainability assessment.

## 2.1. Introduction

There is a general agreement that the greatest challenge facing humanity in the 21<sup>st</sup> century is achieving and sustaining the wellbeing of all people without exceeding planetary boundaries (Rockström *et al.*, 2009). Within this context the concept of sustainable development (SD) has been widely discussed (UNFCCC, 2015; United Nations, 2015; Roy *et al.*, 2018). Sustainably producing food is at the heart of the solution to achieving SD (Wollenberg *et al.*, 2016; Porter *et al.*, 2017; Valentini *et al.*, 2019). To facilitate the sustainable progress in agri-food production, a number of tools, methods, frameworks, indicators and metrics have been developed to assess sustainability of farms (De Olde *et al.*, 2016; Galdeano-Gómez *et al.*, 2017; Chaudhary *et al.*, 2018; Kelly *et al.*, 2018; Arulnathan *et al.*, 2020; Coteur *et al.*, 2020; Chopin *et al.*, 2021; Dabkiene *et al.*, 2021). In general, these tools or methods integrate multiple indicators and metrics that cover different sustainability dimensions (e.g. environmental, economic, social or cultural) and encompass various themes (e.g. greenhouse gas emissions, biodiversity) (De Olde *et al.*, 2016; Chopin *et al.*, 2021). Previous studies have shown the usefulness of sustainability assessment tools in comparing performance between farms and benchmarking a type of farm at regional or country level (Arulnathan *et al.*, 2020). However, many sustainability assessment tools vary considerably in terms of sustainability dimensions (e.g. environmental, economic, social, cultural and governmental), themes (e.g. carbon emission, water, soil, energy), intended users (e.g. farmers, researchers or policy makers), scope of application (generic farms or specific type of farm), etc. This can lead to high variability in the results of sustainability assessment of farms and thus affects further decision making (De Olde *et al.*, 2016).

The growth in greenhouse production has increased the attention of various stakeholders (from producers to consumers) on the sustainability of the production systems. Compared to conventional field production, greenhouse production is characterised by high yield, and also high and consistent quality (Marcelis *et al.*, 2019). An increase in both demand and production for vegetables and fruit can be expected given the current vegetable and fruit deficiency in daily intake in many regions (Food and Agriculture Organization; and World Health Organization, 2017) and growing populations (Willett *et al.*, 2019). This future demand for vegetables and fruit could be partially provided from greenhouse production. Hence monitoring the sustainability of greenhouse production is important and requires appropriate approaches including well-defined methods and frameworks, indicators and metrics.

This chapter aimed to review the main challenges for achieving sustainability and potential approaches for sustainability assessment of greenhouse production systems, including multiple sustainable dimensions (e.g. environmental, economic or social) and themes (e.g. carbon emissions, water, land). The literature review was conducted through three main scholar search engines: Web of Science (searching 'Topic'), Scopus (searching 'TITLE-ABS-KEY') and Google Scholar, with for the three topics in Chapter 2 following ways of searching: 1) sustainability challenges in greenhouse production systems through snowballing method starting with commonly identified issues (e.g. GHG emissions, excessive use of water and nutrients) 2) sustainability assessment in greenhouse production covering multiple dimensions through using different combinations of the following keywords: 'greenhouse production', 'greenhouse vegetable', 'greenhouse horticulture', 'protected cropping', 'sustainability assessment', 'environmental', 'life cycle', 'economic', 'social'; 3) sustainability assessment tools and approaches in agriculture systems by snowballing search method starting with three comprehensive review papers by Binder *et al.* (2010), Schader *et al.* (2014) and Chopin *et al.* (2021).

## 2.2. Overview of greenhouse production and practices

The basic function of greenhouses is to protect plants from adverse weather conditions (e.g. unfavourable temperature, heavy rain) (Marcelis *et al.*, 2019). Nowadays, as greenhouse-related technology is advancing at a rapid pace (Marcelis *et al.*, 2019), greenhouse cultivation not only provides plants with a favourable growth environment (e.g. water, nutrients, temperature) by precisely regulating the fertigation systems and modifying the climate in greenhouses to some extent, but also has the potential to use resources in an efficient way (Marcelis *et al.*, 2019). Main greenhouse production regions are located in Europe and Asia (Figure 2.1) (Marcelis *et al.*, 2019). At a global scale, soil-based greenhouse systems are predominant, of which most are concentrated in Spain and China (Incrocci *et al.*, 2020; Qasim *et al.*, 2021). According to a recent report by Cuesta Roble Consulting (2019), the global area of greenhouse cultivation (excluding low and high tunnels with short lifespan) has exceeded 496,800 ha, with ca. 5% increment over two-year time.



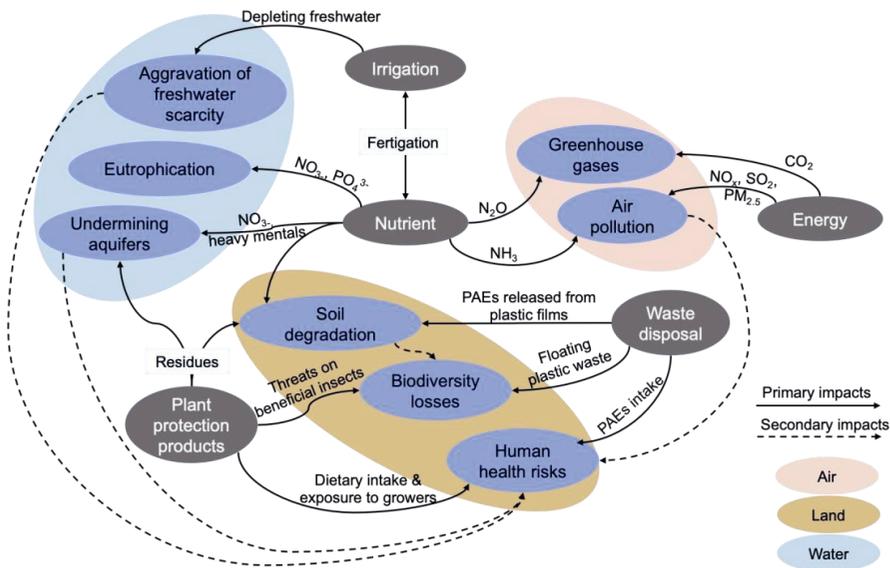
**Figure 2.1.** Overview of greenhouse production regions worldwide. Data were extracted from Marcelis *et al.* (2019).

In comparison to conventional field production, crop productivity in greenhouses can be up to ca. 10 times higher per unit area (Kubota *et al.*, 2018). However, yields can vary greatly between regions, greenhouse types, management practices and more importantly level of technology adopted for cultivation and climate control. There are several ways of categorising or naming types of greenhouses based on covering materials (e.g. glass or plastic), greenhouse structure (e.g. multi-span versus single span, Venlo, solar greenhouse etc.), growing media (soil or substrate), level of technology adopted (low-tech versus high-tech) and ways of cultivation (conventional or organic). For example, 90% of greenhouse production area is covered by plastics with large contributions from Southern Europe (e.g. Spain) and China. Typically, in these regions no or very limited climate control (e.g. no heating) is adopted and soil-based cultivation dominates. While in North Europe, for example in the Netherlands, almost all greenhouses are Venlo type glasshouses. In these glasshouses, plants are cultivated in substrates (e.g. stone wool) rather than in soils and advanced technology is adopted to modify the growing conditions in the greenhouses, such as heating, CO<sub>2</sub> enrichment, supplementary light, and high-tech water and nutrient supply systems. As a result, the yield per area for tomato production in Dutch greenhouse systems (ca. 60–100 kg m<sup>-2</sup>) is far higher than that in the plastic greenhouses in Spain (28 kg m<sup>-2</sup>), outlining the importance of the level of technology adopted (Kubota *et al.*, 2018). Owing to increasing recognition of benefits, such as increased efficiencies of resource use and thus economic benefits, greenhouse systems have been shifting from low-tech or non-climate-control towards high-tech soilless cultivation in some regions, such as Australia (Hadley, 2017). Additionally, with growing

recognition of the perceived health benefits of organic food (e.g. high nutritional value, no synthetic pesticide residues), organic cultivation in greenhouses has been rapidly increasing especially in Europe and North America to meet consumer demands for organic food (Dorais, 2019).

### **2.3. Challenges for achieving sustainability**

Greenhouse production is facing several sustainability challenges, chiefly depending upon cultivation systems and growers' management. Most challenges are derived from environmental pollution which poses threats on economic and social (including cultural) sustainability dimensions, affecting the overall sustainability performance of greenhouse production. For instance, apart from providing high-quality fresh produce all year round, greenhouse production also generates considerable amounts of waste (e.g. plastic, used growing medium), pollutants (e.g. chemical residue from nutrient losses, fine particulate matter) and greenhouse gas (GHG) emissions (e.g. CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O), directly impacting the environment and ecosystems via atmosphere, soil and water (Figure 2.2) (Hu *et al.*, 2017; Incrocci *et al.*, 2020; Qasim *et al.*, 2021). Consequently, these environmental impacts have raised increasing concerns from the public regarding greenhouse production systems, which may change decision-making on consumers' purchases, which in turn would influence the operation practices through the supply chain of greenhouse produces. Hence, understanding the current sustainability challenges and how they may influence the sustainability performance of greenhouse production systems is an essential step for the selection or formulation of suitable methods and metrics for sustainability assessment (Binder *et al.*, 2010). Below, the environmental problems were reviewed, focussing on three main concerns derived from greenhouse production: (1) nutrient losses, (2) GHG emissions and air pollutants, and (3) liquid and solid waste. How these concerns could affect social and economic sustainability in different greenhouse production systems is also discussed.



**Figure 2.2.** Summarised impacts of five critical themes in greenhouse production: irrigation, nutrient (e.g. nitrogen), energy, plant protection products and waste disposal. The impacts were clustered into three areas: air, land and water. Solid arrows denote the direct, primary impacts due to the critical themes; Dashed arrows denote the indirect impact in relation to the critical themes.  $\text{NO}_3^-$ : nitrates;  $\text{PO}_4^{3-}$ : phosphates;  $\text{NH}_3$ : ammonia;  $\text{NO}_x$ : nitrogen oxides;  $\text{SO}_2$ : sulphur dioxide;  $\text{CO}_2$ : carbon dioxide;  $\text{PM}_{2.5}$ : particulate matter 2.5; PAEs: phthalic acid esters.

### ***Nutrient losses to the environment and depletion of freshwater***

Excessive use of nutrients in greenhouse production systems, especially nitrogen, poses threats on the environment and ecosystems via air, soil and water, and thus human health and biodiversity (Galloway *et al.*, 2004; Sutton *et al.*, 2011, 2013; Qasim *et al.*, 2021). Additionally, nitrogen losses are often accompanied with excess irrigation and vice versa, due to the common application of combined fertilisation and irrigation (referred to as fertigation) (Thompson *et al.*, 2020). Hence, nutrient losses reflect low fertiliser use efficiency and potentially low water use efficiency as well.

Nutrient losses mainly occur through hydrological (leaching and surface runoff) and gaseous (e.g.  $\text{N}_2\text{O}$  emission) pathways (Zhu *et al.*, 2019). A global meta-analysis by Qasim *et al.* (2021) showed that the soil  $\text{N}_2\text{O}$  emissions and nitrate leaching in greenhouse production systems are much larger than in open-field production. Gruda *et al.* (2019) conducted a review on the impacts of greenhouse production on climate change, in which soil  $\text{N}_2\text{O}$  emissions was identified as one of the main sources of GHG emissions. Nutrient leaching (e.g. nitrates) accounts for the major nutrient losses (Min *et al.*, 2012; Qasim *et al.*, 2021), and has been widely identified in both low-tech, soil-based (Yan *et al.*, 2013;

Kalkhajeh *et al.*, 2017; Zhen *et al.*, 2020; Liang *et al.*, 2021) and high-tech soilless (Voogt *et al.*, 2013; Beerling *et al.*, 2014, 2017; Vermeulen *et al.*, 2017; Van Os *et al.*, 2019) greenhouse systems across several regions. Nutrient leaching, primarily nitrates, can contaminate aquifers and surface water bodies which are important sources of drinking water (Zotarelli *et al.*, 2007; Liang *et al.*, 2019d), and further contribute to potential eutrophication (Mugnozza *et al.*, 2007; Torrellas *et al.*, 2012a). The contamination of drinking water by nitrates directly impacts on human health (Ward *et al.*, 2018) which has caused extensive concern in relation to several large greenhouse production areas in Europe (Thompson *et al.*, 2020; Van Der Salm *et al.*, 2020) and China (Song *et al.*, 2009; Zhang *et al.*, 2019). For example, in Europe, legislation has been implemented to reduce the contamination in water bodies in several large greenhouse production regions (European Commission, 2018), such as southwestern Spain (Thompson *et al.*, 2020) and the Netherlands (Van Os *et al.*, 2019).

In addition to the impacts on water quality, nutrient leaching from soil-based greenhouses have led to acidity, salinity, and accumulation of heavy metals (e.g. Cd, Cu, Pb, and Zn) in the soils, thereby causing irreversible damage to soil quality (Kalkhajeh *et al.*, 2021). These soil degradation issues have been widely identified in most greenhouse production areas in China (Hu *et al.*, 2017; Kalkhajeh *et al.*, 2021), owing to much higher rates of fertilisation (e.g. 2000 kg N ha<sup>-1</sup> year<sup>-1</sup>) compared to the practices in European countries (Yang *et al.*, 2016; Qasim *et al.*, 2021). Given the large proportion of greenhouse production in terms of land use (20%) and production volume (35%) in total vegetable production in China, concerns about the soil quality and food safety have become evident from the general public to researchers (Kalkhajeh *et al.*, 2021). In China, greenhouse-grown vegetable production generally leads to high concentrations of heavy metals (primarily Pb, Cu, and Zn) and nitrate in the soils, and consumption of the vegetables from these production systems which may contain high concentration of heavy metals could cause risks to human health, especially for children (Chen *et al.*, 2013; Hu *et al.*, 2014; Yang *et al.*, 2016).

Excess irrigation occurs commonly in greenhouse production systems, especially in soil-based ones (Voogt and Bar-Yosef, 2019; Incrocci *et al.*, 2020; Van Der Salm *et al.*, 2020). Excess irrigation can accelerate nutrient leaching which in turn pollutes sources of irrigation and drinking water, meanwhile leading to depletion of local freshwater which could be a severe environmental burden to regions where freshwater is scarce, such as South-eastern Spain (Muñoz *et al.*, 2010), Northern China (Kang *et al.*, 2017) and

mainland Australia (Page *et al.*, 2014). Management of irrigation and nutrients play an important role in the overall sustainability performance of greenhouse production systems.

### ***Greenhouse gas emissions and air pollutants due to greenhouse heating***

In temperate or cold regions, greenhouse heating is essential to ensure sufficient plant growth when the temperature is low, which is mainly in the winter season (Marcelis and Heuvelink, 2019). However, use of fossil fuels for greenhouse heating produces large amounts of GHG emissions (e.g. CO<sub>2</sub>) that drives climate change (Gruda *et al.*, 2019), and several air pollutants such as sulphur dioxide (SO<sub>2</sub>), nitrogen oxides (NO<sub>x</sub>) and fine particulate matter (e.g. PM<sub>2.5</sub>) that impact human health (Pluimers *et al.*, 2000; Canaj *et al.*, 2020). The consumption of fossil energy has become a key factor hindering the progress towards sustainability in high-tech, heated greenhouse systems. Given the growing public concern on climate change and increasing demand for sustainably-produced food, greenhouse growers have to reduce GHG emissions due to use of fossil fuels, and regulations at both national and regional levels have been implemented on this matter (Verreth, 2013). In the Netherlands, where greenhouse industry represents an important user of energy and a major contributor to CO<sub>2</sub> emissions, the greenhouse horticultural sector has made several agreements with the Dutch government (known as 'Klimaataakkoord') (Netherlands Ministry of Economic Affairs, 2019) in order to limit global warming to below 2°C, as laid down in the Paris Agreement.

### ***Pesticide residues and waste management in low-tech systems***

Potential health risks of synthetic pesticide residues (also called plant protection products) in fresh produce are a common concern in greenhouse production systems, especially in low-tech plastic greenhouse systems (Bojacá *et al.*, 2012; Torrellas *et al.*, 2012a; Nordey *et al.*, 2017) due to extensive use of synthetic pesticides (Sun *et al.*, 2020; Wang *et al.*, 2020; Hepsağ and Kizildeniz, 2021; Kalkhajeh *et al.*, 2021). In addition to direct health hazards through exposure and human diets, pesticide residues could lead to local biodiversity losses (e.g. insects) (Schiesari *et al.*, 2013), and contaminate soils and aquifers (e.g. drinking water) (Roseth and Haarstad, 2010). Moreover, low-tech greenhouses produce large amounts of plastic waste (Antón *et al.*, 2005a; Chang *et al.*, 2013; Sayadi-Gmada *et al.*, 2020; Qiu and Wu, 2021) due to extensive use of plastic covers with a short lifespan (e.g. three years) (Antón *et al.*, 2005a) and plastic mulching (particularly in China) (Zhang *et al.*, 2020). The management of plastic waste has raised several concerns in some regions, such as potential threats on marine animals due to

floating plastic waste around Spain (Serrano-Arcos *et al.*, 2018) and damage on soil properties due to the residues of plastic mulching (e.g. phthalic acid esters) (Kalkhaje *et al.*, 2021). Therefore, quantitative analysis on the benefits and costs of sustainable use and waste management of plastic is needed for future optimisation in decision-making and associated policy making (such as subsidies).

### **2.4. Approaches and metrics for measuring sustainability in greenhouse production**

The definition of sustainability proposed in the Brundtland Report (World Commission on Environment and Development, 1987) suggests that its measurement and interpretation need to be framed in a complex manner that should at least capture issues of environmental, economic and social dimensions, and the potential interactions between them (trade-offs and synergies). To date, studies evaluating the sustainability of greenhouse production systems that consider multiple dimensions remain limited (Table 2.1) (Chang *et al.*, 2011; Torrellas *et al.*, 2012b; Yang *et al.*, 2016; Galdeano-Gómez *et al.*, 2017; Theurl *et al.*, 2017; Liang *et al.*, 2019c; Hollingsworth *et al.*, 2020; Zhen *et al.*, 2020; Qiu and Wu, 2021; García García and García García, 2022; Maureira *et al.*, 2022). Only three studies were found that simultaneously consider the environmental, economic and social dimensions of sustainability in greenhouse production systems (Yang *et al.*, 2016; Galdeano-Gómez *et al.*, 2017; Theurl *et al.*, 2017). Social dimension showed limited coverage among three dimensions and there is little consensus of indicators selected (Table 2.1). The latter was also true for other agriculture systems (De Olde *et al.*, 2017). The latter was also true for other agriculture systems (De Olde *et al.*, 2017). A large number of publications focuses only on a single dimension of sustainability alone, with the environmental dimension being mostly studied (Gruda *et al.*, 2019; Liang *et al.*, 2019c; Ntinis *et al.*, 2020).

**Table 2.1.** Sustainability dimensions and themes of the studies conducting a multi-dimensional assessment on the sustainability in greenhouse production systems.

Study	Region	Cultivation system	Sustainability dimensions			Approach or guidelines
			Environmental	Economic	Social	
Yang <i>et al.</i> , 2016	Eastern China	Unheated, soil-based	Fertiliser use & its impacts Pesticide use & its impacts	Stability of production Profitability Subsidies	Job opportunities Efficiency of technical support of cultivation practices	—
Galdeano-Gómez <i>et al.</i> , 2017	South-eastern Spain	Unheated, soil-based	Water use Fertiliser use & its impacts Pesticide use & its impacts Waste disposal	Profitability Labour productivity Value added Subsidies	Employment Contribution to local development Social capital and network function	SAFA <sup>1</sup>
Theurl <i>et al.</i> , 2017	Austria	Heated & unheated, soil-based	Greenhouse gas emissions Fertiliser use & its impacts Resource use Land degradation Agrobiodiversity	Product quality Profitability Subsidies Value added Stability of supply	Image of products Work satisfaction Capacity Development	SAFA
Chang <i>et al.</i> , 2011	Northern China	Unheated, soil-based	Greenhouse gas emissions Impacts on soil Impacts on water Waste generation	Crop yield Net economic benefit	—	Ecosystem services
Torrellas <i>et al.</i> , 2012b	Europe	Heated & unheated, soilless	Greenhouse gases Energy use & its impacts Fertiliser use & its impacts Pesticide use & its impacts Waste management	Production cost Profitability Capital investment	—	Life cycle approach

Liang <i>et al.</i> , 2019c	North China Plains	Unheated, soil-based	Energy use Greenhouse gases Water use	Profitability	—	Life cycle approach
Hollingsworth <i>et al.</i> , 2020	U.S.	Heated, soil-based	Energy use Water use Greenhouse gases Water quality Air pollution	Production cost Profitability	—	Life cycle approach
Zhen <i>et al.</i> , 2020	Beijing, China	Unheated, soil-based	Energy use Greenhouse gases Water use Fertiliser use & its impacts Pesticide use & its impacts	Production cost Profitability	—	Life cycle approach
Qiu and Wu, 2021	Eastern China	Unheated, soil-based	Greenhouse gases Waste disposal	Profitability	—	Ecosystem services
García García and García, 2022	South-eastern Spain	Unheated, soil-based	Greenhouse gases Fertiliser use Energy use Water quality Ecotoxicity Air pollution Waste disposal	Production cost Profitability	—	Life cycle approach
Maureira <i>et al.</i> , 2022	Washington state, U.S.	Heated, soilless	Energy use Water use Greenhouse gases	Crop yield Production cost Profitability	—	Life cycle approach

<sup>1</sup> SAFA is Sustainability assessment of food and agriculture systems guidelines (Food and Agriculture Organisation, 2014).

## **Resource use efficiency**

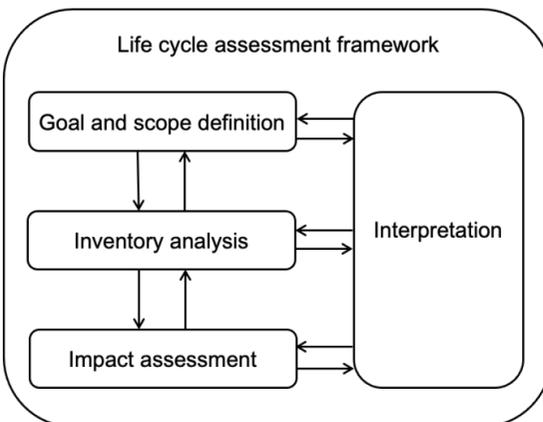
Proper use of resources, especially natural resources, is critical for achieving SD, supporting social and economic development (World Commission on Environment and Development, 1987). A group of indicators has been widely used to measure, monitor and optimise the performance of resource use efficiency (RUE) in agriculture production by companies, researchers, and policy makers (Steyn *et al.*, 2016; Rong *et al.*, 2021). For instance, water use efficiency (WUE) and nitrogen use efficiency (NUE) have been frequently used in sustainability studies of field crop production systems (Chopin *et al.*, 2021; Alaoui *et al.*, 2022). In greenhouse studies, WUE and NUE are mainly involved in two types of research: 1) comparing different resource management practices (e.g. irrigation and fertilisation methods) through experimental studies (De Pascale *et al.*, 2011; Quemada and Gabriel, 2016; Zhao *et al.*, 2019; Taguta *et al.*, 2022); 2) evaluating performance of greenhouse production in a given region through on-farm survey assessment (Liang *et al.*, 2019b; Tseng *et al.*, 2021). Since effects of water and N use are interlinked, many studies have simultaneously evaluated both WUE and NUE and interactive effects of water and N use. For example, several studies found that irrigation is directly associated to N leaching in soil-cultivated greenhouse production (Bai *et al.*, 2020; Incrocci *et al.*, 2020).

The large body of literature available reporting values of WUE and NUE provides an important source of information in understanding the performance of water and N management across various greenhouse production systems and regions (Molden *et al.*, 2010; Silva *et al.*, 2021). For example, Gu *et al.* (2020) used WUE and NUE to benchmark crop productivity, resource use, and nitrous emissions in greenhouse vegetable production in China. Qasim *et al.* (2021) evaluated the N losses from greenhouse vegetable production at a global scale. Ntinis *et al.* (2020) and Galdeano-Gómez *et al.* (2017) used WUE as an indicator in evaluating the sustainable performance of heated greenhouse production in Northern countries and unheated greenhouse cultivation in southeast Spain. To date, a benchmarking study is missing that uses both WUE and NUE as indicators to provide a quantitative understanding of water and N use across greenhouse systems with various growing conditions from a global scale. Such analysis can reflect implications on multiple dimensions of sustainability performance of greenhouse production in general, and more practically, will identify science-based strategies of optimising fertilisation and irrigation at the farm level (Qin *et al.*, 2016).

## Life cycle thinking approaches

Although it has been widely agreed that all three dimensions of sustainability assessment should be considered concomitantly, most work in relation to the sustainable performance of greenhouse production systems have been dedicated to environmental aspects, thanks to the well-developed approaches based on life cycle thinking (LCT). LCT has been extensively applied to assess environmental performance and identify trade-offs in field of industrial ecology and agriculture. This is further elaborated on in Chapter 4. A review study by Pineda *et al.* (2021) identified that 36 studies have assessed the environmental impacts of greenhouse tomato production through adopting LCT approaches.

The core concept of LCT is to consider all inputs, outputs and potential environmental impacts during a product's life cycle (cradle-to-grave) from raw material extraction, production, use of the product, and final waste disposal after use (ISO, 2006). Life cycle assessment (LCA) represents a complete analysis based on LCT, including four stages: goal and scope definition, inventory analysis, impact assessment and interpretation (Figure 2.3) (ISO, 2006). Given the comprehensive information provided on the potential environmental impacts, LCT has become a powerful tool for researchers and policy makers in formulating science-based strategies of mitigating environmental impacts (Antón *et al.*, 2019), and in assisting stakeholders (e.g. supermarkets) to prove that their operation meets the sustainability requirements demanded by the public (Visentin *et al.*, 2020; Charpentier Poncelet *et al.*, 2022).



**Figure 2.3.** Framework of life cycle assessment (LCA).

Through an LCA, a spectrum of categories is available for environmental impact assessment (Table 2.2). Notably, for most impact categories, several different indicators or

modelling choices are available to simulate the potential environmental impacts, and their selection can lead to very different results (Ridoutt *et al.*, 2016). For example, to evaluate the potential impacts on climate change, selection is required firstly on indicators, which are carbon footprint and global warming potential in this case (Table 2.2), and secondly on the modelling for calculating the selected indicator. For the calculation of carbon footprint (referring to the amount of GHG emissions associated with human activities), several choices are available in the modelling, such as 100-year global warming potential or 20-year global warming potential (Pandey *et al.*, 2011). Therefore, extra attention should be paid to the indicator or methods selected when comparing the results between different studies.

**Table 2.2.** Main inputs and activities of greenhouse production and selected contributing environmental impact categories, corresponding substances and environmental indicators (adapted from Pluimers, 2001).

Inputs and activities	Impact categories	Main chemical compounds or substances	Indicators
Use of fossil fuels for greenhouse heating	Climate change	CO <sub>2</sub> , CH <sub>4</sub> , N <sub>2</sub> O	Carbon footprint Global warming potential100
Fertiliser application	Abiotic depletion	Hard coal, natural gas, crude oil, metals	Abiotic depletion potential
Greenhouse construction	Acidification	NO <sub>x</sub> , NH <sub>3</sub> , SO <sub>2</sub>	Air acidification potential Terrestrial acidification potential
	Photochemical oxidation (summer smog)	NO <sub>x</sub> , non-methane volatile organic compounds	Photochemical oxidation potential
Greenhouse structure	Energy consumption	Fuels and electricity	Cumulative energy use
Fertiliser production			
Use of fossil fuel			
Fertiliser application	Eutrophication	NH <sub>3</sub> , NO <sub>x</sub> , NO <sub>3</sub> <sup>-</sup> , PO <sub>4</sub> <sup>-3</sup>	Freshwater eutrophication potential Marine eutrophication potential Nitrogen footprint Nitrogen use efficiency
Pesticides application	Ecotoxicity	Residues of pesticides, heavy metals (cadmium, lead, mercury etc.)	Terrestrial ecotoxicity potential Aquatic ecotoxicity potential
Fertiliser application			
Disposal of waste			
Pesticides application	Human toxicity	Residues of pesticides, small particulate matter (e.g. PM <sub>2.5</sub> ), heavy metals (cadmium, lead, mercury etc.)	Human toxicity potential Human carcinogenic toxicity potential Human non-carcinogenic toxicity potential
Combustion of fossil fuels			
Fertiliser application			

Water use for irrigation	Freshwater depletion	Freshwater	Water footprint Water use Water scarcity index
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Selection of environmental impact categories varies with the research interests or environmental concerns being addressed, and greatly depends upon the types of greenhouse systems being assessed (Table 2.3). Generally, in cool climate regions (e.g. the Netherlands), heating is essential for greenhouse production when the indoor temperature is insufficient for plant growth. Thus, the use of energy, typically fossil-based energy, is the biggest driver of most environmental impacts, especially climate change. While for plastic greenhouses in warmer climates, for example the Mediterranean basin, heating and climate control are rare, and therefore energy use is much lower. Instead, application of fertilisers and synthetic pesticides are the major contributors to the environment impacts of such greenhouses, such as through eutrophication and ecotoxicity (Antón *et al.*, 2019). Table 2.3 summarises selected impact categories and methods used for impact assessment from 28 studies across different greenhouse production systems (e.g. climate control and cultivation) and countries. A literature review by Gruda *et al.* (2019) concluded that in both heated high-tech and unheated low-tech greenhouses, the potential impact on climate change needs to be mitigated in the future development of greenhouse production. In most greenhouse studies, climate change appeared to be the most frequently selected impact category for the impact assessment, regardless of the type of greenhouse (Table 2.3). Given the increasing global attention on climate change ranging from individuals, organisations (e.g. IPCC) to countries (e.g. Paris Agreement), it can be projected that mitigation related to climate change will continue to be one of the most crucial tasks for the improvement of greenhouse production. Additionally, the use of cumulative energy demand is also very common in LCA studies to quantify energy use from different sources (e.g. non-renewable energy) and to indicate the impact of energy use on climate change, in particular for production in heated greenhouses. Moreover, air acidification, abiotic depletion, eutrophication (including freshwater aquatic and marine systems), and photochemical oxidation are considered in most studies. This is consistent with Pineda *et al.* (2021) who conducted a literature review on LCA studies of greenhouse tomato production. The authors indicated that terrestrial ecotoxicity was considered in some studies, which is also found in studies summarised in Table 2.3. Apart from ecotoxicity on ecosystems, Pineda *et al.* (2021) also showed that human toxicity was selected to assess especially the impacts of pesticides application in low-tech unheated greenhouses.

**Table 2.3.** Selection of environmental impact categories and corresponding methods in life cycle assessment across various greenhouse production systems in different countries.

Reference	Region	Type of cultivation	Impact assessment method	Impact categories
<b>Heated</b>				
Almeida <i>et al.</i> , 2014	Italy	Soilless	IPCC, CED,	CC, CED, WD
Antón <i>et al.</i> , 2012	The Netherlands	Soilless	CML 2001, CED	AA, AD, CC, CED, EU, PO
Boulard <i>et al.</i> , 2011	France	Soilless	CED, IPCC, GML	AA, CC, CED, EU, OD, PO, TE, AE, HT
Dias <i>et al.</i> , 2017	Canada	Soilless	TRACI2.1(v.1.00), CED, ReCiPe 1.07	AA, CC, CED, EU, OD, PO, RE, WD
Hendricks, 2012	Canada	Soilless	TRACI, CED	AA, CC, CED, EU, OD, PO
Heuts <i>et al.</i> , 2012	Belgium	Soilless	CML 2001, CED	AA, AD, CC, CED, EU, OD, PO, TE, HT
Ninas <i>et al.</i> , 2017	Greece, Germany	Soilless & Soil	IPCC, CED	CC, CED, WU
Page <i>et al.</i> , 2014	Australia	Soilless & soil	ReCiPe 1.07, Ridoutt and Pfister, 2010	CC, EU, WD, AE, TE, LU
Page <i>et al.</i> , 2012	Australia	Soilless & soil	IPCC, CED	CC, CED, WD
Pluimers <i>et al.</i> , 2000	The Netherlands	Soilless	IPCC, Heijungs <i>et al.</i> , 1992	AA, CC, EU
Röös and Karlsson, 2013	Sweden	Soilless	IPCC	CC
Theurl <i>et al.</i> , 2014	Austria	Soilless	IPCC	CC
Torrellas <i>et al.</i> , 2012b	The Netherlands, Hungary	Soilless	CML 2001, CED	AA, AD, CC, CED, EU, PO
Williams <i>et al.</i> , 2006	UK	Soilless	IPCC, CML	AA, AD, CC, CED, EU, LU
Vermeulen and Lans, 2011	The Netherlands	Organic	IPCC	CC
<b>Unheated</b>				
Antón <i>et al.</i> , 2005b	Spain	Soilless	—	AA, AD, CC, EU, OD, PO, HT, AE, TE
Antón <i>et al.</i> , 2005a	Spain	Soilless	TEAM 3.0	AA, AD, CC, EU, OD, PO, HT, AE, TE, WD
Bojacá <i>et al.</i> , 2014	Columbia	Soil	CML 2001	AA, AD, CC, EU, OD, PO, TE, AE, HT
Cellura <i>et al.</i> , 2012a	Italy	Soil	EPD scheme, CED	AA, CC, CED, EU, OD, PO, WD
Cellura <i>et al.</i> , 2012b	Italy	Soil	CML, CED	AA, CC, CED, EU, OD, PO, TE, AE, HT

Canaj <i>et al.</i> , 2020	Albania	Soil	ReCiPe 2016	AA, AD, CC, EU, FPM, IR, OD, PO, TE, AE, HT, LU, WD
He <i>et al.</i> , 2016	China	Organic & conventional soil	IPCC, CML, CED	AA, CC, EU, CED, AE, HT, TE, LU, WD
Khoshnevisan <i>et al.</i> , 2014	Iran	Soil	CML	AA, AD, CC, EU, OD, PO, TE, AE, HT
Muñoz <i>et al.</i> , 2008b	Spain	Soil	CML 2001	AA, AD, CC, CED, EU, OD, WD
Romero-Gómez <i>et al.</i> , 2014	Spain	Soil	Williams <i>et al.</i> , 2006	AA, AD, CC, CED, EU,
Romero-Gómez <i>et al.</i> , 2017	Spain	Soilless & soil	ReCiPe, USEtox	AA, AD, CC, EU,
Theurl <i>et al.</i> , 2014	Austria	Organic	IPCC	CC
Torrellas <i>et al.</i> , 2012a	Spain	Soilless	CML 2001, CED	AA, AD, CC, CED, EU, PO

IPCC: Intergovernmental Panel on Climate Change (IPCC, 2007);

CEM: Cumulative Energy Demand, expressed in MJ of lower heating values of fuels involved in the calculation;

CML: A method developed by the Institute of Environmental Sciences, Leiden University (Guinée, 2001);

EPD scheme: Environmental Product Declaration (IEC, 2008);

TEAM: Tools for Environmental Analysis and Management (Ecobilan Group, 1999);

TRACI: A tool for the reduction and assessment of chemical and other environmental impacts (Bare, 2011);

ReCiPe: A method for the life cycle impact assessment that developed in 2008 through cooperation between RIVM, Radboud University Nijmegen, Leiden University and PRé Sustainability (Huijbregts *et al.*, 2017);

USEtox: A model for characterizing human and ecotoxicological impacts of chemicals (Rosenbaum *et al.*, 2008);

AA = Air Acidification; AD = Abiotic Depletion; CC = Climate Change; CED = Cumulative Energy Demand; EU = Eutrophication; FPM = Fine Particulate Matter; LU = Land Use; IR = Ionizing Radiation; OD = Ozone Depletion; PO = Photochemical Oxidation; TE = Terrestrial Ecotoxicity; AE = Aquatic Ecotoxicity; HT = Human Toxicity; WD = Water Depletion.

## ***Sustainable development goals***

To aid in the transformation towards sustainable greenhouse production, understanding and monitoring the sustainability status from three dimensions is vital. This requires normative, rigorous and quantitative information that must be provided through transparent, traceable and measurable ways (Bartke and Schwarze, 2015). A wide range of frameworks and tools have been developed and applied for the sustainability assessment with indicators of three dimensions in other agri-food production (Chaudhary *et al.*, 2018; Arulnathan *et al.*, 2020; Chopin *et al.*, 2021; Alaoui *et al.*, 2022), but this is not so for greenhouse horticulture. Nonetheless, there is no consensus in the choices of methods to select, owing to wide variation in sustainability themes (e.g. water, soil quality etc.), scope (e.g. farm-level, sector-level), end users (e.g. farmers, policy makers), and weighing methods (De Olde *et al.*, 2016; Chopin *et al.*, 2021). Regarding farm-level sustainability assessment tools or frameworks, the actual application in agriculture production remains limited (De Olde *et al.*, 2016; Chopin *et al.*, 2021).

Given the lack of a harmonised method for sustainability assessment in agri-food production, and the large variation between conventional agricultural production and greenhouse cultivation, a new approach with legitimate indicators is needed to comparatively evaluate greenhouse production systems. The Sustainable Development Goals (SDGs) defined by the United Nations (2015) has emerged as the most important international framework that guides societies towards sustainability given the wide adoption by all UN members (Leal Filho *et al.*, 2018; Wood *et al.*, 2018; Mio *et al.*, 2020). Compared to the three-dimension lens (environment, economy, society), the SDGs represents a broader version of sustainability with expanded dimensions, such as cultural and governments (Nadaraja *et al.*, 2021). With the defined 17 SDGs (Table 2.4) and the linked 169 targets, this agenda provides a practical framework, covering multiple dimensions of sustainability for all countries and stakeholders to assess and improve global and local sustainability. Hence, SDGs offer a promising opportunity that engages different societal groups (e.g. farmers) across a wide range of scales (global, national, regional, individual farm) in their implementation (Salvia *et al.*, 2019).

**Table 2.4.** Sustainable development goals (SDGs) defined by the United Nations. SDGs identified to be associated with agri-food production are outlined in bold (Chaudhary *et al.*, 2018).

No.	SDGs
1	<b>End poverty in all its forms everywhere</b>
2	<b>End hunger, achieve food security and improved nutrition and promote sustainable agriculture</b>
3	<b>Ensure healthy lives and promote well-being for all at all ages</b>
4	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
5	Achieve gender equality and empower all women and girls
6	<b>Ensure availability and sustainable management of water and sanitation for all</b>
7	<b>Ensure access to affordable, reliable, sustainable and modern energy for all</b>
8	<b>Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all</b>
9	<b>Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation</b>
10	<b>Reduce inequality within and among countries</b>
11	Make cities and human settlements inclusive, safe, resilient and sustainable
12	<b>Ensure sustainable consumption and production patterns</b>
13	<b>Take urgent action to combat climate change and its impacts</b>
14	<b>Conserve and sustainably use the oceans, seas and marine resources for sustainable development</b>
15	<b>Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss</b>
16	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
17	Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development

The SDGs have become a heuristic framework in sustainability assessment in agriculture production (Leal Filho *et al.*, 2018). An increasing number of studies have assessed the sustainability of agriculture production on the basis of SDGs (Chaudhary *et al.*, 2018; Nhemachena *et al.*, 2018; Saladini *et al.*, 2018; Karnauskaite *et al.*, 2019; Hinz *et al.*, 2020; Streimikis and Baležentis, 2020; Adhikari *et al.*, 2021; Nadaraja *et al.*, 2021; Diogo *et al.*, 2022). Chaudhary *et al.* (2018) identified that 12 out of 17 SDGs are associated with agricultural production (Table 2.4), pointing out that agriculture is critical for achieving overall sustainability for humanity (Talukder *et al.*, 2020). Meanwhile, several studies demonstrated the compatibility between existing sustainability assessment methods and SDGs (Rasul, 2016; Giupponi and Gain, 2017; Randers *et al.*, 2018; Wulf *et al.*, 2018;

MacPherson *et al.*, 2020; Visentin *et al.*, 2020; Alejandrino *et al.*, 2021). In particular, LCT has been identified as having many shared considerations of environmental aspects with SDGs (Wulf *et al.*, 2018). Moreover, Gil *et al.* (2019) explored suitable indicators for evaluating SDG2 (end hunger, achieve food security and improved nutrition and promote sustainable agriculture) and considered WUE and NUE as two tangible indicators for the assessment on the sustainable performance of agriculture practices (Target 2.4). As previously discussed, large bodies of studies have employed RUE and LCT approaches in assessing single or multiple dimensions of sustainability in greenhouse production systems. These studies provide useful data sources which have great potential in interpreting the sustainability of greenhouse production systems. Therefore, RUE and LCT provide options of suitable indicators that could be potentially incorporated within the SDGs framework for the sustainability assessment of greenhouse horticulture.

## 2.5. Conclusions

Greenhouse systems provide a unique method for food production, being substantially different from conventional open-field production, in terms of inputs and outputs for the production. Hence, contextualisation is essential for approaches for assessing the sustainability of greenhouse production systems. Most studies on sustainability assessment of greenhouse production have emphasised environmental aspects, not considering the economic and particularly social dimensions. An analytical framework with tangible themes and indicators is required for comprehensive understanding on the sustainability of greenhouse production which ultimately facilitates the transformation towards sustainable development in the sector. Resource use efficiency and life cycle thinking approaches are identified as two key approaches to consider the environmental sustainability of greenhouse horticulture. The SDGs provides considerable potential for interpreting multiple dimensions of sustainability and allows for the identification of interconnections between sustainability themes and dimensions for greenhouse production. Collectively, this review suggests that resource use efficiency and metrics based on life cycle thinking are suitable indicators for understanding the sustainability of greenhouse production, and thus important components in constructing a comprehensive analytical framework in line with the SDGs.



## **CHAPTER 3**

### **Efficiencies of water and nitrogen fertiliser use for field and greenhouse tomato production: A global quantitative synthesis**

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## Abstract

Tomato is an important crop worldwide both in field and greenhouse production, requiring large amounts of water and nitrogen (N). Numerous studies have been conducted to optimise the utilisation of water and nitrogen use in tomato production. Efficiencies of water and N fertiliser use vary strongly with growing conditions, agricultural management and production systems. Given the importance and increasing interest in greenhouse tomato production, we conducted a quantitative synthesis to study and compare the effects of water management and N fertiliser use on tomato yield, water use efficiency (WUE) and N fertiliser use efficiency (NUE) of field and greenhouse tomato production systems (primarily soil-based cultivation). We compiled a comprehensive dataset based on 46 publications across a wide range of growing environments, including 430 fresh yields, 296 WUE and 348 NUE datapoints. Tomato yield was strongly affected by water and N inputs and the interaction between them. Correlation between tomato yield and total water input (TWI) differed between field and greenhouse systems, being linear for greenhouse studies and with an optimum relationship for field studies. On average, WUE was 23 kg FW m<sup>-3</sup> and NUE was 278 kg FW kg<sup>-1</sup> N for field studies; WUE was 47 kg FW m<sup>-3</sup> and NUE was 403 kg FW kg<sup>-1</sup> N for greenhouse studies. Greenhouse systems on average showed lower TWI (32%), higher yield (45%), WUE (104%) and NUE (45%) compared to field production. More evident effects of deficit irrigation within a range of 70–100% crop evapotranspiration (ET) were found on the tomato yield, WUE and NUE in greenhouse production in comparison to field production. The highest mean yield, WUE and NUE were found at 80–90%ET in greenhouse studies. Our analysis suggests that 1) efficacy of water-saving measures for tomato production can be markedly different between field and greenhouse production, which should be considered in application of optimisation measures; 2) understanding the interactive effects between water and N use is key for improvement of WUE and NUE simultaneously without compromising tomato yields.

**Key words:** Cultivation systems; N fertilisation; Resource use efficiency; Tomato productivity; Water management.

### 3.1. Introduction

Tomato (*Solanum lycopersicum* L.) is the second most consumed (fresh and processed) vegetable crop worldwide after potato. Annual world production of tomatoes in 2017 was 182 million tonnes with a total harvested area of ca. 4.8 million hectares (Food and Agriculture Organisation, 2017). Resource inputs, such as water and nitrogen (N) are typically high for most tomato production systems (Heuvelink, 2018). Given a rapidly growing world population, the demand for tomatoes is projected to increase further (Lombardi *et al.*, 2016), which will further increase water and N fertiliser requirements for tomato production, unless we can achieve substantial improvements in water and N use efficiencies. In order to deliver on the United Nations Sustainable Development Goals (United Nations, 2015), it is important to improve both water and N fertiliser use efficiencies because: (1) the availability of fresh water is declining, with water demands from other, competing sectors increasing (Wallace, 2000; Kummu *et al.*, 2010; Schewe *et al.*, 2014); (2) fertiliser production and application increases greenhouse gas emissions (Snyder *et al.*, 2009; Walling and Vaneekhaute, 2020) and (3) N losses during and after fertiliser application can contaminate water systems (Song *et al.*, 2009; Agostini *et al.*, 2010). It is of economic and environmental importance to monitor and better manage the use of water and N, given that significant efficiency gains are still possible (Hsiao *et al.*, 2007; Foley *et al.*, 2011; Gastal *et al.*, 2015; Xing *et al.*, 2019).

Tomato is produced globally in various climate zones, using a wide range of production systems from broad scale open-field operations to intensive greenhouse production systems. As for many other crops, water use efficiency (WUE) of tomato production could be improved. Most water is used by crop transpiration and soil evaporation, i.e. evapotranspiration (Allen *et al.*, 1998), leaving a small amount (<10%) for conversion into plant biomass (Van Kooten *et al.*, 2008). Despite that water-saving measures, such as mulching and drip irrigation have been prevalently applied, the amount of water applied in crop production is far beyond the amount of water required for evapotranspiration and biomass accumulation. Du *et al.* (2018) reported that the amount of total water input (irrigation and precipitation) for tomato production ranged from 56 to 1370 mm per growing season. This is larger than the range of the amount of water for evapotranspiration ranging from 284 to 735 mm, indicating large amounts of water being lost due to surface run-off and leaching (Du *et al.*, 2018). Excess irrigation and nitrogen use are interlinked, particularly when fertigation technology is used for combined water and nutrient application (Muñoz *et al.*, 2008b; Zotarelli *et al.*, 2009). Low N fertiliser use efficiency

(NUE) has been recognized in many production systems with losses ranging from 50–70% of N fertiliser applied (Sutton *et al.*, 2013; Abalos *et al.*, 2014). Hence, in order to reliably produce high yields while improving both resource use efficiencies, it is essential to consider the interaction between water and N fertiliser supply (Quemada and Gabriel, 2016).

Greenhouse production systems have become common for tomato production worldwide. Growing crops in greenhouses offers an avenue to improve WUE and NUE through environmental control and precise water and nutrient management. In the Netherlands, producers achieve high WUE and NUE in modern, high-tech greenhouses where a closed, recirculating soilless cultivation system collects the drainage of nutrient solution supplied through the fertigation system for reuse (Stanghellini, 2014). However, low cost, low-tech greenhouses with cultivation in soils are common in large greenhouse production regions, such as China and the Mediterranean area (Heuvelink, 2018). In these greenhouses, yield, WUE and NUE are often suboptimal. A greenhouse study in southern China by Min *et al.* (2012) reported that only around 10–20% of applied N was taken up by the crops, suggesting most applied N either leached out, was lost via denitrification or accumulated in the soil. Such losses are costly for both producers and the environment.

Several studies have explored strategies to optimise water use (Kuscu *et al.*, 2014; Wei *et al.*, 2016; Hou *et al.*, 2017; Li *et al.*, 2017b) and N fertiliser use (Tei *et al.*, 2002; He *et al.*, 2007; Zotarelli *et al.*, 2007; Elia and Conversa, 2012; Min *et al.*, 2012), and the combined use of water and N (Rinaldi *et al.*, 2007; Wang *et al.*, 2015; Du *et al.*, 2017; Li *et al.*, 2017a) in tomato production for specific locations and for specific cultural and crop management practices. However, yield, WUE and NUE vary greatly with environmental conditions. Hence, strategies recommended for a specific production system may have limited applicability for other systems or at other locations. Instead of site-specific strategies, there is a need to understand the range and values of water and N use efficiencies, and the possible interactions between water and N use, across a range of production environments and agricultural practices for both field and greenhouse production. This will then provide an important baseline data and information for future resource optimisation efforts for tomato and other vegetable crop production.

A quantitative synthesis can summarize information from many, diverse studies (Stanley and Jarrell, 1989). A meta-analysis by Du *et al.* (2018) has explored the effects of water and N inputs on tomato yield, WUE and NUE, as well as the interactions between them. That study provided recommendations on optimal water and N inputs and saving plans for

different countries. However, these recommendations were given without considering differences between production systems, and therefore may misguide the practices for improvement of resource use efficiency in tomato production. Due to the availability of research and corresponding data on tomato production in both greenhouse and open-field production systems, it becomes possible to compare water and nitrogen usage between the two.

Here we quantified the existing, global variability of tomato yields and their associated WUE and NUE across different environments and production systems. Our specific research objectives were to (1) quantify and compare the relationships between tomato yield, water use, and applied N fertiliser in field and greenhouse production systems; (2) examine the effects of irrigation management in combination with water-saving practices, such as total water input, deficit vs excessive irrigation with and without mulching on yield, WUE and NUE in two production systems; (3) explore the possible interactions between water and N on crop yield, WUE and NUE. This quantitative synthesis provides the necessary baseline figures for future optimisation of resource use in tomato production.

## 3.2. Methods

### *Data collection*

We systematically searched the peer-reviewed literature, conference proceedings, PhD theses and book chapters through three main scholar search engines: Web of Science (searching 'Topic'), Scopus (searching 'TITLE-ABS-KEY') and Google Scholar (Supplementary Figure 3.1). Most studies investigated the relationship either between crop water use and yield, or between N fertiliser use and yield under given growing conditions and agricultural practices. The search was conducted through using different combinations of the following terms: 'tomatoes', '*lycopersicum*', 'yield', 'biomass', 'dry matter', 'water use', 'water productivity', 'evapotranspiration', 'nitrogen fertiliser', 'nitrogen fertilizer', 'nitrogen' in the article title, abstract or key words. The preliminary search yielded ca. 770 publications (excluding duplicates). We then applied the following screening criteria based on the abstracts of the publications: (1) studies must report tomato yield, total water input during the growing season, the rate of N fertiliser application; (2) actual cumulative crop evapotranspiration (ET) was considered as the most common estimation of actual amount of water use required for crop production (Tanner and Sinclair, 1983; Sinclair *et al.*, 1984) and should be reported in the study; (3) production system, irrigation management (e.g. amount of irrigation, furrow versus drip irrigation), water-saving practices (e.g. mulching

versus no mulching), environmental conditions, soil texture and planting density of the experiment were provided.

In the end 46 studies across 13 countries, including 34 field studies and 12 greenhouse studies, met the selection criteria and were used for data extraction (Appendix I). Each datapoint required for the quantitative synthesis was the mean value of a treatment reported in the original study. When data were only available in figures, values were extracted by using G3data (<https://github.com/pn2200/g3data/>). In total, 430 fresh yields, 296 WUE and 348 NUE datapoints were included for the final analysis. All data were classified based on the production system (field or greenhouse).

### Definitions

Total water input (TWI; mm) was calculated as the sum of the amount of precipitation (only for field production) and the amount of irrigation water (mm) applied during the growing season (Equation 1). It was assumed that for greenhouse production systems precipitation was not captured and hence unavailable for plant growth.

$$TWI = \text{Precipitation} + \text{Irrigation water} \quad (1)$$

Irrigation ratio was defined as (Equation 2):

$$IR = \frac{TWI}{ET} \quad (2)$$

Where ET (mm) denotes the cumulative crop evapotranspiration measured or estimated during the growing season. Therefore, IR values <1 and >1 indicate deficit and excess irrigation, respectively. Note that here ET was measured or estimated based on soil water content during the crop production and therefore different from reference evapotranspiration (Allen *et al.*, 1998). The latter is often used as a reference value in designing irrigation strategies before actual crop production occurred. Water use efficiency (WUE; kg FW m<sup>-3</sup>) was defined as (Equation 3):

$$WUE = \frac{\text{Fresh yield}}{TWI} \times 100 \quad (3)$$

where fresh yield (t ha<sup>-1</sup>) is the fresh weight (FW) of tomato yield. N fertiliser use efficiency (NUE; kg FW kg<sup>-1</sup> N) was defined as (Equation 4):

$$NUE = \frac{\text{Fresh yield}}{N \text{ fertiliser supply}} \times 1000 \quad (4)$$

where N fertiliser supply ( $\text{kg N ha}^{-1}$ ) is the total N fertiliser applied during the growing season, including synthetic N fertiliser and farmyard manure (mainly in China and India). For studies where N content of farmyard manure application was not specified and included in the total N supply, estimation of the N content in farmyard manure was based on Liu et al. (2010) and Bandyopadhyay et al. (2010) for studies in China and India, respectively. The observations ( $n = 9$ ) without N fertiliser supply were excluded from the calculation of NUE.

### **Data analysis**

Linear regressions were conducted to examine the relationships between prediction variables (fresh yield, WUE or NUE) and independent variables (TWI, N fertiliser supply or irrigation ratio). Multiple linear regression was used to simultaneously estimate the mean effects of variables on tomato yield, WUE and NUE. TWI and N fertiliser supply as well as their interaction ( $\text{TWI} \times \text{N}$ ) were included in all models as essential variables, as responses of yield to N fertiliser supply and TWI were the main research interest in the present study.

The best model was identified based on the Akaike Information Criterion (AIC) scores, including TWI, N fertiliser supply and their interaction (Equation 5) for explaining fresh yield, WUE and NUE in field and greenhouse systems. Mulch was included as a categorical variable (two levels: mulch, no mulch) for field production systems as it was found to be significant. For greenhouse studies, limited data for systems without using mulch was available, and therefore the effects of mulch were not assessed.

$$\text{Dependent variable} = \alpha + \beta_1 \times \text{TWI} + \beta_2 \times \text{N} + \beta_3 \times \text{TWI} \times \text{N} \quad (5)$$

Where  $\alpha$  denotes intercept and  $\beta_{1-3}$  denote the response of dependent variable (fresh yield, WUE or NUE) to changes in independent variables (TWI, N and  $\text{TWI} \times \text{N}$ ),  $\text{TWI} \times \text{N}$  represents the interaction between TWI and N.

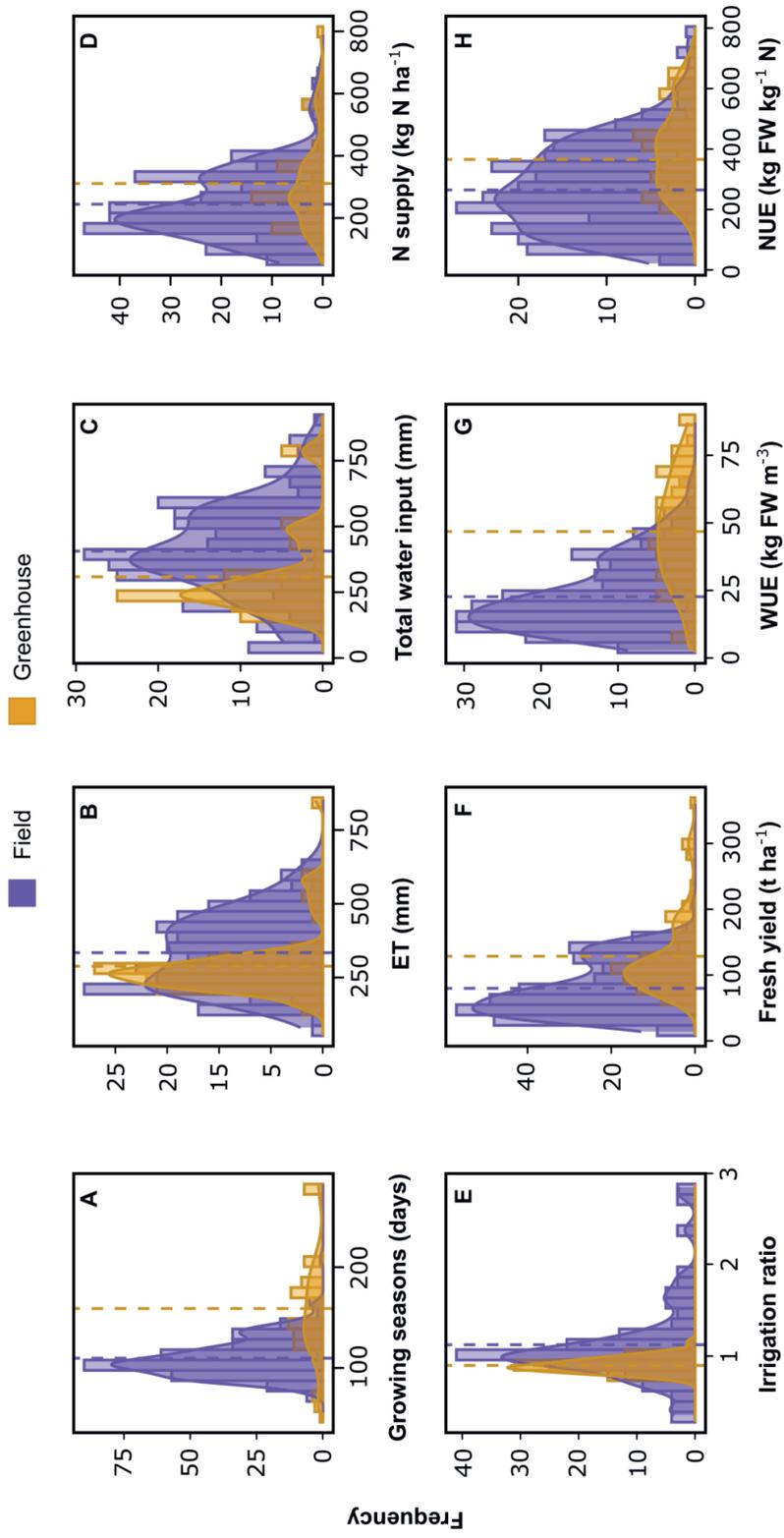
All statistical analyses were conducted in R programming language (R Core Team, 2018, Preprint). Because almost none of the studies used for the quantitative synthesis reported standard deviation or standard error, an unweighted analysis was conducted.

## **3.3. Results**

### **Overview of the datasets**

In general, all variables showed large variations for both field and greenhouse production systems (Figure 3.1). Possible reasons for these variations included very different

environmental conditions and different varieties and agricultural practices. The average length of a growing season for greenhouse production (159 days; Supplementary Table 3.1) was 45% longer than that for field production (110 days; Supplementary Table 3.1) (Figure 3.1A). This may largely explain the higher average yields in greenhouse production ( $129 \text{ t ha}^{-1}$  compared to  $80 \text{ t ha}^{-1}$  for field production; Supplementary Table 3.1) (Figure 3.1E). Nonetheless, average water use in greenhouse production was ca. 14% (ET) or 24% (TWI) lower than that in field production (Figure 3.1B, 3.1C). As a result, the studies on greenhouse production presented on average a higher WUE ( $47 \text{ kg FW m}^{-3}$ ; Supplementary Table 3.1), being about twice as high as for field production (Figure 3.1G). Greenhouse studies reported on average 45% higher N fertiliser supply (Figure 3.1D) and 45% higher NUE (Figure 3.1H) than field studies (Supplementary Table 3.1). For greenhouse studies, irrigation ratio ( $<1$  for deficit irrigation and  $>1$  for excess irrigation) mostly was lower than 1 (Figure 3.1E) with an average value of 0.9 (Supplementary Table 3.1), meaning that deficit irrigation was applied in most of the assessed greenhouse studies. For field studies, a wide range of irrigation ratios were reported, mostly showing excess irrigation (Figure 3.1E).



**Figure 3.1.** Frequency distributions for eight variables in the analysed datasets for field (purple) or greenhouse production systems (orange): length of the growing season (A), actual cumulative crop evapotranspiration (ET; B), total water input (C), N fertilizer supply (N supply; D), irrigation ratio (E), fresh yield (F), water use efficiency (WUE; G) and nitrogen fertilizer use efficiency (NUE; H). Dashed lines denote the mean values of each variable in the two production systems.

To provide a comparison with modern, high-tech greenhouse production systems, data from commercial tomato greenhouses were additionally compiled (Table 3.1). Compared with the greenhouse studies in our dataset, high-tech commercial greenhouses showed much higher crop productivity and water use. For instance, the average yield and water use commercial greenhouses in the Netherlands were respectively 334% and 300% higher (Table 3.1) than those reported in the assessed greenhouse studies (Supplementary Table 3.1). In modern Dutch greenhouses, where soilless cultivation (using substrates such as stone wool) and assimilation lighting have been adopted, yields that are 590% higher than the average yield for greenhouses in our dataset have been reported, while water and N fertiliser losses were considerably lower or even fully eliminated (Table 3.1).

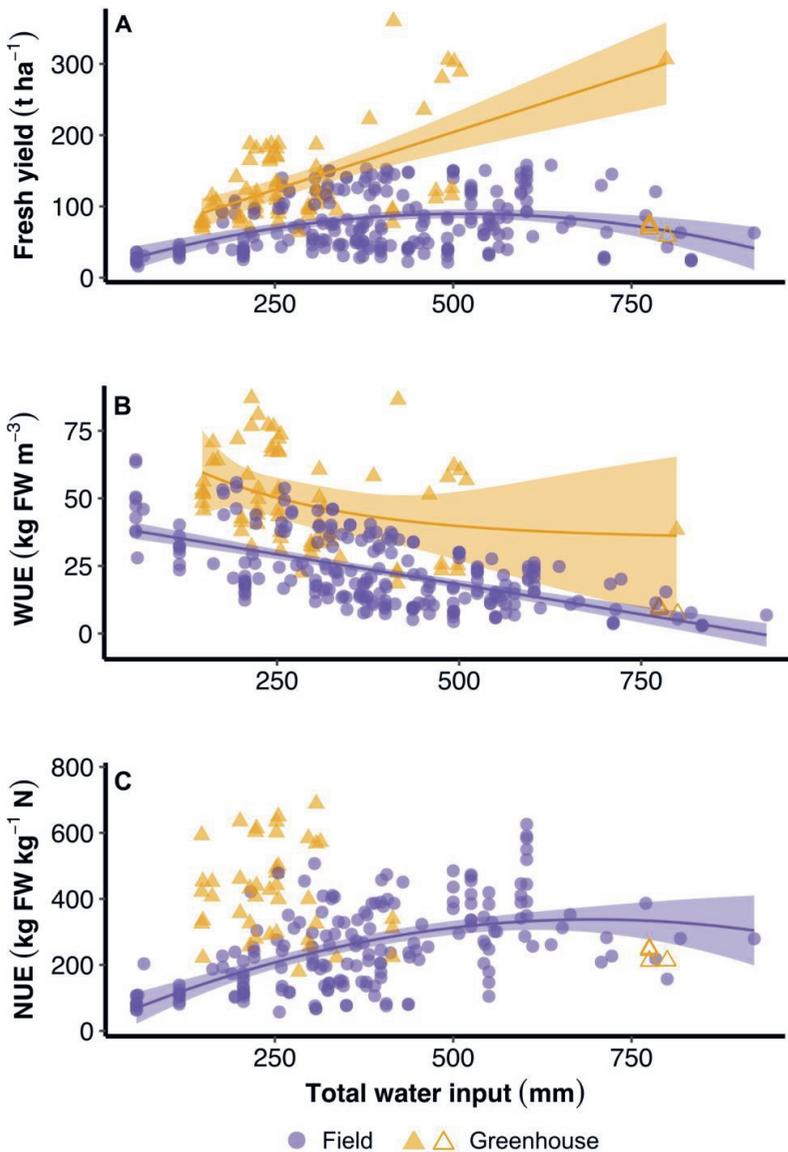
**Table 3.1.** Average yield, total water input, water use efficiency (WUE) and N fertiliser loss per year for tomato production in commercial, high-tech greenhouses<sup>1</sup> in different culture systems, countries or regions. Recirculation indicates if the drain water from the culture system was re-used.

Growing medium	Yield (t ha <sup>-1</sup> )	Total water input (mm)	WUE (kg m <sup>-3</sup> )	N fertiliser supply (kg N ha <sup>-1</sup> )	N loss (kg N ha <sup>-1</sup> )	Recirculation	Country/Region
<b>Soil-based</b>							
Pronk et al., 2007	560	1232	45	300–1700	200–1000	No	The Netherlands
Pronk et al., 2007	630	1260	50	300–1700	200–1000	No	The Netherlands
<b>Soilless</b>							
Vermeulen, 2016	650	1120	63	—	60–107	Yes (85%)	The Netherlands
Pronk et al., 2007	700	1050	67	—	0	Yes (100%)	The Netherlands
Vermeulen, 2016 (with assimilation lighting)	890	—	—	—	—	Yes	The Netherlands
<b>Soil-based or soilless</b>							
Heuvelink, 2018 & Marcelis et al., 2000	500	900	63	300–1700	120	—	North-western Europe
Dias et al., 2017	550	1021	54	1824	—	—	Ontario, Canada
Ozkan et al., 2004	200	700	29	320	—	—	Turkey

<sup>1</sup> These data were sourced from studies that were excluded from the literature selection for the quantitative synthesis. These studies either did not match the selection criteria (e.g. no information on N supply) or did not report experimental observations but rather average values for greenhouses at regional or country scale.

### ***Effects of water management on yield, WUE and NUE***

The datasets of greenhouse studies indicated that tomato yields increased linearly with total water input (TWI; Figure 3.2A;  $P$  value  $< 0.001$ ) and no significant correlation between NUE and TWI (Figure 3.2C). Tomato yields and NUE of field production were quadratically and asymptotically correlated with TWI, respectively (Figure 3.2A, 3.2C). This suggested that the increases in fresh yield and NUE were constrained by other factors when TWI was no longer limiting. WUE was negatively correlated with increased TWI in both systems. The differences in fresh yields between greenhouse and field systems increased with increasing TWI (Figure 3.2A). In contrast, the gap in WUE between the two types of systems declined as TWI increased (Figure 3.2B).

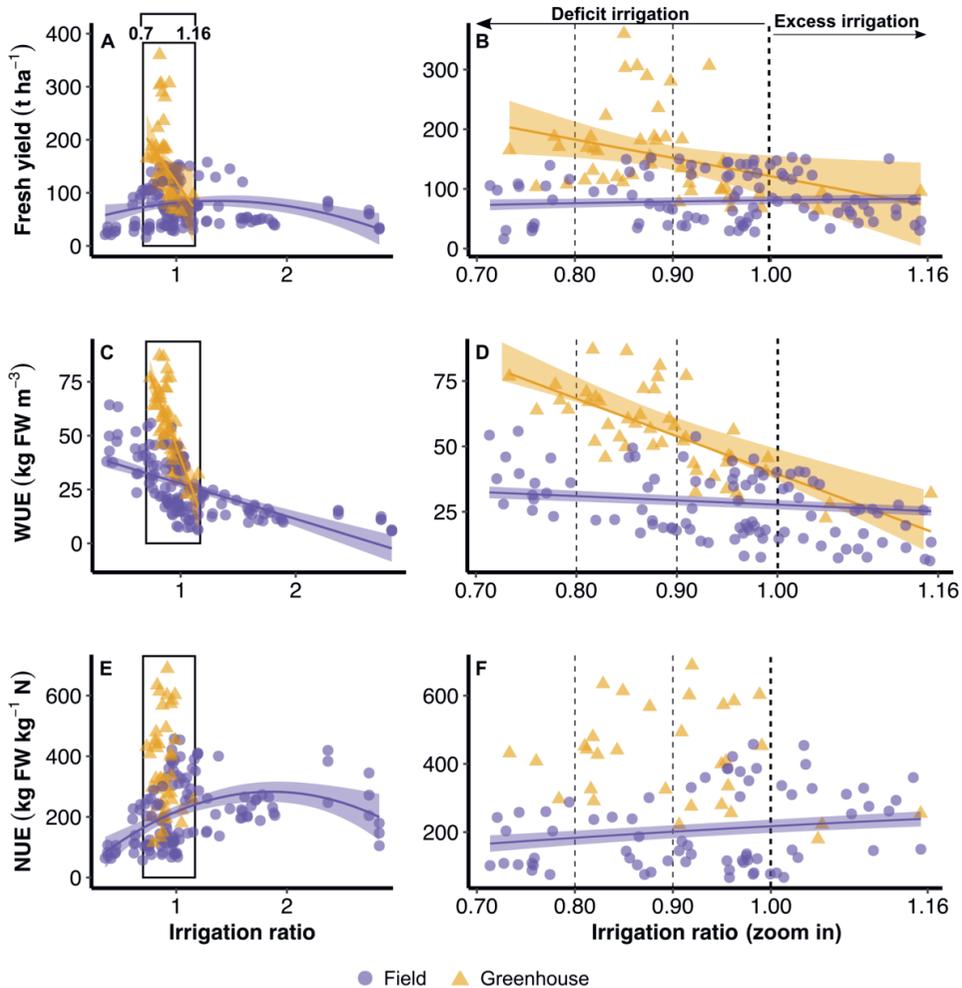


**Figure 3.2.** Fresh yield (**A**), water use efficiency (WUE; **B**) and N fertiliser use efficiency (NUE; **C**) as a function of total water input of tomato production under field (purple dots) and greenhouse (orange triangles) cultivation systems. Solid lines and colour bands indicate significant regressions and 95% confidence intervals. Note that four data points of greenhouse systems (open orange triangles) were not included in the regression analysis as these points were clear outliers and would have strongly influenced the regression.

We additionally assessed the effects of deficit (< ET) or excess irrigation (> ET) on tomato yield, WUE and NUE through a defined indicator termed as irrigation ratio (TWI/ET; Figure 3.3). Fresh yield and WUE significantly decreased with irrigation ratio within a range of

0.7–1.16 in greenhouse production (Figure 3.3A and 3.3C). No clear trend was observed between NUE and irrigation ratio under greenhouse systems (Figure 3.3E). For field production, fresh yield and NUE showed a quadratic response to irrigation ratio (Figure 3.3A and 3.3E). WUE decreased linearly with irrigation ratio in field production (Figure 3.3C).

To better visualise the results of the comparative analyses between field and greenhouse studies, we zoomed in the plots (Figure 3.3A, 3.3C and 3.3E) on data points in the irrigation ratio range between 0.7 and 1.16 (Figure 3.3B, 3.3D and 3.3F). Within this range of irrigation ratios, fresh yield, WUE and NUE were less affected by irrigation ratio for field production than for greenhouse production. Fresh yield, WUE and NUE of greenhouse production were higher than that of field production when deficit irrigation was applied (irrigation ratio < 1; Figure 3.3B, 3.3D and 3.3F). The highest mean values of fresh yield, WUE and NUE under greenhouse conditions appeared around irrigation ratio of 0.8–0.9. Differences in fresh yield and WUE between field and greenhouse systems declined as irrigation ratio increased. For irrigation ratios above 1 (excess irrigation), these differences between systems were not observed.

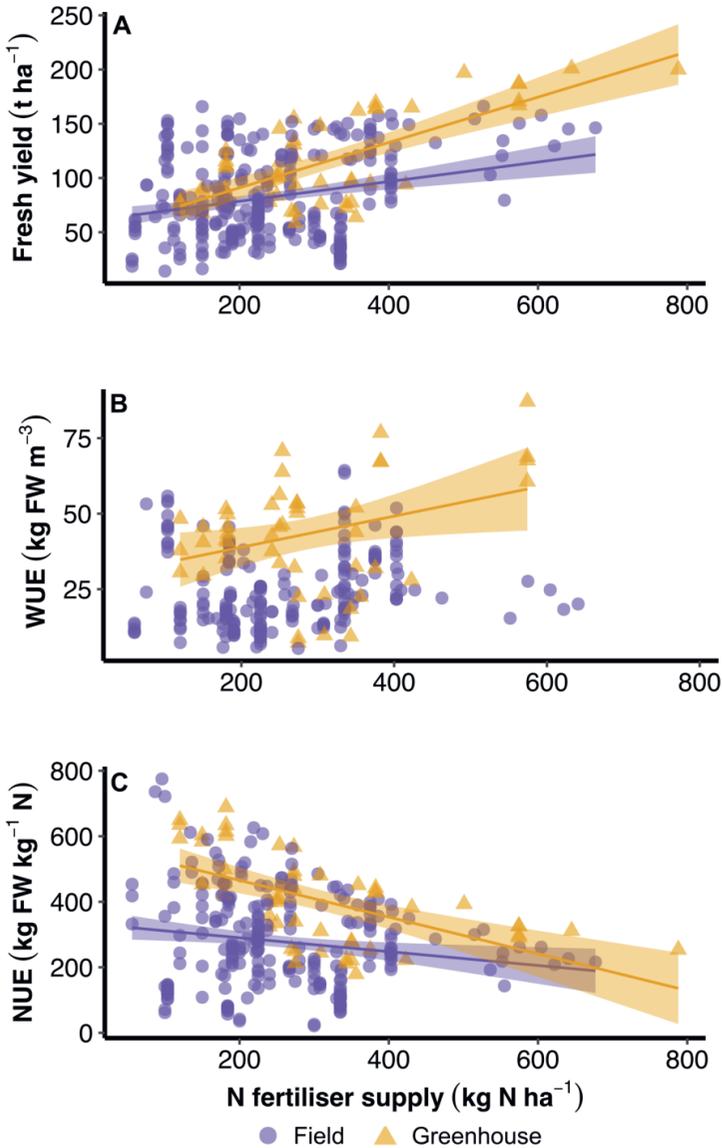


**Figure 3.3.** Effects of irrigation ratio (total water input/actual crop evapotranspiration) on fresh yield (A), water use efficiency (WUE; C) and N fertiliser use efficiency (NUE; E). Solid lines and bands indicate significant regressions and 95% confidence intervals. Panels B, D and F present the zoom-in plots for irrigation ratio between 0.7 and 1.16.

### Effects of N fertiliser use on yield, WUE and NUE

Fresh yield increased and NUE decreased with N fertiliser supply (Figure 3.4A; linear regressions,  $P$  value < 0.001), however, large variations were observed in both systems. Fresh yield and NUE of greenhouse studies were higher than that of field studies at a given level of N fertiliser supply (Figure 3.4A and 3.4C). This yield difference between systems increased with increased N fertiliser supply (Figure 3.4A). In contrast, the differences in NUE between systems declined as the N fertiliser supply increased and fully

disappeared when N supply exceeded 500 kg N ha<sup>-1</sup> (Figure 3.4C). WUE increased linearly with N supply for greenhouse production, whereas no such relationship was observed for field production (Figure 3.4B).



**Figure 3.4.** Fresh yield (A), water use efficiency (WUE; B) and N fertiliser use efficiency (NUE; C) as a function of N fertiliser supply for field production (purple dots) and greenhouse production (orange triangles) of tomato. Solid lines and bands indicate significant regressions and 95% confidence intervals.

**Interactive effects between water and N fertiliser supply for yield, WUE and NUE**

Multiple linear regression revealed a significant interaction between TWI and N fertiliser supply for fresh yield. This interaction was positive for field production with mulch and for greenhouse production, however it was negative for field systems without mulch (Table 3.2). For example, a significant effect of TWI on tomato yield of greenhouse systems was only found at relatively higher levels of N fertiliser supply (500–940 kg N ha<sup>-1</sup>) (Figure 3.5E). For WUE, a positive interaction was observed for field with mulching and greenhouse systems, whereas field production without mulching showed no interaction between TWI and N fertiliser supply. The negative effect of TWI on WUE was stronger at high N fertiliser supply (Figure 3.5B and 3.5F). For NUE, a negative interaction was shown for field with mulch systems (Table 3.2), whereas the other two production systems showed no interaction. The positive effect of TWI on NUE was less strong at higher N fertiliser supply (Figure 3.5C).

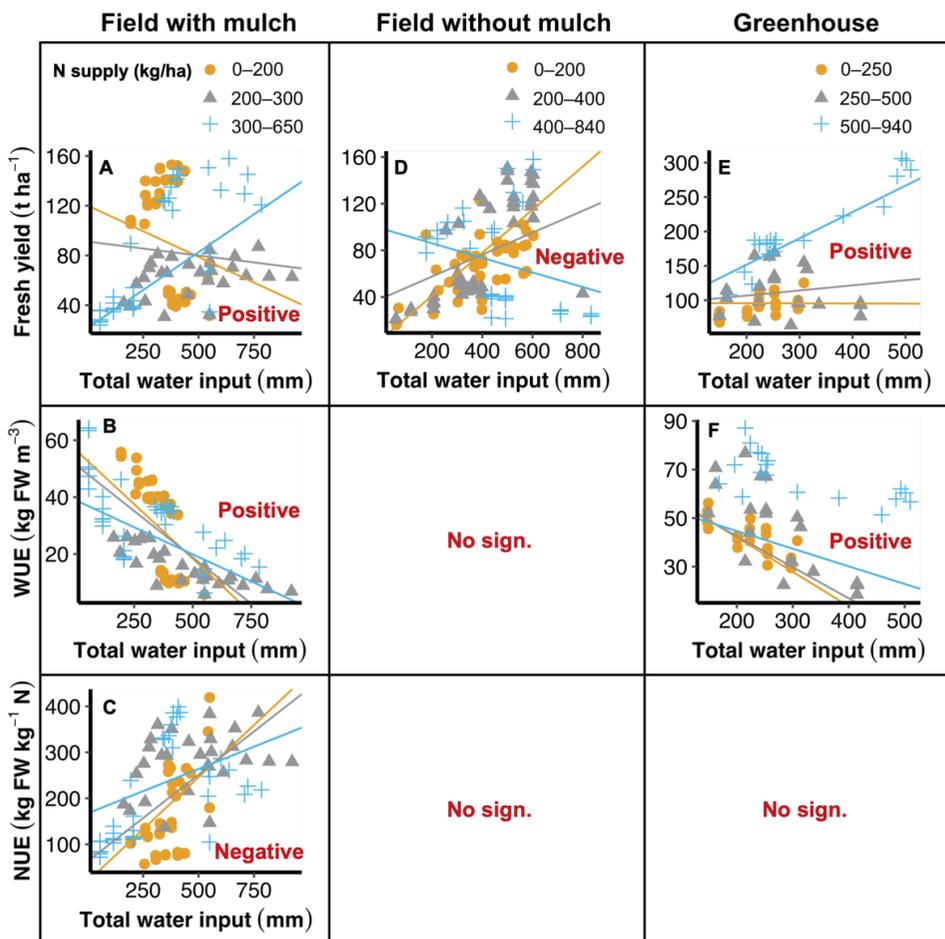
**Table 3.2.** Effects of total water input (TWI), N fertiliser supply (N) and their interaction on fresh yield, water use efficiency (WUE) and N fertiliser use efficiency (NUE) (multiple linear regression models; eqn. 5) under three types of tomato production systems: field with mulching, field without mulching and greenhouses.

System	Variable	Value	Std. error	Sign.	R <sup>2</sup>
<b>Field with mulching</b>					
Fresh yield (t ha <sup>-1</sup> )	$\alpha$ (Intercept)	188.40	26.04	***	0.267
	$\beta_1$ (TWI)	$-2.24 \times 10^{-1}$	$5.60 \times 10^{-2}$	***	
	$\beta_2$ (N)	$-4.33 \times 10^{-1}$	$8.62 \times 10^{-2}$	***	
	$\beta_3$ (TWI $\times$ N)	$9.16 \times 10^{-4}$	$1.69 \times 10^{-4}$	***	
WUE (kg FW m <sup>-3</sup> )	$\alpha$ (Intercept)	68.96	7.68	***	0.460
	$\beta_1$ (TWI)	$-1.03 \times 10^{-1}$	$1.65 \times 10^{-2}$	***	
	$\beta_2$ (N)	$-7.81 \times 10^{-2}$	$2.54 \times 10^{-2}$	**	
	$\beta_3$ (TWI $\times$ N)	$1.70 \times 10^{-4}$	$4.98 \times 10^{-5}$	***	
NUE (kg FW kg <sup>-1</sup> N)	$\alpha$ (Intercept)	-83.20	58.95	ns	0.334
	$\beta_1$ (TWI)	$6.34 \times 10^{-1}$	$1.27 \times 10^{-1}$	***	
	$\beta_2$ (N)	$6.51 \times 10^{-1}$	$1.95 \times 10^{-1}$	**	
	$\beta_3$ (TWI $\times$ N)	$-1.15 \times 10^{-3}$	$3.82 \times 10^{-4}$	**	
<b>Field without mulching</b>					
Fresh yield (t ha <sup>-1</sup> )	$\alpha$ (Intercept)	-28.90	20.95	ns	0.240
	$\beta_1$ (TWI)	0.27	$4.75 \times 10^{-2}$	***	
	$\beta_2$ (N)	0.23	$6.50 \times 10^{-2}$	***	
	$\beta_3$ (TWI $\times$ N)	$-6.14 \times 10^{-4}$	$1.38 \times 10^{-4}$	***	
WUE (kg FW m <sup>-3</sup> )	$\alpha$ (Intercept)	25.38	5.53	***	0.299
	$\beta_1$ (TWI)	$-9.73 \times 10^{-3}$	$1.26 \times 10^{-2}$	ns	

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	$\beta_2$ (N)	$2.57 \times 10^{-2}$	$1.72 \times 10^{-2}$	ns	
	$\beta_3$ (TWI $\times$ N)	$-6.97 \times 10^{-5}$	$3.64 \times 10^{-5}$	ns	
NUE (kg FW kg <sup>-1</sup> N)	$\alpha$ (Intercept)	162.90	93.45	ns	0.457
	$\beta_1$ (TWI)	$7.36 \times 10^{-1}$	$2.46 \times 10^{-1}$	**	
	$\beta_2$ (N)	$-2.92 \times 10^{-1}$	$3.19 \times 10^{-1}$	ns	
	$\beta_3$ (TWI $\times$ N)	$-5.78 \times 10^{-4}$	$8.26 \times 10^{-4}$	ns	
<b>Greenhouse</b>					
Fresh yield (t ha <sup>-1</sup> )	$\alpha$ (Intercept)	101.90	22.70	***	0.796
	$\beta_1$ (TWI)	$-1.09 \times 10^{-1}$	$8.92 \times 10^{-2}$	ns	
	$\beta_2$ (N)	$-3.11 \times 10^{-2}$	$3.61 \times 10^{-2}$	ns	
	$\beta_3$ (TWI $\times$ N)	$5.73 \times 10^{-4}$	$1.23 \times 10^{-4}$	***	
WUE (kg FW m <sup>-3</sup> )	$\alpha$ (Intercept)	73.51	8.29	***	0.624
	$\beta_1$ (TWI)	$-1.61 \times 10^{-1}$	$3.26 \times 10^{-2}$	***	
	$\beta_2$ (N)	$1.67 \times 10^{-2}$	$1.32 \times 10^{-2}$	ns	
	$\beta_3$ (TWI $\times$ N)	$1.03 \times 10^{-4}$	$4.50 \times 10^{-5}$	*	
NUE (kg FW kg <sup>-1</sup> N)	$\alpha$ (Intercept)	348.51	197.13	ns	0.434
	$\beta_1$ (TWI)	1.21	0.82	ns	
	$\beta_2$ (N)	0.28	0.70	ns	
	$\beta_3$ (TWI $\times$ N)	$-4.19 \times 10^{-3}$	$2.81 \times 10^{-3}$	ns	

\* means  $P$  value < 0.05, \*\* means  $P$  value < 0.01, \*\*\* means  $P$  < 0.001 and ns means not significant.



**Figure 3.5.** Correlations between fresh yield, water use efficiency (WUE), N fertiliser use efficiency (NUE) and total water input of three types of tomato production systems: field with mulch, field without mulch and greenhouses. In each panel, data points were grouped according to three levels of N fertiliser supply to visualise the interaction between total water input and N fertiliser supply. Different ranges of three N levels (orange: 0–200 kg/ha, grey: 200–300 kg/ha, light blue: 300–650 kg/ha) were selected for the three cultivation systems to ensure that similar amount of data points was grouped for each N level. Blank panels indicate that there was no significant interaction observed.

### 3.4. Discussion

Our study synthesises and quantitatively analyses 34 field and 12 greenhouse tomato studies. For both greenhouse and field studies, the datasets show large variations due to different environmental conditions, tomato varieties and agricultural practices. Tomato yield ranged from 14 to 207 t ha<sup>-1</sup> in field production and from 58 to 360 t ha<sup>-1</sup> in

greenhouse experiments (Supplementary Table 3.1). This range is similar to the 2 to 306 t ha<sup>-1</sup> reported in a meta-analysis exploring water- and nitrogen-saving potentials for tomato production without distinguishing between field and greenhouse systems (Du *et al.*, 2018). Greenhouse systems showed on average 45% higher tomato yield than field systems (Supplementary Table 3.1). Tomato yield for Dutch commercial greenhouses has been reported 430–690% higher than the average yield of our greenhouse dataset (560–890 t ha<sup>-1</sup>) (Table 3.1). This is probably mainly due to the shorter growing season in the greenhouse experiments compared to commercial greenhouses (usually 11 months) (Marcelis *et al.*, 2019). Additionally, optimised growing conditions and precise fertigation management also lead to higher yields in Dutch greenhouses (Marcelis *et al.*, 2019). Our data suggest that the higher tomato yield in greenhouse systems may be the result of combined effects of multiple factors. Firstly, the growing season of greenhouse cultivation was on average 45% longer than for field cultivation (Supplementary Table 3.1). Secondly, the temperature in greenhouses is more favourable for plant growth (higher average minimum and lower maximum temperatures; Supplementary Table 3.1), which is combined with better protection from adverse weather events. Collectively, the growing conditions in greenhouses are more favourable compared to field production.

Greenhouse tomato yield increased linearly with TWI, whereas this relationship was quadratic for field production systems (Figure 3.2A). These different relations between water input and tomato yield between systems can be attributed to multiple factors, such as growing conditions, crop varieties, and crop management. The quadratic relation between tomato yield and water input in field production reveals that there are factors other than water (e.g. N fertiliser supply) that limit the increase in yield when water is not limiting. Tomato yield is also affected by the interaction between TWI and N fertiliser supply, presenting a positive effect in greenhouse systems and field systems with mulching and a negative effect in field systems without mulching (Table 3.2; Figure 3.5A, 3.5D and 3.5E). The positive interaction between TWI and N supply on tomato yield is consistent with the results of the meta-analysis study by Du *et al.* (2018) in which variation due to production systems was not considered.

#### ***Potential of improving water use efficiency and water saving***

Enhancing WUE and water-saving is not only important for conserving water sources but may also concomitantly lead to reduction in N leaching and thus contamination of soils and aquifers (Quemada and Gabriel, 2016). TWI was on average 32% lower and WUE was on average 104% higher in greenhouse systems than in field cultivation (Supplementary

Table 3.1). This lower TWI in greenhouse systems may be partly due to the lower crop ET (16% lower in cumulative ET and 65% lower in daily ET) in greenhouses (Supplementary Table 3.1). ET is an important reference of designing irrigation in crop production. Compared to open-field production, greenhouse cultivation can lower the ET inside of greenhouses and thus crop water requirement due to several factors, such as reduced wind speed and solar radiation, and higher relative humidity (Orgaz *et al.*, 2005; Yan *et al.*, 2018). This means that crop water requirement (full irrigation) is lower in greenhouse cultivation than open-field production. Harmanto *et al.* (2005) demonstrated that ET of tomato production inside a greenhouse in tropical climate was reduced to 75–80% of the ET outside the greenhouse. This reduction in ET in greenhouses is even larger in Mediterranean regions where a reduction to 30–40% has been reported (Stanghellini, 1993; Orgaz *et al.*, 2005).

Soil mulching is a common water-saving measure in field crop production. The beneficial effects of soil mulching include reducing soil evaporation, increasing soil temperature and thus microbial activity, weed control, and therefore reducing water use, increasing yield and WUE (Qin *et al.*, 2015). Our field data indicate that application of mulch showed on average 42% higher WUE but no increase in tomato yield, compared to cultivation without mulching (Supplementary Figure 3.2A and 3.2B). This suggests that soil mulching may be an effective measure to increase the efficient of water use in field tomato production. A recent meta-analysis on the effects of mulching without considering the effects of production systems (Zhang *et al.*, 2022) reported that mulching combined with drip irrigation resulted in 16% increase in tomato yield and 6% increase in WUE.

Deficit irrigation is a proven measure for water saving improving water use efficiency in crop production (Costa *et al.*, 2007; Fereres and Soriano, 2007; Geerts and Raes, 2009). Several synthesis studies have explored the water-saving potential of deficit irrigation and its combination with other management practices for tomato production (Lu *et al.*, 2019; Chand *et al.*, 2020; Cheng *et al.*, 2021b; Singh *et al.*, 2021). We calculated the irrigation ratio (TWI/ET; Eqn. 2) to indicate the actual extent of deficit or excessive irrigation based on TWI and actual crop evapotranspiration (ET). WUE in both cultivation systems was negatively affected by increased irrigation ratio (Figure 3.3B), and the changes in WUE were more pronounced in greenhouse systems compared to field production. This is in line with the meta-analysis by Singh *et al.* (2021) in which effects of different levels of deficit irrigation on yield and WUE of various crops were assessed. These authors found that the improvement in WUE due to deficit irrigation was larger in greenhouse systems than field

production (Singh *et al.*, 2021). Additionally, the highest mean tomato yield, WUE and NUE for greenhouse systems appeared at the deficit irrigation with 80–90%ET (Figure 3.3A). Previous studies (Nangare *et al.*, 2016; Zhang *et al.*, 2017b; Singh *et al.*, 2021) reported that in greenhouse production deficit irrigation with 80%ET achieved similar yield as 100%ET (full irrigation) did and substantially increased WUE, which is consistent with our results. Singh *et al.* (2009) reported that in their experiment the highest WUE appeared at 80%ET deficit irrigation with application of mulching. However, a few studies have also demonstrated that deficit irrigation could reduce leaf area index, photosynthesis and caused significant yield losses (Singh *et al.*, 2021; Ullah *et al.*, 2021; Li *et al.*, 2022). The extent of these reductions depends on the timing and level of deficit irrigation applied and other factors, such as fertilisation and crop variety. Hence, application of deficit irrigation requires consideration of its trade-off between improvement of WUE and yield decline. Therefore, deficit irrigation is often applied in arid, semi-arid and Mediterranean regions where improving WUE is prioritised over yield.

#### ***Potential of improving N fertiliser use***

In our dataset N fertiliser supply varies between 56 and 677 kg N ha<sup>-1</sup> in field production and between 120 and 788 kg N ha<sup>-1</sup> in greenhouse production (Supplementary Table 3.1). These ranges are much smaller than the range reported by Du *et al.* (2018) in which data without N application was included (0–1550 kg N ha<sup>-1</sup>). The range of N fertiliser supply in greenhouse systems is also smaller than in a meta-analysis study in greenhouse systems by Cheng *et al.* (2021a) (28–900 kg N ha<sup>-1</sup>). This is likely due to different criteria for literature selection between studies. On average, greenhouse production presents 45% higher NUE in comparison to field production (Supplementary Table 3.1). There is no evident difference in daily N supply between greenhouse and field production, and the higher average N supply for greenhouse systems (345 kg N ha<sup>-1</sup>) compared to field production (238 kg N ha<sup>-1</sup>) as a result from a longer growing season under greenhouse cultivation (Supplementary Table 3.1).

Tomato yield as a function of N fertiliser supply showed large variations (Figure 3.4A). The multiple linear regression for greenhouse data showed that there was no significant effect of N fertiliser supply on yield (Table 3.2). This could be partly explained by differences in growing conditions (e.g. soil type, climate etc.), crop management and other practices (e.g. irrigation) (Cheng *et al.*, 2021a). Additionally, the uncertainty of estimating N content of manure fertiliser application induces extra variation in the analyses in relation to total N fertiliser supply. For instance, farmyard manure is commonly applied to improve soil

organic content in studies in Asia (such as China and India) which were included in the current synthesis. The N content in farmyard manure varies with the composition of the manure (Liu *et al.*, 2010) and was mostly not specified in the original studies. Our estimation of the N content in farmyard manure may create inevitable errors, which therefore affects the analysis related to N use. Moreover, many studies did not report the N content in the soils before application of fertilisation. Soto *et al.* (2015) noted that many studies did not consider the available N derived from soils and manure in the calculation of NUE, leading to large overestimations in the efficiency of N use. One study included in the present quantitative synthesis reported that the N content in the soils was very high and around 1480 kg ha<sup>-1</sup> before the experiment (Wang *et al.*, 2015).

Regardless of the variations indicated above, our analysis shows that at a given N supply level, higher NUE occur for greenhouse compared to field production (Figure 3.4C, Supplementary Figure 3.3C), which is consistent with the observation in tomato yield (Figure 3.4A, Supplementary Figure 3.3A). This may be attributed to a relatively optimal environment (e.g. temperature) (Cheng *et al.*, 2021a), and irrigation management (e.g. deficit irrigation). Several studies reported that reduced irrigation input can decrease N leaching, thus resulting in sufficient N available for plants to use (Du *et al.*, 2017; Bai *et al.*, 2020; Lv *et al.*, 2021; Qasim *et al.*, 2021). Wu *et al.* (2022) investigated the effects of deficit irrigation on N uptake and soil mineral N in lucerne (*Medicago sativa*). These authors observed that no significant N leaching occurred under deficit irrigation. Moreover, a meta-analysis on effects of N supply on tomato by Cheng *et al.* (2021a) reported that higher tomato yield could be more easily obtained under field production than greenhouses. The authors (Cheng *et al.*, 2021a) speculated that this was due to a shorter growing duration under greenhouse cultivation as a result of higher temperature, which is opposite to our findings in which growing season is on average longer in greenhouses than in field production (Supplementary Table 3.1). We argue that the length of growing season in greenhouse and field production is greatly dependent on the local climate where the production is located. Through analysing sub-datasets based on four levels of N fertiliser supply (Supplementary Figure 3.3), we found that at 150–250 kg N ha<sup>-1</sup>, differences in mean tomato yield, WUE and NUE were the largest between greenhouse and field systems. For field production, our analysis showed that 350–650 kg N ha<sup>-1</sup> seems to be an optimal N fertiliser supply given the highest mean yield, WUE and moderate NUE (Supplementary Figure 3.3). Whereas a trade-off is evident for the N application in greenhouse systems, with the higher yield and WUE at 350–650 kg N ha<sup>-1</sup> but higher NUE at 150–250 kg N ha<sup>-1</sup>. This is in agreement with the findings by Cheng *et al.* (2021);

optimal N level to obtain the highest yield: 236–354 kg N ha<sup>-1</sup>) and Qasim et al. (2021; optimal N level to obtain the highest yield: < 500 kg N ha<sup>-1</sup>). However, Du et al. (2018) provided the optimal N inputs (defined by the lowest N level that produced the highest tomato yield) for various counties, ranging from 50 to 176 kg N ha<sup>-1</sup>. This range largely differs from the ranges that we found in the present study and from other studies (Cheng et al., 2021a; Qasim et al., 2021).

#### ***Limitations of the present study***

The large variations within the dataset and the unequal numbers of studies between field and greenhouse systems induced some unavoidable uncertainties in the present study; often vital information (e.g. N content in soils) that would have helped with interpreting the results was missing. A considerable number of studies from commercial tomato greenhouse production (Table 3.1) had to be excluded from the current quantitative synthesis because these studies failed to meet the essential criteria for inclusion in the literature selection. For instance, several studies did not report experimental observations but rather average values for greenhouses at regional or country scale. However, these commercial data represent the real-world performance of high-tech greenhouse production systems. We identified large gaps in yield and water use between greenhouse studies included in our analysis and commercial greenhouse data, which may limit the relevance of the results of the current quantitative synthesis for these high-tech greenhouse systems.

### **3.5. Conclusions**

The present study synthesised and quantitatively analysed the effects of water management and N fertiliser supply on tomato yield, WUE and NUE in greenhouse and open-field production. The effects of water management were examined from three dimensions, including total water input (TWI), application of soil mulching (for open-field production) and irrigation ratio (ratio of TWI to actual crop evapotranspiration). Overall, tomato yield is positively correlated to both TWI and N fertiliser supply, and additionally affected by the interaction between TWI and N fertiliser supply, presenting higher effect of TWI at higher levels of N supply when mulching is applied. This, in combination with commonality in application of fertigation, emphasises that optimisation of water and N is theoretically and practically interlinked, which is key to achieving high efficiencies for both resources. Our dataset shows that greenhouse systems present on average 45% higher tomato yield, 104% higher WUE, 45% higher NUE and 32% lower TWI compared with field production.

Soil mulching in field production on average resulted in 12% lower water input and 32% higher WUE without significant yield loss. Positive effects of deficit irrigation (70–100%ET) were more apparent for tomato yield, WUE and NUE of greenhouse systems compared to that of field production, suggesting that the efficacy of deficit irrigation may be higher in greenhouse cultivation. 80–90%ET led to the highest yield, WUE and NUE of greenhouse systems compared to higher or lower %ET values.

Considerable variations were shown in the regression correlations between N fertiliser supply and tomato yield, WUE and NUE in both systems, presenting scattering data points. This may reflect a lack of accuracy in the estimation of total N supply since in some studies available N in soils before fertilisation and N content in farmyard manure were not considered. In future evaluation on the performance of N management, we strongly suggest that attention should be paid to standardising calculations of NUE. For instance, considering total N available in soils before fertilisation, and fertilisation levels from previous cultivation seasons, is vital for obtaining an accurate understanding of NUE. Additionally, using multiple N indicators (e.g. N leaching) (Qasim *et al.*, 2021) can provide a more comprehensive understanding of N use and its fate, which would help optimise performance of N management in both field and greenhouse tomato production. Overall, tomato yield was significantly affected by TWI and N fertiliser supply as well as their interaction. This correlation shows difference between field and greenhouse systems. Altogether, our findings suggest that future optimisation strategies for water and N fertiliser use should consider the large variations existing between production systems.

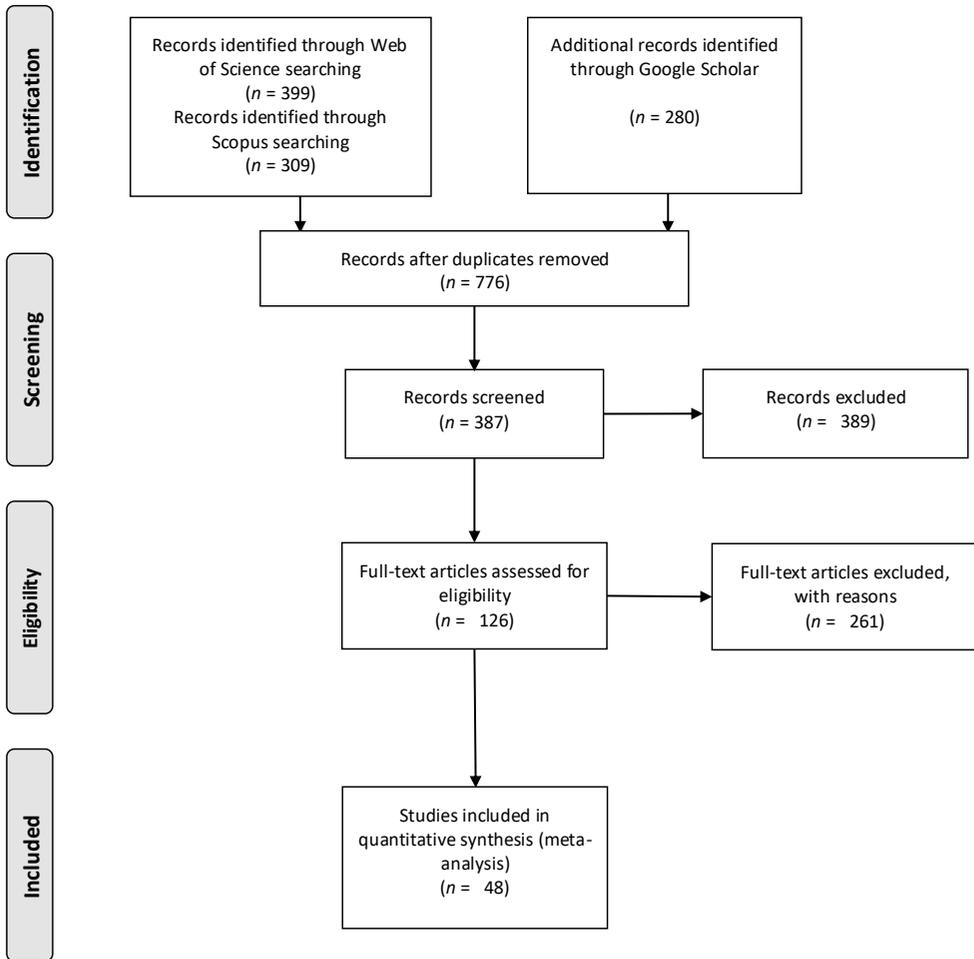
### 3.6. Supplementary materials

**Supplementary Table 3.1.** Summarized statistics for analysed datasets under field and greenhouse tomato production systems. Variables include growing season, total water input (TWI; sum of rainfall and irrigation), daily water input (TWI divided by length of growing season), total N fertiliser supply, daily N fertiliser supply, cumulative crop evapotranspiration (ET), irrigation ratio (ET/TWI), fresh yield, water use efficiency (WUE), N fertiliser use efficiency (NUE), minimum, maximum and mean temperature during the growing season. The mean values and corresponding standard deviations (St. Dev), minimum and maximum values were calculated on a combined data set collected from all primary studies.

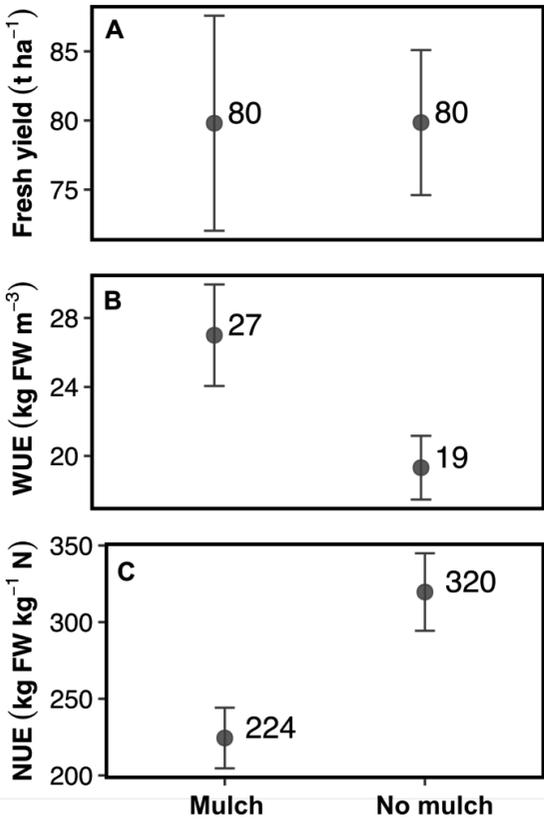
	No. of data points	Mean	Minimum	Maximum
<b>Field</b>				
Growing season (days)	327	110 ± 19	77	210
Total water input (mm)	242	406 ± 174	56	922
Daily water input (mm)	234	3.8 ± 1.8	0.4	10.7
Total N fertiliser supply (kg N ha <sup>-1</sup> )	322	238 ± 112	56	677

### Chapter 3

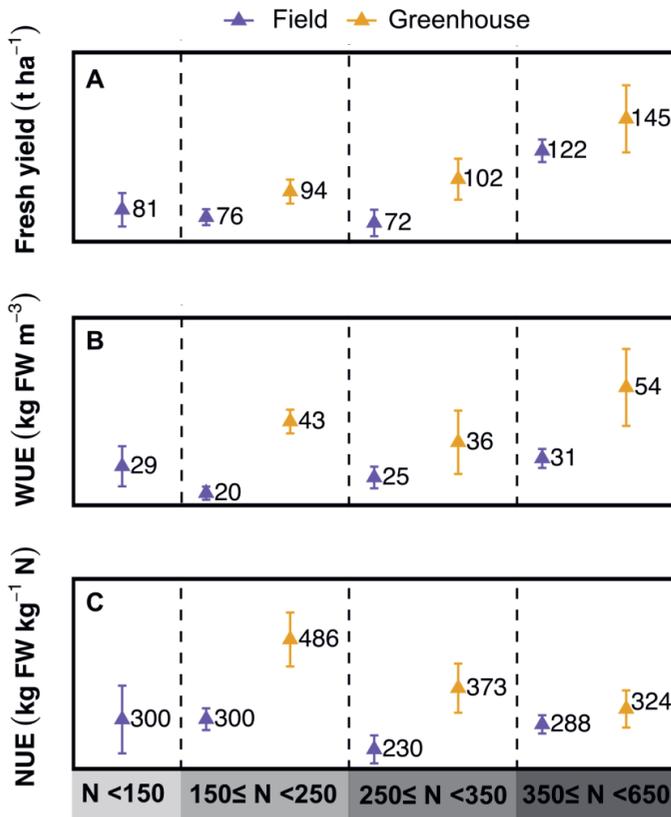
Daily N fertiliser supply (kg N ha <sup>-1</sup> )	288	2.2 ± 1.0	0.6	6.2
Cumulative ET (mm)	177	334 ± 127	80	649
Irrigation ratio	166	1.1 ± 0.5	0.4	2.8
Fresh yield (t ha <sup>-1</sup> )	328	80 ± 40	14	207
WUE (kg FW m <sup>-3</sup> )	225	23 ± 13	3	64
NUe (kg FW kg <sup>-1</sup> N)	265	278 ± 144	21	775
Minimum temperature (°C)	215	13.7 ± 5.1	4.5	24.9
Maximum temperature (°C)	215	29.9 ± 5.4	20.3	41.2
Mean temperature (°C)	215	21.8 ± 3.1	16.1	31.8
<b>Greenhouse</b>				
Growing season (days)	82	159 ± 54	56	282
Total water input (mm)	83	308 ± 155	147	800
Daily water input (mm)	74	2.3 ± 1.7	0.9	8.2
Total N fertiliser supply (kg N ha <sup>-1</sup> )	65	345 ± 148	120	788
Daily N fertiliser supply (kg N ha <sup>-1</sup> )	56	2.3 ± 1.1	0.7	4.9
Cumulative ET (mm)	82	288 ± 110	150	852
Irrigation ratio	59	0.9 ± 0.1	0.7	1.2
Fresh yield (t ha <sup>-1</sup> )	102	129 ± 60	58	360
WUE (kg FW m <sup>-3</sup> )	71	47 ± 20	7	87
NUe (kg FW kg <sup>-1</sup> N)	53	403 ± 137	180	689
Minimum temperature (°C)	51	15.7 ± 5.2	6.5	23.1
Maximum temperature (°C)	51	27.1 ± 7.3	19.0	42.2
Mean temperature (°C)	51	21.4 ± 5.5	14.5	32.6



**Supplementary Figure. 3.1.** Diagram of literature selection based on the PRISMA principle (Moher *et al.*, 2009).



**Supplementary Figure 3.2.** Effects of mulching on fresh yield (**A**), water use efficiency (WUE; **B**) and N fertiliser use efficiency (NUE; **C**) in field tomato production. Mean values are shown next to the confidence intervals.



**Supplementary Figure 3.3.** Mean values and 95% confidence intervals of fresh yield (**A**), water use efficiency (WUE; **B**) and N fertiliser use efficiency (NUE; **C**) from field and greenhouse tomato production in response to four ranges of N fertiliser supply (0–150, 150–250, 250–350 and 350–650 kg/ha). Mean values are shown next to the confidence intervals.



## **CHAPTER 4**

### **Evaluating the environmental sustainability of small-scale tomato greenhouse farms through life cycle assessment—An Australian case study**

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## Abstract

High-tech greenhouses play an important role in our modern food systems as their high productivity and high-quality, year-round fresh vegetables for supplying large populations. However, there are rising concerns around their environmental performance, particularly due to their use of large amounts of fossil fuels and fresh water. Previous studies have emphasised that improving environmental knowledge and understanding of local greenhouse industries are vital for exploring feasible solutions to mitigate emissions. In this study, we evaluated the environmental performance of three different tomato greenhouse production systems with varying geographical locations thus climate (cool and warm), energy sources (fossil fuels and wood biomass), availability of local freshwater resources and greenhouse management (e.g. growing medium), in south-east Australia. This study aimed to evaluate the environmental sustainability of local greenhouse growers' sustainable choices and then identify the environmental trade-offs of these options, taking local resource constraints into account. A life cycle assessment (LCA) was used to quantify the potential environmental impacts of each system at a cradle-to-farmgate scale. In an Australian context, availability of local freshwater resources is a key factor influencing the overall environmental performance of greenhouse production, given freshwater is scarce in most areas of Australia. The impact of water use for irrigation at greenhouses primarily depends on the status of local freshwater scarcity. Using wood biomass for greenhouse heating led to a reduction of 80% in potential global warming but generated 170% higher impacts related to air pollution, compared to use of fossil fuels for greenhouse heating. The attribution of the environmental cost of using coco coir as a growing substrate primarily depends on whether coco coir is considered a by-product or a waste product of coconut production. If it is considered a type of waste, the use of this material in greenhouses does not share the environmental impacts related to coconut production from a life-cycle perspective. Consequently, this leads to a calculated 30% reduction in marine eutrophication when coco coir is treated as a type of waste compared to considering it as a by-product. This study concludes that planning future greenhouse expansion in Australia should prioritise consideration of local freshwater availability and provides insights into trade-offs (use of wood biomass) and unseen environmental impacts (use of coco coir) of growers' practices towards sustainable development in greenhouse production.

**Key words:** Freshwater scarcity; GHG mitigation; Life cycle assessment; Tomato; Wood biomass.

## 4.1. Introduction

In Australia, fresh produce from greenhouses has increased considerably over the past decades (Connellan and Parks, 2015; Heuvelink, 2018). Greenhouses with advanced climate control systems and soilless cultivation have been gradually replacing existing low-tech greenhouses with minimal climate control, and now dominate Australia's greenhouse production (Parks, 2010; Hadley, 2017). The main driver for this change is the demand for year-round fresh produce of consistently high quality (Connellan and Parks, 2015). To meet the growing population and the recommendation of vegetable consumption by the Food and Agriculture Organisation and World Health Organisation of the United Nations (2017), a further increase in the demand for fresh produce is anticipated (Norris and Congreves, 2018). Therefore, it is expected that Australia's greenhouse industry will continue to grow through expanding production areas and diversifying greenhouse-grown crops. Even though high-tech greenhouses are seen as a highly productive method of providing nutritious food, concerns have been raised regarding their environmental sustainability (Pluimers *et al.*, 2000; Vermeulen and Lans, 2011; Page *et al.*, 2012; Dias *et al.*, 2017) and economic costs (Torrellas *et al.*, 2012b).

Over the last two decades, the environmental performance of greenhouse production systems has been investigated in various countries and regions (Gruda *et al.*, 2019; Pineda *et al.*, 2021). Approaches based on life cycle thinking have been extensively applied to understand the environmental sustainability of agri-food production systems (Notarnicola *et al.*, 2017). The concept of life cycle assessment (LCA) aims to assess the environmental performance of a product in a holistic way (ISO, 2006). It considers all inputs, outputs and potential environmental impacts during a product's life cycle (cradle-to-grave) from raw material extraction, production, use of the product, and final waste disposal after use (ISO, 2006). For studies in greenhouse production systems, LCA has been primarily used to identify the main burdens to the environmental impacts of the product (Antón *et al.*, 2003, 2012; Boulard *et al.*, 2011; Cellura *et al.*, 2012a), or compare the environmental performance between systems (Muñoz *et al.*, 2008a; Torrellas *et al.*, 2012b; Zhang *et al.*, 2017a). Such LCA studies have been widely conducted in greenhouse production systems in European countries, but only a limited number of studies have been conducted in Australia (Roggeveen, 2010; Page *et al.*, 2011, 2012, 2014).

Several studies have been conducted on high-tech, heated greenhouse production systems and options for improving their environmental performance in Northern countries.

In general, most studies reported that greenhouse heating, greenhouse infrastructure, production and use of fertilisers are the main contributors to the environmental impacts in such systems (Van Woerden, 2001; Antón *et al.*, 2012; Torrellas *et al.*, 2012b; Dias *et al.*, 2017). Among these, greenhouse heating leads to the biggest environmental burden, accounting for 70-97% of total environmental impacts at the greenhouse gate (Van Woerden, 2001; Williams *et al.*, 2006; Boulard *et al.*, 2011; Antón *et al.*, 2012; Page *et al.*, 2012; Torrellas *et al.*, 2012b; Dias *et al.*, 2017). In particular, greenhouse heating is the major source of greenhouse gas (GHG) emissions contributing to climate change (Gruda *et al.*, 2019). To reduce emissions due to fossil energy use, several studies have investigated the use of alternative energy sources for greenhouse heating (Dias *et al.*, 2017; Bibbiani *et al.*, 2016; Wu *et al.*, 2016; Almeida *et al.*, 2014; Page *et al.*, 2014; Theurl *et al.*, 2014). However, the feasibility of these solutions is highly restricted by the costs and availability of readily accessible, local resources, which limits growers' choices.

In Australia, despite ~60% of greenhouse production occurring in large-scale (ca. 20 ha) greenhouses (Hadley, 2017), small-scale greenhouses with a size of ca. 0.5 ha dominate in terms of number of growers (Connellan and Parks, 2015). Large-scale greenhouses are often characterised by the most advanced greenhouse technologies and standardised greenhouse management, and thus have relatively higher performance in terms of productivity and resource use efficiencies. The level of technologies adopted, and greenhouse management vary considerably among regions and small-scale greenhouses, resulting in high variability in their productivity and environmental performance. Therefore, understanding the management options of these small-scale greenhouse growers is vital for exploring feasible solutions for mitigating environmental impacts of greenhouse production in Australia.

An early study by Roggeveen (2010) primarily evaluated the GHG emissions of greenhouse tomato production in the Sydney area in Australia, considering emissions from the greenhouse gate to local supermarkets. The author outlined that the GHG emissions occurring during production at greenhouses are the major contributor to total GHG emissions over the supply chain. Page *et al.* (2011, 2012, 2014) have evaluated the role of technologies and greenhouse location in reducing the environmental impacts (mainly carbon and water footprint) of greenhouse production systems in New South Wales. The authors suggested that exploring renewable energy is an important way of reducing the environmental burden due to greenhouse heating. Additionally, there might be a need for considering relocation of the existing greenhouses to further mitigate the overall

environmental impacts via seeking climate regions where greenhouse heating can be reduced and utilising freshwater resources with lower scarcity (Page *et al.*, 2014). The availability of existing infrastructure providing renewable energy is often associated with the greenhouse location, which topic has not yet been addressed in Australia's context by Page *et al.* (2014).

Australia has a large forest industry, with an abundance of wood waste produced. The use of wood (biomass) waste from forestry to substitute fossil fuels has been studied for greenhouse heating in Italy (Bibbiani *et al.*, 2016), Canada (Wu *et al.*, 2016; Dias *et al.*, 2017) and Austria (Theurl *et al.*, 2014). In Australia, wood biomass is widely used for household heating, and has gradually been adopted for greenhouse heating in some regions, such as Tasmania (Parsons, 2010). Such local energy resources may be a promising option to mitigate emissions related to greenhouse heating. Nevertheless, before there is extensive use of wood biomass in greenhouse heating, the potential environmental impacts of such application should be thoroughly evaluated. Understanding how local resources affect the environmental performance of greenhouse production and identifying trade-offs between using different resources will provide crucial information in decision-making on locations for future greenhouse expansion.

This study aims to evaluate the environmental performance of greenhouse production systems, considering the effects of using alternative energy sources, and freshwater with different levels of scarcity. We conducted an Australian case study in two greenhouse areas where natural gas (South Australia) and wood biomass (Tasmania) are used for greenhouse heating. Tomato production was used in the current study due to its large production area and popularity. Both production of medium/large and small (cherry) tomato fruits were included due to their importance in consumers' demand, and the increasing popularity of cherry tomatoes (Connellan and Parks, 2015). The specific aims are three-fold: 1) to assess the environmental impacts of tomato production in three small-scale greenhouse production systems and identify the main contributors to environmental impacts in each system; 2) to compare the quantitative and qualitative impact due to freshwater use; 3) to identify the environmental trade-offs of using wood biomass instead of fossil fuel for greenhouse heating.

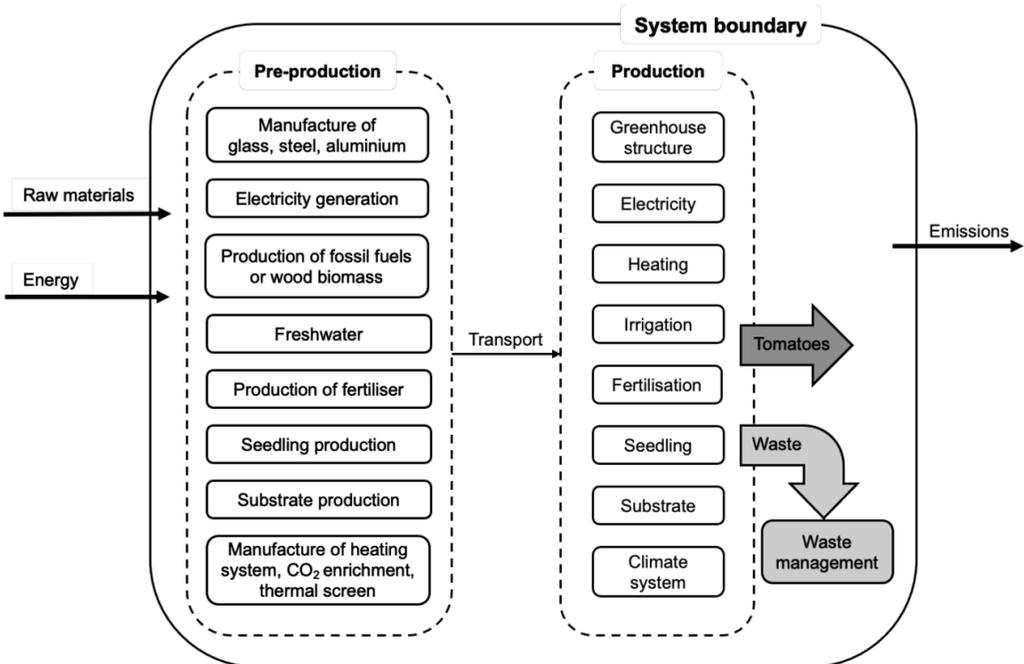
## 4.2. Methods

We used an attributional LCA (Ekvall *et al.*, 2005) to quantify and compare the environmental profiles of tomato products between greenhouse production systems. The

analysis of the environmental impacts followed the framework described in ISO standard 14044 (2006), where four phases are involved: goal and scope definition, inventory analysis, impact assessment and interpretation.

**Goal and scope definition**

The present study focused on the environmental performance of three different greenhouse production systems (Table 4.1). Given that the environmental impacts derived from greenhouse production was the major cause over the supply chain (Roggeveen, 2010; Page *et al.*, 2014), the concept of cradle-to-farmgate was employed as the system boundary to study the environmental impacts. Each greenhouse production system was divided into nine components: greenhouse structure, irrigation, electricity for greenhouse operation, greenhouse heating, tomato seedling production, growing substrate, climate system (cooling system and CO<sub>2</sub> enrichment), fertigation system and waste management (Figure 4.1: grey areas). Manufacture and transportation of all inputs were included in each structural stage of greenhouse production (Figure 4.1). The functional unit used was 1 kg loose tomatoes produced at the greenhouse gate. Packaging and transportation from production location to markets were not considered as the main goal was to evaluate the different means of producing tomatoes.



**Figure 4.1.** System boundary and processes considered for the life cycle assessment of all three greenhouse tomato production systems.

Collection of primary data such as greenhouse dimensions and resource inputs (i.e. water) was conducted from 2017–2019 at three commercial greenhouses: two in Tasmania (TAS: GH1, GH2) and one in South Australia (SA: GH3) (Table 4.1), through a survey-based interview and follow-up questions (Appendix II).

**Table 4.1.** Key information, material and resource inputs, and outputs of two greenhouse production systems (GH1, GH2) in Tasmania (TAS) and one (GH3) in South Australia (SA).

Key information	GH1	GH2	GH3
Climate	Venlo <sup>1</sup> , TAS	Venlo, TAS	Venlo, SA
Greenhouse area (m <sup>2</sup> )	Cool <sup>2</sup>	Cool <sup>2</sup>	Warm <sup>3</sup>
Water source(s)	4032	5000	4095
	Town-supply water	Town-supply water, recycled water <sup>4</sup>	Rainwater, Town-supply water, recycled water
Crop type indicated by fruit size	Large <sup>5</sup>	Cherry <sup>6</sup>	Large
Crop period (weeks)	42	50	40
Annual yield (kg m <sup>-2</sup> )	57	28	60
Growing substrate	Stone wool	Coco coir, stone wool	Stone wool
Heating	Yes	Yes	Yes
Fuels	Wood chips	Wood residue, waste oil, LPG <sup>7</sup>	Natural gas
Water content of wood biomass (%)	30	40	—
Lower heating value <sup>8</sup> (MJ kg <sup>-1</sup> )	12.2	9.3–46.6	47.1
Boiler efficiency (%)	88 <sup>9</sup>	88 <sup>9</sup> and 94 <sup>10</sup>	94 <sup>10</sup>
CO <sub>2</sub> enrichment	Yes	Yes	No
CO <sub>2</sub> source	Liquid CO <sub>2</sub>	Exhaust CO <sub>2</sub> of LPG combustion	—
<b>Inputs</b>			
<b>Greenhouse structure</b>			
Aluminium (kg m <sup>-2</sup> )	2.5	2.5	2.5
Glass (kg m <sup>-2</sup> )	8.6	7.7	8.4
Steel (kg m <sup>-2</sup> )	13.0	12.4	12.9
<b>Water use at greenhouse</b>			
Irrigation (L kg <sup>-1</sup> )	45	38	57
<b>Energy consumption</b>			
Electricity (kWh m <sup>-2</sup> )	10.5	13.5	12
<b>Heating fuel</b>			
Natural gas (m <sup>3</sup> m <sup>-2</sup> )	—	—	62
Wood biomass (kg m <sup>-2</sup> )	197	220	—
LPG (L m <sup>-2</sup> )	—	8.4	—
Waste oil (L m <sup>-2</sup> )	—	0.2	—
<b>Growing substrate</b>			
Stone wool (kg ha <sup>-1</sup> y <sup>-1</sup> )	9158	823	7722
Coco coir (kg ha <sup>-1</sup> y <sup>-1</sup> )	—	15300	—
<b>Fertilisers</b>			
Calcium nitrate – Ca(NO <sub>3</sub> ) <sub>2</sub> (kg ha <sup>-1</sup> )	5771	4574	5882
Potassium nitrate – KNO <sub>3</sub> (kg ha <sup>-1</sup> )	2309	4163	3000
Magnesium sulphate – MgSO <sub>4</sub> (kg ha <sup>-1</sup> )	2180	718	4285

Monopotassium – phosphate $\text{KH}_2\text{PO}_4$ ( $\text{kg ha}^{-1}$ )	1282	869	1316
Potassium sulphate – $\text{K}_2\text{SO}_4$ ( $\text{kg ha}^{-1}$ )	2437	—	—
<b>Total (<math>\text{kg ha}^{-1}</math>)</b>			
N	1211	1279	1323
$\text{P}_2\text{O}_5$	667	452	684
$\text{K}_2\text{O}$	2693	2169	1797
<b>Outputs</b>			
<b>Emissions to air</b>			
$\text{N}_2\text{O-N}$ ( $\text{kg ha}^{-1}$ )	40	42	44
$\text{NO}_x\text{-N}$ ( $\text{kg ha}^{-1}$ )	8.4	8.8	9.1
<b>Emissions to water (<math>\text{kg ha}^{-1}</math>)</b>			
$\text{NO}_3\text{-N}$ ( $\text{kg ha}^{-1}$ )	140	957	210
<b>Solid waste</b>			
Green waste ( $\text{kg ha}^{-1}$ )	228175	138000 <sup>11</sup>	240000
Plastics ( $\text{kg ha}^{-1}$ )	184	148	281
Substrate ( $\text{kg ha}^{-1}$ )	9158	16123 <sup>12</sup>	7722
Wood ash ( $\text{kg ha}^{-1}$ )	19841	1320	—

<sup>1</sup> Venlo type glasshouse is characteristic by high-tech climate control system and mostly soilless cultivation.

<sup>2</sup> Annual average temperature in Hobart was 8.2–17.6 °C according to the record by the nearest weather station.

<sup>3</sup> Annual average temperature in Adelaide was 12.3–22.5 °C according to the record by the nearest weather station.

<sup>4</sup> Recycled water indicates that drainage water was collected from the cultivation system, purified by ultraviolet and reused in the plant growth.

<sup>5</sup> 47–65 mm;

<sup>6</sup> < 15 mm;

<sup>7</sup> Liquefied petroleum gas;

<sup>8</sup> Lower heating value is defined as the value of the specific energy of combustion for unit mass of a fuel burned in oxygen at constant pressure under such conditions that all the water of reaction products remain as water vapour (at 0.1 Mpa) (Food and Agriculture Organisation, 2013).

<sup>9</sup> Efficiency of biomass boilers was assumed according to Wu et al. (2016);

<sup>10</sup> Efficiency of fossil fuels boilers was assumed according to Van Beveren et al. (2019);

<sup>11</sup> The amount of green waste in GH2 was lower due to more than one third of tomato plants being terminated after 34 weeks of growth;

<sup>12</sup> In comparison to GH1 and GH3, the amount of used substrate was much higher in GH2 because additional substrate was used for growing tomato seedlings on-site in a greenhouse.

### **Life cycle inventory analysis**

At the stage of life cycle inventory, foreground data (e.g. fertiliser application rate) was collected and all inputs and outputs were mainly calculated based on the databases of background processes (e.g. manufacturing of steel) (Appendix III). The Australian National Life Cycle Inventory Database (AusLCI) was primarily used to calculate the background processes for manufacturing or production conducted in Australia (e.g. fertiliser production). The Ecoinvent database was used when the processes occurred overseas, or the data were not available in AusLCI. The lifespan of equipment and materials was estimated according to the information provided by the supplier (Appendix IV).

### ***Greenhouse structure***

In all three greenhouse systems, Venlo type glasshouses were used. A lifespan of 30 years was assumed, according to the consultation with Australian greenhouse industry experts. The main materials used for greenhouse construction included steel, aluminium and glass. Information on the location of suppliers of these materials was provided by a major Australian greenhouse construction company. Concrete was not considered in the current study due to the lack of data. According to the estimates by Torrellas et al. (2013), metal and glass rather than concrete are the major contributors to environmental impacts at the greenhouse structure stage. For all greenhouses studied, glass was sourced from the Netherlands, and steel and aluminium were sourced from Australia. Emissions of the materials were estimated based on the manufacturing processes in the sourcing countries.

### ***Water consumption at greenhouse production***

The water consumption during greenhouse production includes irrigation water use, cooling and greenhouse maintenance (e.g. cleaning), of which irrigation water use is predominant. For the cherry tomato greenhouse production in Tasmania ca. 30% of drain water was collected from the fertigation system, and thereafter disinfected and recycled for fertigation. Such practice was also applied in the large tomato greenhouse production in South Australia, however only 20% of drain water was recycled.

### ***Energy use for greenhouse heating and operation***

Regarding heating fuels, wood biomass was primarily used in the greenhouses in Tasmania (TAS: GH1, GH2), and natural gas was solely used in the greenhouse in South Australia (SA: GH3). The calorific value or heating value of wood biomass mostly depends on its moisture content (Food and Agriculture Organisation, 2013). For GH1, pine wood chips (*Pinus radiata*) with 30% water content were used. For GH2, sawdust of mixed wood waste (mainly *Pinus radiata* and *Acacia melanoxylon*) with ca. 40% water content was primarily used (Table 4.1), accounting for 99% of total fuels used. Waste oil was used as an energy source for supplementary greenhouse heating, with a calorific value of 40893 kJ kg<sup>-1</sup> waste oil (Kanokkantapong *et al.*, 2009). Emission factors reported by (Boughton and Horvath, 2004) were used to calculate the life cycle inventory data for waste oil combustion. It was assumed that biomass boiler capacities were the same with ca. 300 kWh in both greenhouses in TAS in agreement with similar greenhouse size. In the greenhouse in SA, a conventional natural gas boiler of 500 kWh was used.

Electricity consumption for greenhouse operation was included. Therefore, related emissions include electricity production and transmission based on the regional electricity generation mix. In Tasmania during the period of data collection (2017–2018), the electricity generation mix consisted of 80.7% hydro, 10.5% wind, and 8.8% natural gas (Australian Energy Regulator, 2017). In GH2, electricity generated from a solar photovoltaic system on top of neighbouring buildings was additionally used for greenhouse operation, accounting for 22% of total electricity use at the greenhouse. In South Australia during the data collection period (2017–2018), the electricity generation mix was 40.2% wind, 39.1% gas, 11.6% brown coal and 9.1% rooftop solar (Australian Energy Regulator, 2017).

### ***Seedling and substrate***

For all three systems, tomato seedlings were obtained from specialised nurseries. Resource inputs for seedling production and associated emissions were modelled through using the datasets associated with seedling production in the Australian database, AusLCl. The transportation of seedlings from the nursery to the greenhouse gate was also considered. Stone wool was used as the growing medium in GH1 and GH3, and both coco coir and stone wool were used in GH2 (at the ratio of 84:16). Stone wool was mainly sourced from the Netherlands and coco coir was sourced from India. Emissions associated with production and transportation of substrates were modelled based on the databases Ecoinvent and Agri-footprint (Blonk Agri-footprint BV, 2014) (Appendix III).

### ***Climate systems***

Climate systems includes all infrastructure and equipment installed in the greenhouses except for the energy use for greenhouse heating and electricity for greenhouse operation. For instance, thermal screen and equipment for heating including heat storage tank, distribution pipes and boilers were used in all three systems. CO<sub>2</sub> enrichment was applied in the greenhouses in Tasmania but not in the one in South Australia. Production of pure CO<sub>2</sub> and CO<sub>2</sub> distribution tubes were considered. Transportation of the equipment mentioned above was also included in the inventory stage.

### ***Fertilisation system***

In all systems only mineral fertiliser was used. Total quantities of N, P<sub>2</sub>O<sub>5</sub> and K<sub>2</sub>O were provided by the growers (Table 4.1). Emissions generated from fertiliser production and application were considered. To estimate the emissions generated from activities (e.g.

application of fertilisers), emission factors are required. An emission factor indicates the amount of a compound emitted per unit of material used for an activity, which is also called activity levels (Equation 1).

$$\text{Emission} = \text{Activity level} \times \text{Emission factor} \quad (1)$$

Emissions due to the application of N fertiliser included nitrous oxide (N<sub>2</sub>O–N) and nitrogen oxides (NO<sub>x</sub>–N) into the atmosphere and NO<sub>3</sub>–N emission to water. It is noted that there was no ammonia-based fertiliser applied in all three systems, and therefore emission of ammoniacal nitrogen was not considered. Estimations of three types of emissions were based on total amount of N fertiliser applied. The N<sub>2</sub>O–N emission factor was considered to be 2.1% of the total N applied according to the environmental assessment of irrigated vegetable production in Australia (Maraseni *et al.*, 2010). NO<sub>x</sub>–N emissions were calculated as 10% of N<sub>2</sub>O–N emissions (Audsley, 1997). Potential NO<sub>3</sub>–N emissions at a river basin scale was estimated as 30% (Van Drecht *et al.*, 2003) of total N applied after subtracting N<sub>2</sub>O–N and NO<sub>x</sub> emissions and an uptake of 1.89 g N kg<sup>-1</sup> of tomatoes (Sonneveld, 2000), as following the method of Torrellas *et al.* (2013). For all three systems, growers indicated that the use of synthetic pesticides was rare. Therefore, pesticides were excluded from the present study.

### **Waste management**

Solid waste included tomato stem and leaves from pruning and plant residues from after the production period, used substrate and its plastic packing, and wood ash from energy use where a biomass fuel was used. The waste of metal and glass generated from the greenhouse structure was assumed to be 100% recycled. These recycling processes are part of the production of new products, and therefore were not considered in the waste management of the present study, according to the cut-off criteria for allocation procedures (Ekvall and Tillman, 1997). Nevertheless, the transportation of metals and glass from greenhouse site to recycling treatment plants were included in the waste treatment. Disposal of each type of waste was based on growers' information (Table 4.2). While all stone wool waste went to landfill, for coco coir waste, 40% was composted and the rest incinerated. Emissions generated from waste treatments and transportation from the greenhouse gate to the disposal location (e.g. landfill) were estimated. A distance of 25 km from greenhouse gate to disposal location was assumed for all three greenhouses.

**Table 4.2.** Fraction of disposal for four types of waste (green waste, plastics, substrate, wood ash) for three different tomato greenhouse production systems (GH1, GH2, GH3) located in two states: Tasmania (TAS) and South Australia (SA).

Type of waste	GH1-TAS	GH2-TAS	GH3-SA
Green waste	Compost plant (100%)	Incinerator (100%)	Landfill (100%)
Plastics	Landfill (100%)	Landfill (100%)	Landfill (100%)
Substrate	Landfill (100%)	Compost plant (40%) Incinerator (60%)	Landfill (100%)
Wood ash	Landfill (100%)	Landfill (100%)	—

**Transportation**

Transportation is an essential component in greenhouse production, including from the suppliers or production points of inputs to greenhouse gate, and from greenhouse gate to waste disposal points. The inventory of transportation included: manufacture, maintenance, operation and disposal of the selected transportation tool (e.g. freight) (Spielmann and Scholz, 2005). Databases AusLCI and Ecoinvent were used for accounting for transportation emissions occurring in Australia and overseas respectively. To quantify the transportation required in greenhouse production, transportation was calculated through the formula: distance (km) x mass (ton), being expressed per ton kilometre (tkm).

**Life cycle impact assessment**

Life cycle impact assessment (LCIA) is a phase that helps to understand which emission and resource consumption is associated with which potential environmental impact of a product. There are four essential steps to conduct an LCIA: 1) selecting impact categories (e.g. climate change) based on the research purposes, 2) assigning the inventory results (substance, e.g. CO<sub>2</sub>) to different impact categories, 3) selecting impact indicators (e.g. potential global warming) for modelling the selected impact categories, 4) calculating indicator results through Equation 2, which is commonly termed as characterisation.

$$Impact\ indicator\ result_c = \sum_s Characterisation\ factor_{cs} \times Substance\ emission \quad (2)$$

Where *c* denotes the impact category that the impact indicator is related to, *s* is a specific substance emission, and therefore *cs* indicates a characterisation factor that connects the specific substance emission (*s*) with a specific impact category (*c*). For example, Equation 3 demonstrates how an impact indicator, potential global warming is calculated.

$$Global\ warming = \sum_s Global\ warming\ potential_s \times Substance\ emission \quad (3)$$

ReCiPe 2016 in SimaPro program version 8.5.2.0 (PRé Consultants, 2017) was employed for conducting the impact assessment. Six midpoint impact categories defined by ReCiPe 2016 version 1.1 (Huijbregts *et al.*, 2017) and an indicator for demonstrating energy use, called cumulative energy demand (Frischknecht *et al.*, 2007), were selected in the impact assessment (Table 4.3).

**Table 4.3.** Selected impact categories, measurement units, methods used for the measurement and main compounds for each impact category.

Impact categories	Unit	Method
Cumulative energy demand <sup>1</sup>	MJ	Frischknecht et al. (2007)
Potential global warming <sup>2</sup>	kg CO <sub>2</sub> eq	ReCiPe 2016
Photochemical ozone formation <sup>3</sup>	kg NO <sub>x</sub> eq	ReCiPe 2016
Particulate matter formation	kg PM <sub>2.5</sub> eq	ReCiPe 2016
Terrestrial acidification	kg SO <sub>2</sub> eq	ReCiPe 2016
Freshwater eutrophication	kg P eq	ReCiPe 2016
Marine eutrophication	kg N eq	ReCiPe 2016
Water scarcity footprint	L H <sub>2</sub> O eq	Ridoutt and Pfister (2010)

<sup>1</sup> All direct and indirect energy use for producing 1 kg tomatoes, including energy use for extraction and manufacturing of materials and processes involved (e.g. manufacturing of steel);

<sup>2</sup> Considering 100 years;

<sup>3</sup> Impact on human health.

To assess the potential impact of freshwater use on corresponding watersheds, a scarcity-weighted water footprint indicator proposed by Ridoutt and Pfister (2010) was used as following the ISO standard 14046 on water footprints (ISO, 2014). In brief, the calculation of water scarcity footprint is defined as multiplying the amount of water consumed at each stage of fresh tomatoes' life cycle by the characterisation factor at the corresponding location where the water was extracted and then summed as described in Equation 4:

$$\text{Water scarcity footprint} = \sum_l \text{Consumptive water}_l \times WSI_l \times 1000 \quad (4)$$

Where  $l$  denotes the location where the water is consumed, and consumptive water is the volume of blue water (surface and ground water sources) consumed at a specific location ( $l$ ). Blue water volume in this study was counted from direct water consumption (irrigation) and indirect water consumption (e.g. fertiliser production). Water stress index ( $WSI$ ; m<sup>3</sup> H<sub>2</sub>O m<sup>-3</sup> H<sub>2</sub>O) denotes the characterisation factor defined by Ridoutt and Pfister (2010), meaning the water scarcity based on water withdrawal-to-availability ratio of local water resources (Pfister *et al.*, 2009). Therefore,  $WSI_l$  denotes the water stress index at a specific location (Table 4.4).

In addition to assess the water use over the life cycle of tomato production, the water scarcity footprint was also applied to evaluate the impact due to water use for irrigation. To compare the results of using characterisation factors derived from different methods, the AWARE (the available water remaining) method proposed by Boulay et al. (2018) was used to calculate the water scarcity footprint of water use for irrigation at greenhouses (Table 4.4). The choice of adopting the water footprint indicator proposed by Ridoutt and Pfister (2010) in the present study was in agreement with Page et al. (2011), which makes it possible to compare the impacts of freshwater use between greenhouse studies in Australia's context.

**Table 4.4.** Characterisation factors of relevant watersheds for three greenhouses: GH1-TAS, GH2-TAS and GH3-SA derived from the water stress index method proposed by Ridoutt and Pfister (2010), and the available water remaining (AWARE) method proposed by Boulay et al. (2018).

	<b>GH1-TAS</b>	<b>GH2-TAS</b>	<b>GH3-SA</b>
Water stress index ( $\text{m}^3 \text{ eq H}_2\text{O m}^{-3}$ )	0.0166	0.0114	0.815
AWARE characterisation factor ( $\text{m}^3 \text{ eq H}_2\text{O m}^{-3}$ )	3.1	1.5	74.3

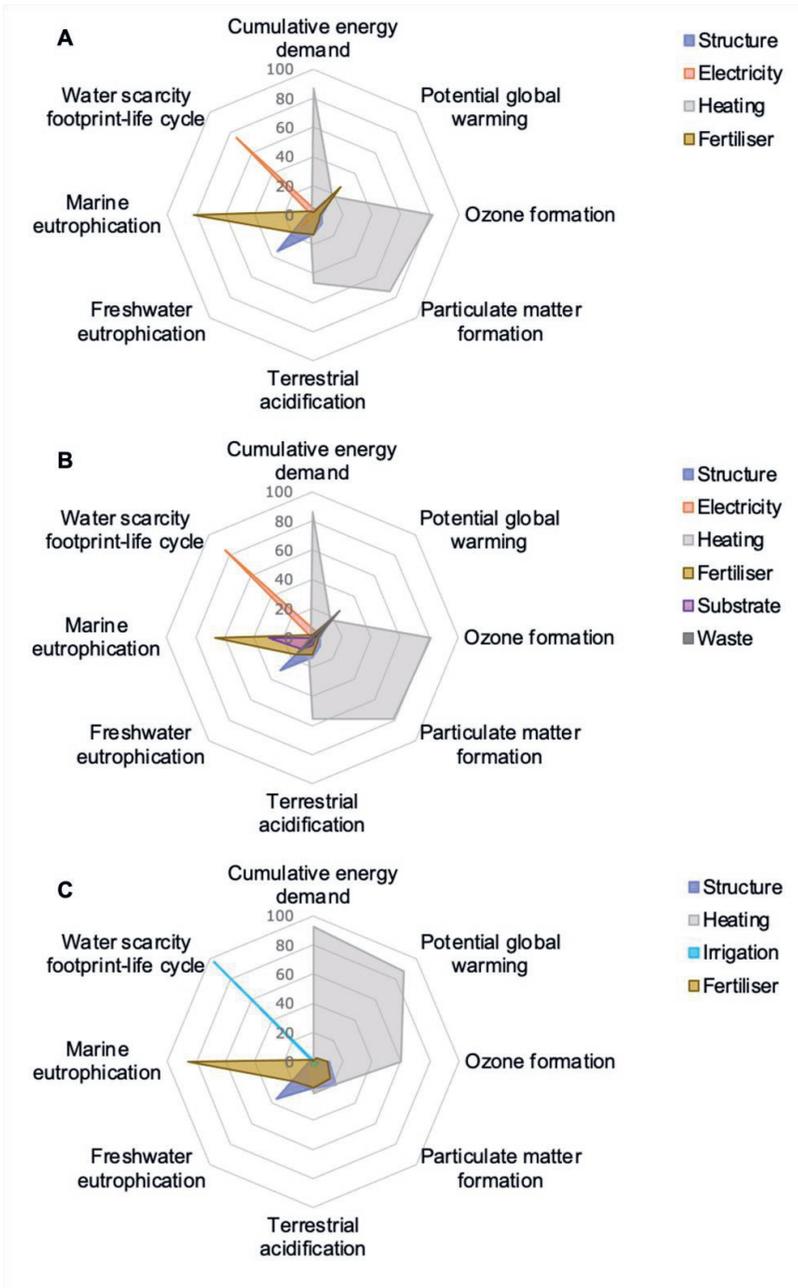
### ***Sensitivity analysis***

Sensitivity analysis represents systematic procedures that estimate the effects of choices made for input data, models for life cycle inventory analysis and methods on the outcome of a LCA study (ISO, 2006). In recent times, as an alternative to stone wool, coco coir has gained increasing application in greenhouse cultivation mainly due to its low cost and perceived environmental benefits. However, the environmental performance of coco coir is dependent upon how coco coir is treated in the evaluation (as a type of waste or as a by-product in the processes of coconut production). This can profoundly change the quantification of the environmental performance of the application of coco coir in greenhouse cultivation. Whether or not treating coco coir as a type of waste depends on the information provided by the coco coir manufacturer. In the current study, information on original source of coco coir is not available. Therefore, a sensitivity analysis was carried out to determine if the allocation method of the production of coco coir (used as the growing substrate in GH2 in TAS) would result in any changes in the outcomes of life cycle impact assessment for GH2 and comparisons between the three systems. For instance, two methods were used to account the environmental impacts of the production of coco coir: 1) coco coir was treated as a by-product of coconut production, therefore 39% of environmental impacts resulting from coconut production were allocated to coco coir. This

allocation was based on confidential information obtained from a coconut processor in Sri Lanka as indicated in the inventory database 'Agri-footprint 1.0' (Blonk Agri-footprint BV, 2014); and 2) coco coir was treated as a type of waste of coconut production, and therefore did not share the environmental impacts of coconut production (no allocation was applied).

### 4.3. Results

The assessment of the contribution of greenhouse components on impact categories showed that greenhouse heating, fertiliser production and application, and greenhouse structure, were each responsible for at least 20% of the contribution of the total impact on multiple impact categories in all three greenhouses (Figure 4.2). The impacts due to greenhouse heating was the highest, being the biggest burden to cumulative energy demand (ca. 90% of the total impact), ozone formation (ca. 60–80% of the total impact), particulate matter formation (ca. 20–80% of the total impact), and terrestrial acidification (ca. 20–60%), regardless of what type of energy sources were used in the production system (Figure 4.2). In the greenhouse in South Australia, where natural gas was mainly used, greenhouse heating was the biggest contributor to potential global warming, being ca. 80% of the total impact (Figure 4.2C). Fertiliser was the biggest contributor to potential marine eutrophication, and greenhouse structure was the major cause of potential freshwater aquatic eutrophication in all three systems (Figure 4.2). Regarding the impact of freshwater use, the water scarcity footprint indicator showed that electricity use was the major burden in GH1 and GH2 in Tasmania (TAS) (Figure 4.2A and 4.2B), and that irrigation was the main burden in GH3 in South Australia (SA) (Figure 4.2C).



**Figure 4.2.** Radar graphs for major greenhouse components with identified contribution greater than 20% to each midpoint impact category for 1 kg fresh tomatoes produced from three different greenhouse production systems: **(A)** a greenhouse using wood biomass for heating in Tasmania (GH1-TAS), **(B)** a greenhouse using multiple types of fuels for heating in Tasmania (GH2-TAS), and **(C)** a greenhouse using natural gas for heating in South Australia (GH3-SA). Note that for the analysis of GH2-TAS, 31% of the inputs of coconut production was allocated to the production of coco coir as a by-product with regard to the calculation of the environmental impacts of coco coir.

### Tomato production in biomass-heated greenhouses in Tasmania

In general, the environmental impacts per unit cherry tomatoes in GH2-TAS were on average 50% higher than that of large tomatoes in GH1-TAS (Table 4.5). This was mainly attributed to a lower yield of cherry tomatoes in GH2-TAS (28 kg m<sup>-2</sup>) compared to that of large tomatoes in GH1-TAS (57 kg m<sup>-2</sup>). Cumulative energy demand was 21 and 38 MJ kg<sup>-1</sup> tomatoes for GH1-TAS and GH2-TAS, respectively (Table 4.5). In both greenhouses, around 87% of the cumulative energy demand was caused by greenhouse heating (Figure 4.3A and 4.3B). Additionally, heating was the biggest burden to photochemical ozone formation, particulate matter formation, and terrestrial acidification, which are the main causes of air pollution, representing 47–81% of the total for these impact categories (Figure 4.3A and 4.3B). Regarding the impact on potential global warming, 0.28 kg CO<sub>2</sub> eq per kg tomatoes was generated from GH1-TAS (Table 4.5). Production in GH2-TAS gave more than 160% higher CO<sub>2</sub> eq per kg tomatoes than that in GH1-TAS, being an emission of 0.73 kg (Table 4.5). Despite being the biggest contributor to cumulative energy demand, greenhouse heating was not the biggest cause of potential global warming in both greenhouses where wood biomass was used for heating (Figure 4.3A and 4.3B).

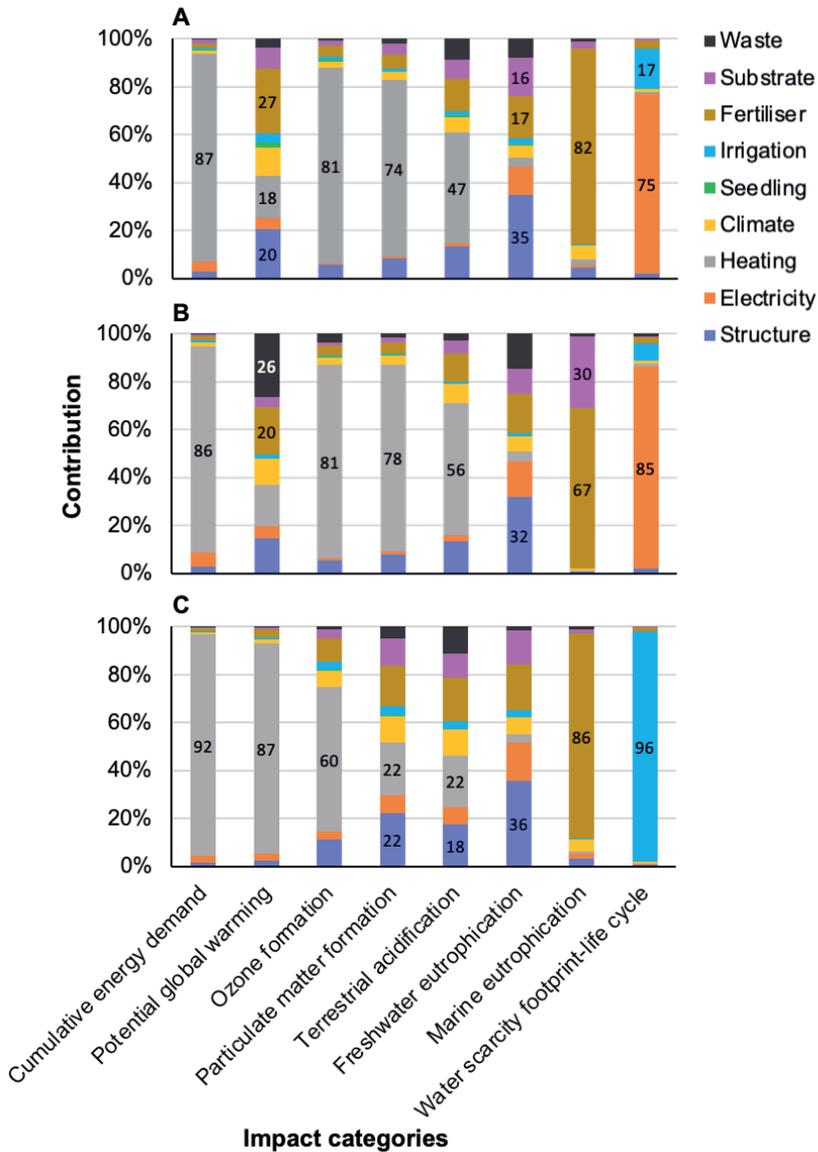
**Table 4.5.** Results of nine impact categories: cumulative energy demand, potential global warming, photochemical ozone formation, particulate matter formation, terrestrial acidification, freshwater eutrophication, marine eutrophication and water scarcity footprint for producing 1 kg tomatoes from three different greenhouse systems (GH1, GH2, GH3) spreading in two states: Tasmania (TAS) and South Australia (SA). For the substrate of GH2-TAS, two methods were used to calculate the environmental impacts of coco coir: (a) 31% of the inputs of coconut production was allocated to the production of coco coir as a by-product, referred to as allocation; (b) no allocation was considered for the production of coco coir as it is treated as a type of waste of coconut production.

Impact category	Unit	GH1-TAS	GH2-TAS (allocation)	GH2-TAS (no allocation)	GH3-SA
Cumulative energy demand	MJ	2.1E+01	3.8E+01	3.8E+01	3.9E+01
Potential global warming	kg CO <sub>2</sub> eq	2.8E-01	7.3E-01	7.1E-01	2.3E+00
Ozone formation	kg NO <sub>x</sub> eq	2.7E-03	5.8E-03	5.7E-03	1.3E-03
Particulate matter formation	kg PM <sub>2.5</sub> eq	1.4E-03	2.8E-03	2.8E-03	4.8E-04
Terrestrial acidification	kg SO <sub>2</sub> eq	2.1E-03	4.0E-03	3.9E-03	1.5E-03
Freshwater eutrophication	kg P eq	4.7E-05	9.8E-05	8.9E-05	4.3E-05
Marine eutrophication	kg N eq	2.1E-05	3.4E-04	2.4E-04	2.8E-05
Water scarcity footprint-life cycle	L H <sub>2</sub> O eq	1.8E+01	3.6E+01	3.6E+01	3.9E+01

Fertiliser production and application contributed the most to potential global warming from in GH1-TAS (Figure 4.3A), which was mainly derived from fertiliser production. For tomato production in GH2-TAS, waste management was the biggest contributor to potential global

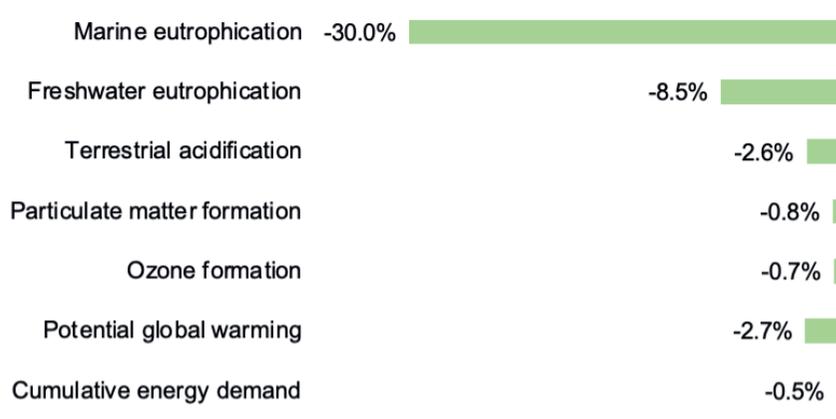
warming, with a contribution of 26% of the total impact (Figure 4.3B). This was mainly caused by burning a considerable amount of green waste and used substrate (coco coir) after production (Appendix V).

For the impact due to freshwater use, water scarcity footprint was 18 L H<sub>2</sub>O eq kg<sup>-1</sup> in GH1-TAS and 36 L H<sub>2</sub>O eq kg<sup>-1</sup> in GH2-TAS (Table 4.5), with the major contribution (75–85%) from electricity (Figure 4.3A and 4.3B) as a result of hydropower generation in Tasmania. In terms of the impacts on water quality, eutrophication in both freshwater and marine systems was higher in GH2-TAS than GH1-TAS (Table 4.5). It is notable that the potential marine eutrophication per unit of tomato production in GH2-TAS was 14 times that of tomato production in GH1-TAS.



**Figure 4.3.** Contributions (%) of greenhouse components (waste management, substrate, fertiliser production and application, irrigation at greenhouse, tomato seedlings, climate system, heating, electricity and greenhouse structure) to eight midpoint impact categories for 1 kg fresh tomatoes produced from three different greenhouse production systems: (A) a greenhouse using wood biomass for heating in Tasmania (GH1-TAS), (B) a greenhouse using multiple types of fuels for heating in Tasmania (GH2-TAS), and (C) a greenhouse using natural gas for heating in South Australia (GH3-SA). For the impact assessment of substrate of GH2-TAS, 31% of the inputs of coconut production was allocated to the production of coco coir as a by-product.

A sensitivity analysis was carried out to examine the effects of different ways of quantifying the environmental impacts of coco coir (whether or not consider coco coir as a by-product of coconut production) on the overall environmental performance of tomato production in GH2-TAS. When coco coir was treated as a waste of coconut production, reductions were observed in all the seven impact categories, with 30% reduction for marine eutrophication being the largest reduction (Figure 4.4).



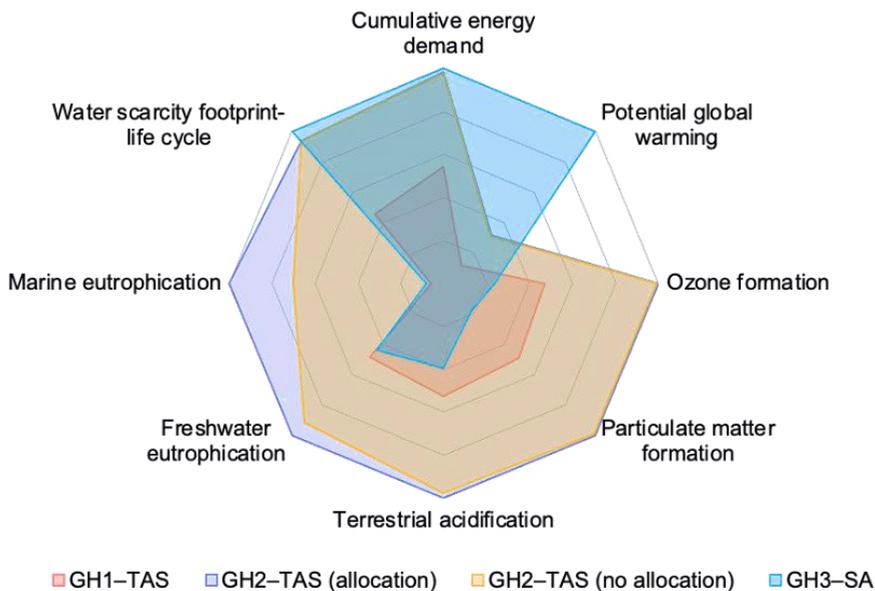
**Figure 4.4.** Reduction in seven impact categories of the cherry tomato greenhouse production in Tasmania (GH2-TAS) when coco coir (substrate used in GH2-TAS) was treated as waste of coconut production in comparison with when coco coir was considered as a by-product of coconut production. Comparison is based on 1 kg of loose tomatoes. Please note that coconut production is rainfed in India and thus water use for irrigation is omitted (Blonk Agri-footprint BV, 2014), and therefore was not included in the present figure.

### ***Tomato production in a natural-gas-heated greenhouse in South Australia***

The cumulative energy demand was 39 MJ kg<sup>-1</sup> for the greenhouse in South Australia (GH3-SA) (Table 4.5), 92% of which was used for greenhouse heating (Figure 4.3C). Hence, heating was the dominant contributor for potential global warming in GH3-SA, accounting for 87% of the total impact (Figure 4.3C). Total potential global warming from GH3 was 2.3 kg CO<sub>2</sub> eq kg<sup>-1</sup> tomatoes (Table 4.5). Fertiliser production and application was the second biggest burden in GH3-SA, primarily contributing to marine eutrophication (94%), freshwater eutrophication (23%), acidification (23%) and particulate matter formation (21%) (Figure 4.3C). In terms of the impact due to freshwater use, water scarcity footprint was 39 L eq H<sub>2</sub>O for 1 kg tomatoes of GH3-SA (Table 4.5) and water use for irrigation accounted for 96% of the total impact (Figure 4.3C).

### Comparing environmental performance of three tomato production systems

Tomato production in GH3-SA presented the highest impact on cumulative energy use, potential global warming and water scarcity footprint (Figure 4.5). For instance, potential global warming generated from GH3-SA was 3–8 times that from GH1-TAS and GH2-TAS. The water scarcity footprint of per unit tomatoes in GH3-SA was twice that of GH1-TAS. In terms of the impact due to water use for irrigation, tomato production of GH3-SA presented the highest water use and GH2-TAS led to the lowest water use across all metrics used (Table 4.6). Use of different metrics showed consistent results in comparing the impact of irrigation water use between systems. However, large differences in terms of the magnitude were shown between these metrics (Table 4.6). The tomatoes of GH3-SA had lower air- pollution-related impacts, such as ozone formation and particulate matter formation and terrestrial acidification (Figure 4.5). Cherry tomato production in GH2-TAS was associated with much higher environmental impacts compared to production of large-fruited tomatoes in GH1-TAS and GH3-SA, mainly owing to the much lower yield of cherry tomato production. For instance, production in GH2-TAS led to the highest potential eutrophication for both freshwater aquatic and marine systems, regardless of allocation of coco coir production was considered in the impact assessment (Figure 4.5).



**Figure 4.5.** Radar graphs for comparisons between tomato production from three different greenhouse systems (GH1, GH2 and GH3) in two states: Tasmania (TAS) and South Australia

(SA) for eight impact categories. For the substrate of GH2-TAS, two methods were used to calculate the environmental impacts of coco coir: (a) 31% of the inputs of coconut production was allocated to the production of coco coir as a by-product; (b) no allocation was considered for the production of coco coir as it is treated as a type of waste of coconut production.

**Table 4.6.** Water use per 1 kg fresh tomatoes for three different greenhouse production systems (GH1-TAS, GH2-TAS, GH3-SA) and water scarcity footprint calculated according to three different methods.

	Unit	GH1-TAS	GH2-TAS	GH3-SA
Water use for irrigation	L	45	38	57
WSF <sup>1</sup> <sub>Ridoutt &amp; Pfister</sub> for irrigation	L eq H <sub>2</sub> O	0.7	0.4	37
WSF <sub>AWARE</sub> for irrigation <sup>2</sup>	L eq H <sub>2</sub> O	139.5	57.0	3373.2
WSF-life cycle <sup>3</sup>	L eq H <sub>2</sub> O	18	36	39

<sup>1</sup> Water scarcity footprint;

<sup>2</sup> Note that the values of WSF by using AWARE method are normally much higher than using the method by Ridoutt & Pfister, 2010 as a result of different scales of characterisation factors (AWARE: 0.1-100; water stress index: 0–1);

<sup>3</sup> WSF-life cycle was calculated based on the method by Ridoutt & Pfister, 2010.

## 4.4. Discussion

In the present study, life cycle assessment was used to evaluate the potential environmental impacts of tomato production in three different greenhouse systems where locations of the greenhouses, energy sources and growing substrate were the major differences. The largest greenhouse production area in Australia, being ca. 1100 ha, is located in the Northern Adelaide Plains region in South Australia (Government of South Australia, 2020). Despite Tasmania having the smallest area of greenhouse production in Australia, it is considered to have the potential for future expansion of greenhouse production due to the favourable climate (Parks, 2010; Smith, 2011). In the present study, major contributors of eight impact categories of each greenhouse production system were identified, taking local resource availability into account.

### ***Overall environmental performance of three cases in Australia***

Cumulative energy demand was 38 MJ kg<sup>-1</sup> for the cherry tomato production in GH2-TAS, 21 and 39 MJ kg<sup>-1</sup> for the large tomatoes in GH1-TAS and GH3-SA, respectively. For large tomatoes, an LCA study conducted in New South Wales (NSW) in Australia (Page *et al.*, 2012) reported that energy use of the tomato production (57 kg m<sup>-2</sup>) in high-tech heated greenhouse was 27 MJ kg<sup>-1</sup> where greenhouse structure was excluded. Considering the similarities in annual yield and climate, the heating requirement in the GH1-TAS might be comparable to that in the Netherlands or North of France. The assessment conducted in the Chapter 5 of the present thesis presents that the average energy demand was 13–24 MJ kg<sup>-1</sup> of tomatoes produced in hi-tech, heated glasshouses in the Netherlands (Table

4.7). A study by Boulard *et al.* (2011) reported that 32 MJ was used for producing 1 kg tomatoes in North of France (Table 7). These values are comparable to the results in the present study. In our assessment cumulative energy use was higher in GH3-SA (39 MJ kg<sup>-1</sup>) than that in GH1-TAS and also reported by Page *et al.* (2012). This is opposite to what we expected considering the warmer climate and therefore lower heating demand in South Australia (Appendix VI). Energy use can vary greatly with study boundaries, yield differences, local climate, the technologies adopted and growers' practices. As reported previously, energy use of tomato production in heated greenhouses ranges from 7 to 130 MJ kg<sup>-1</sup> (Table 4.7). A possible explanation is that the higher energy use in GH3-SA is a result of greenhouse management decisions, which might not reflect the average energy use for tomato greenhouse production in the region. The high energy consumption per kg cherry tomatoes were mainly attributed to a lower yield, which is normal for cherry tomato production (Cellura *et al.*, 2012*b*). Studies on cherry tomato greenhouse production systems (Cellura *et al.*, 2012*a, b*) reported that the energy use was around 23 MJ kg<sup>-1</sup> in the south of Italy where greenhouse heating was not required. This is lower than the cumulative energy use of cherry tomato production in the present study, which could be explained mainly due to the heating requirements for cherry tomato in GH2-TAS.

Regarding the impact of GHG emissions, 2.3 kg CO<sub>2</sub> eq was generated from tomato production in the natural-gas-heated greenhouse (GH3-SA) (Table 4.5). This is much higher than the GHG emissions of Dutch greenhouses (0.65–1.2 kg CO<sub>2</sub> eq; Table 4.7) but falls within the range of tomato production in heated greenhouses where natural gas was used for heating in other studies (1.7–9.4 kg CO<sub>2</sub> eq kg<sup>-1</sup>; Table 4.7) (Boulard *et al.*, 2011; Page *et al.*, 2012; Almeida *et al.*, 2014; Dias *et al.*, 2017). In heated greenhouses, combustion of fossil fuels was the biggest burden to potential global warming potential, taking up at least 80% of the total (Chau *et al.*, 2009*a*; Bibbiani *et al.*, 2016; Huang *et al.*, 2020). From the total global warming potential 87% was due to greenhouse heating where natural gas was solely used as the fuel (Figure 4.3C). In comparison to Dutch greenhouses, the higher GHG emissions from GH3-SA might be attributed to the grower's practices and lack of adopting combined heat and power (CHP) (Vermeulen and Lans, 2011). For the tomato production in greenhouses in Tasmania where wood biomass was primarily used, a much smaller GHG emissions were determined, being 0.28–0.73 kg CO<sub>2</sub> eq per kg tomatoes (Table 4.5). This GHG emission is also lower than other heated greenhouses where fossil-based energy were used (Table 4.7). In an LCA study conducted in Sweden (Röös and Karlsson, 2013), 0.29 kg CO<sub>2</sub> eq kg<sup>-1</sup> was reported for tomato production from wood-biomass-heated greenhouses with a yield of 57 kg m<sup>-2</sup>,

which is comparable to the large-fruited tomato production from our study where yield was also 57 kg m<sup>-2</sup>. Additionally, a scenario study of greenhouse tomato production in Southern Ontario, Canada (Hendricks, 2012), compared the use of different energy sources for heating and found that heating with willow biomass had the lowest impact on potential global warming with an emission of 0.267 kg CO<sub>2</sub> eq kg<sup>-1</sup>, considering an average yield of 56.4 kg m<sup>-2</sup>. Unlike heating with fossil fuels, our study found that in the wood-biomass-heated greenhouses, greenhouse heating was no longer dominant for potential global warming, with a relatively smaller contribution compared to other components of greenhouse production, such as fertilisation and waste management (Figure 4.3A and 4.3B). This suggests that in biomass-heated greenhouse systems, further GHG mitigation could consider improving practices on other greenhouse production components. For example, for GH2-TAS waste management was the biggest contributor to GHG emissions (Figure 4.3B), of which disposal of used substrates (coco coir and stone wool) is the major cause. In addition to potential global warming potential, combustion of fuels for greenhouse heating was also primarily responsible for ozone formation and terrestrial acidification in all systems (Figure 4.3). This is consistent with previous studies (Pluimers, 2001; Antón *et al.*, 2012; Torrellas *et al.*, 2012b; Dias *et al.*, 2017).

**Table 4.7.** Comparison of energy use, potential global warming potential and energy sources for producing 1 kg tomatoes in heated greenhouses.

Country	Energy use (MJ)	Potential global warming <sup>1</sup> (kg CO <sub>2</sub> eq)	Energy source(s)	Reference
Australia (GH1-TAS)	21	0.28	Wood chips	This study
Australia (GH2-TAS)	38	0.73	Wood waste, waste oil & Liquefied petroleum gas	This study
Australia (GH3-SA)	39	2.3	Natural gas	This study
Australia (NSW <sup>2</sup> )	27	1.9	Natural gas	Page <i>et al.</i> , 2012
	21	1.7	Coal	Page <i>et al.</i> , 2012
Canada (Ontario)	59	2.5–3.2	Natural gas & bunker oil	Dias <i>et al.</i> , 2017; Hendricks, 2012
		2.3–3.1	Natural gas	Dias <i>et al.</i> , 2017; Hendricks, 2012
		0.3–0.9	Wood chips	Dias <i>et al.</i> , 2017; Hendricks, 2012
Hungary	7	0.44	Geothermal energy <sup>3</sup>	Torrellas <i>et al.</i> , 2012b
	87	5	Natural gas	Torrellas <i>et al.</i> , 2012b
The Netherlands	13–24	0.65–1.2	Natural gas	Chapter 5
Northern France	32	2 <sup>4</sup>	Natural gas	Boulard <i>et al.</i> , 2011

Northern Italy	96	2.3	Canola oil & natural gas	Almeida <i>et al.</i> , 2014
	64	3.6	Natural gas	Almeida <i>et al.</i> , 2014
	35	1.4	Municipal solid waste	Almeida <i>et al.</i> , 2014
Sweden	25	0.29	Wood chips	Röös and Karlsson, 2013
Swiss	22–38	—	—	Jolliet, 1993
UK	130	9.4	Natural gas	Williams <i>et al.</i> , 2006

<sup>1</sup> Values were calculated as global warming potential for 100 years except when indicated otherwise;

<sup>2</sup> New South Wales;

<sup>3</sup> In this case geothermal energy was stored as hot water at ca. 80 °C around 1600 metres below ground;

<sup>4</sup> Value was estimated as global warming potential for 20 years.

### **Impacts on freshwater quantity and quality**

Depletion of freshwater has become a global environmental issue. This is particularly crucial for agriculture given 70% of global freshwater being consumed for agriculture production (Rockström *et al.*, 2009; Willett *et al.*, 2019). We used a water scarcity footprint to evaluate the quantitative impact of freshwater use during the life cycle of tomato production for three greenhouse systems. Additionally, the water use for irrigation at greenhouses reported by the growers and its water scarcity footprint serve as important indicators of water at the management level (Table 4.6). As expected, use of different water metrics led to very different results (Table 4.6) and thus provides the understanding of water use through different lenses. For instance, the water use for irrigation at GH3-SA was 1.27 times that of GH1-TAS. When the irrigation water use was weighted by local water stress index, producing tomatoes at GH3-SA led to a more than 50 times higher impact on local freshwater scarcity compared to GH1-TAS (Table 4.6).

Previous studies have assessed that the water use for tomato production at greenhouse location ranged from 14 L kg<sup>-1</sup> to 80 L kg<sup>-1</sup> (Table 4.8), which is largely dependent upon the indoor greenhouse climate and water management. The water use for irrigation of producing 1 kg large tomatoes in GH1-TAS and GH3-SA is higher than that in greenhouses in the Sydney region and the New South Wales Tablelands region (Page *et al.*, 2011), but falls within the range established by previous studies (Table 4.8). Reuse of drain water is an effective way of reducing water use and nutrient losses (Gruda, 2019). In Chapter 5 of the present thesis, it is concluded that greenhouse systems with 85% of reused drain water had the lowest water use (14 L) for producing 1 kg of tomatoes. However, in the three greenhouse systems, much lower recycling rates (20–30%) were implemented in the fertigation management, suggesting there is a substantial potential for improving water use in these greenhouses.

**Table 4.8.** Comparison of irrigation water use for 1 kg tomatoes produced in greenhouse systems.

Country	Water use for irrigation (L)	Reference
Australia (NSW <sup>1</sup> tableland)	39	Page <i>et al.</i> , 2011
Australia (Sydney)	40	Page <i>et al.</i> , 2011
China (Beijing)	76	Huang <i>et al.</i> , 2014
China (Shouguang)	80	Huang <i>et al.</i> , 2014
Canada (Ontario)	18	Dias <i>et al.</i> , 2017; Hendricks, 2012
Hungary	15	Torrellas <i>et al.</i> , 2012b
Netherlands	14	Torrellas <i>et al.</i> , 2012b
France	25–50	Boulard <i>et al.</i> , 2011
Northern Italy	47	Almeida <i>et al.</i> , 2014

<sup>1</sup> New South Wales.

The water scarcity footprint of 1 kg large tomatoes was 18 L H<sub>2</sub>O eq in GH1-TAS and 39 L H<sub>2</sub>O eq in GH3-SA (Table 4.5), suggesting 50% less impact on freshwater scarcity from the production in GH1-TAS. The main burden to freshwater scarcity is the electricity generation from upstream processes in GH1-TAS and GH2-TAS, and irrigation in GH3-SA (Figure 4.2). The freshwater used in GH3-SA was mainly sourced from the Murray-Darling basin where freshwater is often scarce with a water stress index of 0.815 (Table 4.4). In Tasmania, freshwater is more reliably available; Tasmania holds 12% of Australia's freshwater resources, despite comprising less than 1% of Australia's surface land (Australian Government Bureau of Meteorology, 2013). In a previous Australian study by Page *et al.* (2012) a water scarcity footprint using the same method (Ridoutt and Pfister, 2010) as used in our assessment (water scarcity footprint-life cycle) indicated that the water use of producing 1 kg tomatoes from greenhouses in NSW ranged from 5.4 to 53 L kg<sup>-1</sup>, which was primarily due to differences in the water stress indices (0.015–0.397) identified with the corresponding water resources. Hence, it is important to use region-specific factors to evaluate impacts of freshwater use in countries with great heterogeneity in water flows of watersheds and river basins.

Reducing fertiliser application and leaching is another beneficial effect of water saving (Incrocci *et al.*, 2020), which is rarely mentioned in the context of Australia's agriculture, but this is particularly important for greenhouse production (Grewal *et al.*, 2011). Fertiliser application is the major cause of eutrophication in greenhouse production (Incrocci *et al.*, 2020), which is also reported in the current study (Figure 4.3). In GH2-TAS and GH3-TAS, 30% and 20% of drain water was reused in the fertigation system respectively, which is lower than the proportion of recirculation (85%) in the greenhouse systems in the Netherlands (Chapter 5). The results showed that marine eutrophication was 0.000021–0.00034 kg N eq per kg tomatoes (Table 4.5), which is associated with N leaching from the

greenhouse production. This is lower than the potential marine eutrophication of tomato production of greenhouses in NSW (0.0005–0.0007 kg N eq kg<sup>-1</sup> tomatoes) (Page *et al.*, 2014). A possible explanation could be a much lower rates of N fertilisation in the three greenhouse systems (2.1–4.7 g N kg<sup>-1</sup> tomatoes) compared to that in Page *et al.* (4.7–6.8 N kg<sup>-1</sup> tomatoes; 2014). Notably, the sensitivity analysis showed that in GH2-TAS use of coco coir as growing medium can lead to considerable impact on eutrophication in both freshwater and marine water bodies when coco coir was considered as a by-production of coconut production (Figure 4.4). Due to the different methods applied for calculating eutrophication in LCA studies, comparison with other studies is difficult. Regardless of what method used, the values of eutrophication in marine or freshwater systems in the current study were mostly lower than the range of eutrophication potential (0.00017–0.0026) reported in heated, soilless greenhouse tomato production in previous studies (Torrellas *et al.*, 2012b; Dias *et al.*, 2017). Eutrophication is a site-specific environmental impact and thus highly site-dependent (Page *et al.*, 2014). However, due to the lack of regional characterisation factors for modelling eutrophication, global values were used in the present study, which may lower the confidence of the results of eutrophication. Therefore, we suggest that site-dependent characterisation factors need to be developed in an Australian context in future research.

### ***Trade-offs in using wood biomass fuel for greenhouse heating***

Fossil fuel energy to heat greenhouses is the major source of GHG emissions and should be reduced. Use of wood biomass is commonly treated as carbon neutral in life cycle assessment as carbon sequestration from regrowth or growth of forests with large scales offsets the carbon emission due to wood use (Grassi *et al.* 2018). However, a recent study by Peng *et al.* (2023) pointed out that this approach to counting the carbon cost of wood use is flawed, given that carbon sequestration from forest growing happens anyway. Therefore, use of wood biomass cannot be merely treated as carbon neutral if a long-term time course is considered. Additionally, use of wood biomass can substantially increases other emissions that directly impact on human health (Chau *et al.*, 2009a,b; Bibbiani *et al.*, 2016). Ozone formation and particulate matter formation in the wood-biomass-heating greenhouses in Tasmania were approximately twice that of the natural-gas-heated greenhouse in South Australia (Table 4.5). Both ozone formation and particulate matter formation are air pollutants that have negative impacts on human health, causing respiratory problems. Moreover, combustion of wood biomass generates a higher volume of SO<sub>x</sub>, which is the main cause of terrestrial acidification (Figure 4.3A and 4.3B). Dias *et*

al. (2017) conducted a scenario study where the environmental effects of substituting willow biomass for heating were assessed, and reported that compared to fossil fuels, the use of willow biomass generated 65%, 126% and 45% more ozone formation, particulate matter formation and acidification, respectively. The authors suggested that for future adoption of wood biomass for greenhouse heating, better combustion and emission control of the biomass boilers must be applied (Dias *et al.*, 2017). Additionally, flue gas from the combustion can be an alternative source of CO<sub>2</sub> enrichment for greenhouse production (Bibbiani *et al.*, 2016) but its purification is challenging given high-level and high costs of technologies required and therefore has not been adopted by growers in the current study.

### ***Regional factors for planning future greenhouse production***

In the context of the current study, the environmental performance of heated greenhouse production is largely influenced by two key inputs, energy and freshwater, which are predominantly constrained by the location of the greenhouse. Hence, a comprehensive understanding of effects associated with greenhouse location is essential for optimising the performance of existing greenhouse production and future greenhouse expansion. Page *et al.* (2011, 2014) assessed the effects of greenhouse location mainly in NSW, from viewpoints of the regional water scarcity and the transportation from greenhouse production points to markets. The authors suggested that relocation of existing greenhouses might reduce environmental burdens in terms of local freshwater scarcity, emissions due to transportation or greenhouse heating. In the current study, we assessed the environmental performance of three greenhouses in TAS and SA, with climates which are different from NSW, implying that resource availability and amount of energy used for heating varies greatly. Selected greenhouse production systems in TAS led to much smaller impacts on freshwater scarcity and climate change than the system in SA. This is mainly due to different degrees of local water scarcity and accessibility to cleaner energy sources. Nevertheless, use of wood biomass in the systems in TAS induced large amounts of air pollution that are associated with human health. Hence, it is worth noting that using alternative energy sources can alleviate some environmental impacts but aggravate other impacts, making overall environmental performance even worse. The large differences in environmental performance identified were mainly due to location-constrained resources, which is consistent with the study in NSW by Page *et al.* (2011, 2014).

To alleviate location-driven environmental problems of existing greenhouse production, we argue that relocation may not be a feasible solution particularly for small-scale greenhouse growers, considering the capital cost of relocating or setting up new greenhouse facilities. As the environmental concern is rising from different levels (from individual to nation), increasing pressure has been put on growers for mitigating the environmental impacts of their production systems. A study by Ellen *et al.* (2021) assessed farmers' interests on adopting options on mitigating climate change and found that economic constraint is the key factor determining farmers' actions. According to the current study, greenhouse growers are willing to and have made relevant efforts (e.g. using alternative energy sources and plant-based growing media) to manage greenhouse production towards environmental sustainability. However, in the assessed three greenhouses, mitigation options are highly location-constrained. For instance, freshwater resources and wood biomass are abundant in Tasmania, providing reliable sources for irrigation with a much lower impact on local watersheds and basins and fuels with a much lower GHG emissions for greenhouse heating. These resources are quite limited in South Australia, meaning the greenhouse growers in this region must explore other ways of reducing the environmental impacts of their greenhouses. In such regions, improvements in the environmental performance of greenhouse production systems mainly rely on technological innovation, such as recycling water, use of seawater for irrigation and solar energy (Parks, 2010; Page *et al.*, 2014).

For the existing greenhouse production systems, mitigation strategies should consider local constraints and economic feasibility for required technology adoption. For future high-tech greenhouse expansion, local resource situation, such as freshwater scarcity, source of electricity generation and the availability of cleaner energy sources, may be as important as local climate, given the use of water and energy are the main cause of environmental impacts. Moreover, it is also important to consider the impacts due to climate change on renewable energy generation (Cronin *et al.*, 2018; Solaun and Cerdá, 2019). Several studies (Cronin *et al.*, 2018; Solaun and Cerdá, 2019) pointed out that future climate change might have a big impact on hydropower generation through various pathways (e.g. hydrological cycle). Hence, to ensure the long-term stability of greenhouse operations, we suggest that future greenhouse locations could consider the regions where multiple renewable energy sources are available. To improve the accuracy and precision of life cycle impact assessments, site-specific methods and characterisation factors (e.g. eutrophication) are required, as suggested in previous studies (Torrellas *et al.*, 2012b;

Page *et al.*, 2014; Dias *et al.*, 2017; Canaj *et al.*, 2020; Pfister *et al.*, 2020; Verones *et al.*, 2020).

## 4.5. Conclusion

Large differences were identified in the environmental performance between the three tomato greenhouse production systems studied. The selected tomato production system in South Australia led to higher impact on potential global warming and freshwater scarcity than that in Tasmania due to the primary use of natural gas for heating and the limited freshwater resources in South Australia. Substantial difference found on the impact by water use in the three greenhouse systems highlights that there is a need for considering availability of local freshwater resource is evaluating the environmental sustainability of greenhouse production in Australia, and Tasmania could be a suitable location for future greenhouse expansion if freshwater scarcity is prioritised as a most urgent environmental issue in Australia's context. There is a clear trade-off on use of wood biomass for greenhouse heating, reducing potential global warming by 80% but increasing air-pollution impacts by 200%. As a sustainable choice for growing substrate by the greenhouse grower, the environmental sustainability of coco coir largely depends on how coco coir is treated (a type of waste versus a by-product of coconut production), having much lower environmental impacts (e.g. 30% reduction in marine eutrophication) as a type of waste from coconut production. However, coco coir has become a type of commodity given the increasing demand for use of coco coir in gardening horticultural cultivation, and therefore should be considered as a by-product in its environmental analysis. Moreover, disposal of used coco coir also determines the environmental performance of coco coir as the 60% of used coco coir was incinerated. Collectively, this study provides growers a comprehensive understanding on their practices in terms of environmental benefits and drawbacks. This will help greenhouse growers further optimise their practices towards sustainability and highlights that LCA is an important method for decision makers to obtain a holistic understanding of greenhouse production from a system thinking.

# CHAPTER 5

## **Towards delivering on the Sustainable Development Goals in greenhouse production systems**

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## Abstract

This review evaluates the sustainability of tomato production in four greenhouse systems: high-tech (the Netherlands) and low-tech (Spain) combined with two ways of cultivation (conventional or organic). The Sustainable Development Goals (SDGs), as defined by the United Nations, were used as a lens to assess the sustainability of these four greenhouse production systems. In total seven SDGs, including 14 targets, were assessed through 12 quantitative and two descriptive indicators. Conventional, high-tech greenhouse systems showed the greatest potential for positive contributions towards four of the SDGs. However, their relatively high energy use makes it difficult to achieve SDG7 on affordable and clean energy, where low-tech systems perform better due to lower energy use from relatively cleaner sources. Lower water use efficiency and higher nutrient losses in all soil-based cultivation systems are barriers to achieving some targets under most of the selected SDGs. Organic cultivation systems show relatively high water and land use, based on the limited data available. Our review highlights the existence of substantial synergies, but also considerable trade-offs between SDGs. This needs to be considered when making policy, investment and management decisions related to greenhouse production.

**Key words:** Greenhouse production; Quantitative assessment; SDGs; Sustainable development; Tomato.

## 5.1. Introduction

The challenge for modern agriculture is to sustainably produce enough nutritious food for everyone while we are facing a climate crisis (United Nations, 2019a). Hence, our current food production systems need to be transformed in terms of their productivity, resource use and environmental impacts (Willett *et al.*, 2019). Food production systems cause nearly 29% of global greenhouse gas (GHG) emissions (Vermeulen *et al.*, 2012) and agriculture is responsible for around 70% of global freshwater use (Food and Agriculture Organization, 2013; Steffen *et al.*, 2015). The tension between human demand for food and the exhaustion of resources and other unwanted environmental impacts is rapidly rising, due to the global population growth and increasing per capita consumption (Tilman *et al.*, 2011). Hence, transformations are needed for existing food production systems that are based on principles of sustainable intensification (Eyhorn *et al.*, 2019; Willett *et al.*, 2019). Food production in greenhouses is one of the possible pathways towards such sustainable intensification.

The high productivity of greenhouses plays an important role in food production systems. The land area used for greenhouse production worldwide exceeds 470,000 ha with yields up to ca. 10 times higher per unit area compared to field production (Heuvelink *et al.*, 2020). Greenhouse production continues to increase, particularly for vegetables (Marcelis *et al.*, 2019). The core concept of greenhouse cultivation is to provide crops with favourable growth conditions by modifying the climate. Greenhouses can be located on land unsuitable for open-field production and strategically placed near transport hubs and population centres to optimise logistics. In recent years, increasing attention has been paid to the environmental sustainability of greenhouse production systems. By using life-cycle based approaches, several studies have focused on evaluating the environmental impacts of greenhouse systems mostly for tomato production (Antón *et al.*, 2005b, 2012; Boulard *et al.*, 2011; Page *et al.*, 2012; Torrellas *et al.*, 2012a,b; Almeida *et al.*, 2014; Bojacá *et al.*, 2014; Dias *et al.*, 2017).

Greenhouses with organic cultivation have emerged in response to the increasing demand for organic products due to their perceived environmental benefits and high profitability (Marcelis and Heuvelink, 2019). There is evidence that organic farming can improve environmental sustainability in terms of CO<sub>2</sub> emission, soil fertility and biodiversity (Reganold and Wachter, 2016). However, organic farming systems often result in low yields, requiring more land per unit of produce. Debates on the sustainability of greenhouse production can be contentious and often lack a scientific evidence base. For

heated, high-tech greenhouses, high CO<sub>2</sub> emissions are problematic, while for low-tech, unheated greenhouses in warmer climates, high nutrient emissions are a concern, as they account for at least 50% of the total environmental impacts of the systems (Torrellas *et al.*, 2012b). These weaknesses highlight the need for more evidence-based actions to improve current practices, which will thereby increase the knowledge about the sustainability of greenhouse production systems and may improve their performance. To achieve this, an internationally recognised benchmark is required to examine the current performance of greenhouse production systems.

In 2015 the United Nations (UN) introduced the 2030 Agenda for Sustainable Development (United Nations, 2015). With the defined 17 Sustainable Development Goals (SDGs) and the linked 169 targets, this agenda provides a practical framework for all countries and stakeholders to assess and improve global and local sustainability. In line with this agenda, a framework with indicators considering country-specific circumstances was adopted to assess current performance, monitor progress of sustainable development, inform policy, and facilitate actions by all stakeholders (Salvia *et al.*, 2019). However, such global approaches usually require modifications of the indicators for implementation at local scales (Hák *et al.*, 2016). According to Salvia *et al.* (2019), scientific research and knowledge-based assessments are essential for the successful implementation of the SDGs. To the best of our knowledge there are no existing detailed analyses of greenhouse production systems through the lens of SDGs.

The aim of this study was to assess the sustainability of four fresh vegetable greenhouse production systems through the lens of SDGs. Specifically, we aimed to: 1) Identify relevant SDGs to evaluate greenhouse production systems; 2) Evaluate the performance against SDG indicators using four different, orthogonal types of greenhouse production systems; 3) Identify the synergies, interlinkages and trade-offs between SDGs in the context of greenhouse production systems.

## 5.2. Methods

### ***Systems description***

Tomato production accounts for the largest area under greenhouses; it is also the crop for which data is most easily accessible. Hence, we used it as a representative crop for our study. To assess the role of technology adoption (high or low) and cultivation types (conventional or organic) on sustainability and production, we evaluated four different greenhouse production systems: (1) Conventional, high-tech production systems, which

refer to the conventional production in high-tech Venlo glasshouses with soilless cultivation (mostly on stone wool) in the Netherlands; (2) Conventional, low-tech production systems which refer to the conventional production in Parral-type plastic greenhouses in Spain; (3) Organic, high-tech production systems which refer to organic production in Venlo glasshouses in the Netherlands; (4) Organic, low-tech production systems which refer to the organic production in both Parral-type and multi-tunnel plastic greenhouses in Spain. The main features for each system are listed in Table 5.1.

**Table 5.1.** Main features of the four production systems evaluated through the lens of SDGs. The production systems include high-tech production systems in the Netherlands (conventional and organic) and low-tech production systems in Spain (conventional and organic).

	Conventional		Organic	
	High-tech	Low-tech	High-tech	Low-tech
Greenhouse structure	Venlo	Parral	Venlo	Parral and multi-tunnel
Growing medium	Stone wool	Soil	Soil	Soil
Heating	Yes	No	Yes	No
CO <sub>2</sub> enrichment	Yes	No	Yes	No
Artificial lighting	Yes/no <sup>1</sup>	No	Limited <sup>2</sup>	No
Fertigation system	Recirculating <sup>3</sup>	Free drainage	Free drainage	Free drainage
Main pest control	Natural enemies	Synthetic pesticides	Natural enemies	Natural enemies
Restriction for fertiliser	No	No	Yes <sup>4</sup>	Yes <sup>5</sup>

<sup>1</sup>Artificial lighting may be used in greenhouses to secure fruit production at times when sunlight is insufficient (Marcelis and Heuvelink, 2019).

<sup>2</sup>Use of artificial lighting in organic production systems is regulated by local legislations. It is allowed in North America but limited to only plant propagation in the Netherlands (Van Der Lans *et al.*, 2011).

<sup>3</sup>Collection and reuse of drain nutrient solution;

<sup>4,5</sup>Maximum manure application of 170 kg N ha<sup>-1</sup> year<sup>-1</sup> (EEC, 1991).

A literature-based study was conducted to collect and synthesise data for the evaluation. Most of the data came from greenhouse cultivation in the Netherlands and Spain, as these countries represent two typical climate regions and associated production methods. For example, production in parts of the U.S., Canada, China and Australia is comparable to the Netherlands, and a large part of the production in other Mediterranean countries and Central and South America is comparable to Spain (Marcelis and Heuvelink, 2019).

### Identifying relevant SDGs

To identify the SDGs that greenhouse production can potentially contribute to, we firstly studied the original agenda proposed by the UN (2015). With each SDG a list of targets has been defined that provide specific measurable objectives accounting for different national and stakeholders' circumstances. Relevant SDGs were identified through searching for connections between the pre-defined keywords by the UN under any target and greenhouse production systems. For example, target 2.1 under SDG2 ("zero hunger":

'ensure access by all people to safe and nutritious food all year around') was considered attainable through greenhouse production systems. Therefore, SDG2 was identified as one of the relevant SDGs for this study. The justifications for selecting other SDGs as being related to greenhouse production systems were given in sections 3.1–3.7.

### ***Selecting indicators and scoring approach***

To evaluate the performance of the four greenhouse production systems for each relevant SDG, indicators are required for corresponding targets such as the original proposed indicators by the UN (2019b). However, due to the lack of clear definition or quantifiable metric of the proposed indicators, we revised or reformulated suitable indicators in the current study. The indicator selection in our study was based on two principles: (1) fact-based relevance to the SDG targets and (2) data available for quantifiable metrics. Based on the data analysis for each indicator, the system that had the highest or lowest value (depending on the objective of the indicator) was considered to perform best for this indicator and was thus labelled with a plus symbol (+). For each SDG, the system that obtained "+" across most indicators was considered to perform best. For indicators relevant to targets under multiple SDGs, no weighing method was applied in the ranking of the different targets under SDGs.

## **5.3. Results**

In total seven SDGs were identified as the most relevant, including SDG2 (zero hunger), SDG3 (good health and well-being), SDG6 (clean water and sanitation), SDG7 (affordable and clean energy), SDG12 (responsible consumption and production), SDG14 (life below water) and SDG15 (life on land). While other SDGs may be affected by food production systems, such as SDG1 (no poverty) and SDG13 (climate actions), the specific mechanisms for achieving these changes in greenhouse production systems were more explicit in the seven SDGs identified, with measurable indicators available. Based on the relevant SDGs, in total 14 indicators (12 quantitative and 2 descriptive) were selected for the evaluation. Some indicators, such as land and water use, were used in the evaluation for multiple SDGs.

### ***SDG 2-Zero Hunger***

Greenhouse production contributed to several targets under SDG2 (zero hunger): nutritious and sufficient food available all year round for all people (Target 2.1), increase (double) agricultural productivity (Target 2.3, 2.4), and production (Target 2.4). The

availability of greenhouse tomatoes to consumers was assessed by the capability of supply and affordability of fresh tomatoes. Harvest season was longest in conventional, high-tech systems and shortest in organic, low-tech greenhouses (Table 5.2). Year-round harvest of tomatoes was only possible in high-tech heated greenhouse systems with supplementary light in Northern Europe and North America (Heuvelink, 2018; Raaphorst *et al.*, 2019). For low-tech greenhouses, the harvest season closely depended on the length of crop cycles, with a maximum period of 36 weeks (Valera-Martínez *et al.*, 2016). Therefore, low-tech greenhouses did not supply fresh tomatoes year around. For organic, high-tech systems in the Netherlands, the harvest season is about 25–33 weeks per year (Tittarelli *et al.*, 2017). Market prices were used as a measure for the affordability of the fresh tomatoes produced from each system. Based on the market prices in the Netherlands and Spain, organic greenhouse tomatoes are around 40–130% (Albert Heijn, 2020; Amsterdam Tips, 2020) and 40% (Fresh Plaza, 2016) more expensive than conventionally grown tomatoes. This limits the affordability of organic tomatoes and therefore their availability to all people. The higher market prices of organic tomatoes may be attributed to the higher production costs related to the extra labour and management involved in weed and pest control, and for nutrients (Pimentel, 1993; Clark *et al.*, 1999; Kaiser and Ernst, 2011). In addition, lower yields in organic systems may also contribute to higher market prices.

To evaluate agricultural productivity and production (Target 2.3, 2.4), annual tomato yield, water and land used for producing a unit of tomatoes were selected as relevant indicators. In general, high-tech systems showed a much higher productivity compared to low-tech systems (Table 5.2). With the same level of technology, the yields and productivity were higher in the greenhouses with conventional cultivation than organically grown systems. For example, the highest yield and productivity were observed in conventional, high-tech systems (Table 5.2). The tomato yield was 50–90 kg m<sup>-2</sup> in high-tech glasshouses where no supplementary light was used (Raaphorst *et al.*, 2019; Heuvelink *et al.*, 2020). However, yield was substantially higher when supplementary lighting was applied (90–100 kg m<sup>-2</sup>) (Raaphorst *et al.*, 2019; Heuvelink *et al.*, 2020), which is the situation for about 40% of the tomato production area in the Netherlands. Accordingly, land use for producing 100 kg tomatoes was the lowest in conventional, high-tech systems (Table 5.2), indicating the highest land use efficiency. In conventional, low-tech greenhouses, tomato yield was ca. 9–17 kg m<sup>-2</sup> (Valera-Martínez *et al.*, 2016) which is only about 10–34% of that in high-tech greenhouses. Therefore, yield per unit area in low-tech greenhouse was ca. 3–11 times lower than in high-tech greenhouses. High-tech greenhouses, where either 85% or

100% recirculation of nutrient solution was applied (Pronk *et al.*, 2007; Van Kooten *et al.*, 2008), used substantially less water to produce 1 kg of tomatoes (16 L and 14 L, respectively) than low-tech systems, which used 29 L on average (Torrellas *et al.*, 2012b).

For organic greenhouses, tomato yields were around 50 kg m<sup>-2</sup> in the Netherlands (Tittarelli *et al.*, 2017) and 6–15 kg m<sup>-2</sup> in Spain (Tittarelli *et al.*, 2017). The largest land use was observed in organic, low-tech greenhouses (7–17 m<sup>2</sup> are required to produce 100 kg tomatoes; Tittarelli *et al.*, 2017). For organic production in high-tech greenhouses water use (22 L kg<sup>-1</sup>; Pronk *et al.*, 2007) was slightly higher than in conventional, high-tech greenhouses but still much lower than for low-tech systems (Torrellas *et al.*, 2012b).

**Table 5.2.** Performance of four greenhouse systems as analysed through the lens of SDG 2-Zero Hunger. Data sources are indicated after each value. Plus (+) denotes the system(s) where the best performance was observed at corresponding indicators.

Targets	Indicator	Conventional		Organic		
		High-tech (without SL <sup>1</sup> )	High-Tech (with SL)	Low-Tech	High-Tech	Low-Tech
<b>2.1</b> By 2030, ensure access by all people to safe, nutritious and sufficient food all year round	Harvest season (weeks)	40–41 <sup>a</sup> +	48 <sup>a</sup> +	12–36 <sup>b</sup>	25–33 <sup>c</sup>	12 <sup>c</sup>
	Market price (€ kg <sup>-1</sup> )	0.83 <sup>d</sup>	0.83 <sup>2</sup>	0.76 <sup>e</sup> +	1.5 <sup>f</sup>	1.07 <sup>e</sup>
<b>2.3</b> By 2030, double the agricultural productivity	Yield (kg m <sup>-2</sup> year <sup>-1</sup> )	50–90 <sup>a</sup> +	90–100 <sup>a</sup> +	9–17 <sup>b</sup>	50 <sup>c</sup> +	6–15 <sup>c</sup>
<b>2.4</b> By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production	Land use (m <sup>2</sup> 100 kg <sup>-1</sup> )	1.1–2 +	1–1.1 +	5.9–11	2 +	6.7–16.7
	Water use (L kg <sup>-1</sup> )	14–16 <sup>g</sup> +	14–16 <sup>3</sup> +	29 <sup>h</sup>	22 <sup>i</sup>	> 29 <sup>4</sup>

<sup>1</sup> SL: Supplementary Lighting;

<sup>2</sup> Prices of tomatoes from conventional, high-tech greenhouses with SL was assumed to be same to that from greenhouses without SL.

<sup>3</sup> Water use from conventional, high-tech greenhouses with SL was assumed to be same to that from greenhouses without SL.

<sup>4</sup> Estimation was based on the lower yield in organic low-tech systems.

<sup>a</sup> Heuvelink, 2018; Raaphorst *et al.*, 2019; <sup>b</sup> Valera-Martinez *et al.*, 2016;

<sup>c</sup> Tittarelli *et al.*, 2017; <sup>d</sup> European Commission, 2020;

<sup>e</sup> Fresh Plaza, 2016; <sup>f</sup> Albert Heijn, 2020; Amsterdam Tips, 2020;

<sup>g</sup> Pronk *et al.*, 2007; Van Kooten *et al.*, 2008; <sup>h</sup> Torrellas *et al.*, 2012b; <sup>i</sup> Pronk *et al.*, 2007.

### **SDG 3-Good Health and Well-being**

Target 3.9 under SDG3 (good health and well-being) aims to reduce the number of deaths and illnesses from air, water, and soil pollution, hazardous chemicals, and contamination (Table 5.3). This target is relevant for our study, as the intensive fertilisation and the use of plant protection products (PPPs, mainly fungicides and insecticides) in greenhouse horticulture, like food production generally, often results in emissions to atmosphere, soil and water. The consequences of these emissions may either directly (e.g. drinking water) or indirectly (e.g. disrupting a food production network) influence human health (Carpenter, 2005).

Compared to other systems, N emissions from high-tech greenhouses with recirculation systems were the lowest, ranging from 64 to 107 kg N ha<sup>-1</sup> year<sup>-1</sup> (Pronk *et al.*, 2007), and can be eliminated when 100% of drain water is reused (Pronk *et al.*, 2007). According to Soto *et al.* (2015), N emissions from low-tech greenhouses were about 2–4 times that from high-tech greenhouses with recirculation. In organic, high-tech tomato production, average N-application was about double the crop demand, resulting in N emissions of around 700 kg N ha<sup>-1</sup> year<sup>-1</sup> (Voogt *et al.*, 2011). The N emissions for producing tomatoes in conventional, high-tech systems were 10 times lower per kg tomato yield than in conventional, low-tech and organic, high-tech systems. Next to N, phosphorus (P) emissions may also affect human health, mainly through undermining water quality (Carpenter, 2005; Yan *et al.*, 2013). Unlike N, phosphorus is very stable and immobile. Excessive P fertiliser is primarily stored in the soil and eventually lost through erosion or runoffs. Due to the lack of data, P emissions were not included as an indicator in this study. Nonetheless, P fertilisation is an important factor in the sustainable management of greenhouse production systems and should be actively managed and monitored. Regarding the use of PPPs, greenhouses with organic cultivation systems were considered to have near zero hazardous residues and emissions due to the prohibition of synthetic PPPs in these systems. In conventional, Dutch tomato production, the average total use of PPPs was 10 kg active ingredient ha<sup>-1</sup> (mainly fungicides; Montero *et al.*, 2011). The use of PPPs was substantially higher in low-tech systems, with 32 kg ha<sup>-1</sup> (Montero *et al.*, 2011).

**Table 5.3.** Performance of four greenhouse systems as analysed through the lens of SDG 3-Good Health and Well-being. Long dash denotes the absence of data. Data sources are indicated after each value. Plus (+) denotes the system(s) where the best performance was observed at corresponding indicators.

Target	Indicator	Conventional		Organic	
		High-Tech	Low-Tech	High-Tech	Low-Tech
3.9 By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination	N emission to water system (kg N ha <sup>-1</sup> year <sup>-1</sup> )	64-107 <sup>a</sup> +	234-262 <sup>b</sup>	709 <sup>c</sup>	—
	PPPs (kg active ingredients ha <sup>-1</sup> year <sup>-1</sup> )	10 <sup>d</sup>	32 <sup>d</sup>	Near zero +	Nero Zero +

<sup>a</sup> Pronk *et al.*, 2007; <sup>b</sup> Soto *et al.*, 2015; <sup>c</sup> Voogt *et al.*, 2011; <sup>d</sup> Montero *et al.*, 2011.

## SDG 6-Clean Water and Sanitation

SDG6 (clean water and sanitation) focuses on reducing pollution, eliminating dumping and minimising release of hazardous chemicals and materials, halving the proportion of untreated wastewater and increasing recycling and safe reuse globally (Target 6.3) and increasing water use efficiency (Target 6.4). Target 6.3 shows overlap with Target 3.9, with both focussing on minimising the release of hazardous chemicals. For Target 6.3, relevant indicators were N emission to water systems (which has been presented under SDG3; Table 5.3), the share of drain water re-used, and whether or not waste water was treated before being released to the environment (Table 5.4).

**Table 5.4.** Performance of four greenhouse systems as analysed through the lens of SDG 6-Clean Water and Sanitation. Data sources are indicated in superscripts after each value. Plus (+) denotes the system(s) where the best performance was observed at corresponding indicators.

Target	Indicator	Conventional		Organic	
		High-Tech	Low-Tech	High-Tech	Low-Tech
<b>6.3</b> By 2030, improve water quality by <u>reducing pollution, eliminating dumping and minimising release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse</u> globally	Proportion of recycling water used (%)	85 <sup>a</sup> +	0	0	0
	Treatment on discharges (yes/no)	Yes <sup>b</sup> +	No	No	No

<sup>a</sup> Pronk *et al.*, 2007; <sup>b</sup> Voogt *et al.*, 2013.

Collecting and reusing drain water can only be applied in high-tech, conventional greenhouses where soilless cultivation is applied, with around 85% of nutrients recycled (Pronk *et al.*, 2007). Likewise, it is only possible to treat wastewater in such systems. Discharge of nutrient solution is the major pathway of releasing emissions of nutrient and PPPs from greenhouses with soilless cultivation (Beerling *et al.*, 2014). In the Netherlands, greenhouse growers applying soilless cultivation are obligated to decrease the amount of discharge by maximising recirculation of nutrient solution, and purifying of discharge (Van Ruijven *et al.*, 2017). Dutch legislation has been set to guide growers to a stepwise reduction of emissions of nutrient and PPPs to zero (Beerling *et al.*, 2017).

The performance on water-use efficiency (Target 6.4) has also been presented under SDG2 (Table 5.2). The amount of water needed to produce 1 kg tomatoes was the lowest (most efficient) for conventional, high-tech greenhouse systems and highest in conventional, low-tech systems. Water use in organic, high-tech greenhouses in the

Netherlands was in between the levels used in conventional Dutch high-tech and Spanish low-tech systems.

### ***SDG 7-Affordable and Clean Energy***

Under SDG7 (affordable and clean energy), increasing the share of renewable energy use (Target 7.2) and doubling the increase in energy efficiency (Target 7.3) were considered relevant (Table 5.5). Table 5.5 shows that the share of renewable energy consumption was 17.4% of gross final energy consumption in Spain in 2018 (Red Eléctrica, 2018) which was more than double that of the Netherlands (8.6% in 2019; Statistics Netherlands, 2020). In the Netherlands, the main energy source in greenhouses is natural gas. Many growers apply cogeneration of heat and power (CHP, fed by natural gas), where the heat is used for heating the greenhouse and electricity is used for lighting or it is delivered to the grid. Most of these growers do not use renewable energy. Consequently, low-tech Spanish greenhouse systems use considerably less non-renewable energy than high-tech Dutch systems.

**Table 5.5.** Performance of four greenhouse systems as analysed through the lens of SDG 7-Affordable and Clean Energy. Data sources are indicated after each value. Plus (+) denotes the system(s) where the best performance was observed at corresponding indicators.

Targets	Indicator	Conventional			Organic		
		High-Tech (without CHP <sup>1</sup> )	High-Tech (with CHP)	Low-Tech	High-Tech (without CHP)	High-Tech (with CHP)	Low-Tech
<b>7.2</b> By 2030, increase substantially the share of renewable energy in the global energy mix	Share of renewable energy use in greenhouse systems (%)	8.6 <sup>a</sup>	0	17.4 <sup>b</sup> +	8.6	0	17.4 +
<b>7.3</b> By 2030, double the global rate of improvement in energy efficiency	Energy use <sup>2</sup> (MJ kg <sup>-1</sup> )	24 <sup>c</sup>	13 <sup>3; c</sup>	4 <sup>d</sup>	33 <sup>e</sup>	15 <sup>4</sup>	< 4 <sup>5</sup> +
	CO <sub>2</sub> emissions at farmgate <sup>6</sup> (kg CO <sub>2</sub> eq kg <sup>-1</sup> )	1.2 <sup>c</sup>	0.7 <sup>7; c</sup>	0.3 <sup>d</sup>	1.9 <sup>f</sup>	0.8 <sup>8; f</sup>	0.1 <sup>9</sup> +

<sup>1</sup> Combined heat and power;

<sup>2</sup> For all systems, energy use for seedling production, climate control and greenhouse operation, production of fertiliser and pesticides were included. For both conventional and organic low-tech greenhouses, energy use for greenhouse construction was additionally included, considering the lifespan of a greenhouse structure.

<sup>3</sup> Net energy use for tomato production, deducting the energy use for the excessive electricity transferred to national electricity grid;

<sup>4</sup> Net energy use for tomato production. Estimation was based on Vermeulen and Lans (2011) and Dorais *et al.* (2014);

<sup>5</sup> Estimation was based on Baptista *et al.* (2017) ;

<sup>6</sup> CO<sub>2</sub> emissions caused by greenhouse construction were only included in low-tech systems, not in high-tech ones. Methods for calculating CO<sub>2</sub> emissions were based on PAS 2050 (Blonk *et al.*, 2010) for high-tech systems and CML 2001 (Guinée, 2001) for low-tech systems;

<sup>7, 8</sup> Net CO<sub>2</sub> emissions for tomato production, deducting the CO<sub>2</sub> emissions of the excessive electricity transferred to national electricity grid.

<sup>a</sup> Statistics Netherlands, 2020;

<sup>b</sup> Red Eléctrica, 2018;

<sup>c</sup> Raaphorst *et al.*, 2019;

<sup>d</sup> Torrellas *et al.*, 2012a;

<sup>e</sup> Dorais *et al.*, 2014;

<sup>f</sup> Vermeulen and Lans, 2011;

<sup>9</sup> Baptista *et al.*, 2017.

The energy required to produce 1 kg tomatoes was used to assess energy use efficiency (Target 7.3). Equivalent CO<sub>2</sub> emission generated from producing 1 kg tomatoes was additionally used to indicate the environmental consequences of the energy use. In general, energy use and CO<sub>2</sub> emissions in low-tech greenhouses were much smaller than in high-tech systems. Per kg tomatoes, 4 MJ of energy was used in conventional, low-tech systems with an emission of 0.3 kg CO<sub>2</sub> eq (Torrellas *et al.*, 2012a), which was about 6 times lower than in high-tech systems. For organic, low-tech greenhouses in Spain, energy consumption was estimated to be lower compared with conventional, low-tech systems, assuming that less energy is required to produce organic fertilisers than synthetic fertiliser (Fadare *et al.*, 2010). Nonetheless, energy use for the production of organic fertiliser such as compost can be much higher than for synthetic fertiliser, greatly depending on the manufacturing processes (Walling and Vaneekhaute, 2020). For example, 1–10 kg CO<sub>2</sub> eq per kg is generated to produce of synthetic N fertiliser, but 1–850 kg CO<sub>2</sub> eq per kg may be emitted to produce of compost N fertiliser (Walling and Vaneekhaute, 2020). It indicates that fertiliser used in organic greenhouse systems can be critical to the environmental impacts.

In conventional, high-tech greenhouses without CHP, the energy required to produce 1 kg tomatoes was 24 MJ in the Netherlands with an emission of 1.2 kg CO<sub>2</sub> eq (Raaphorst *et al.*, 2019). However, energy use greatly depends on the requirement for greenhouse heating which is determined by local climate. In Quebec, Canada, energy use per kg tomatoes was considerably higher, namely 80 MJ with an emission of 5.8 kg CO<sub>2</sub> eq (Dorais *et al.*, 2014). In organic, high-tech greenhouses, as a result of lower yield, the energy required to produce 1 kg tomatoes was around 20–40% higher than in conventional systems, being 33 MJ kg<sup>-1</sup> (without CHP) in the Netherlands and 97 MJ kg<sup>-1</sup> in Quebec, Canada (Dorais *et al.*, 2014). For greenhouses using CHP, electricity production by CHP often exceeds the requirement for tomato production, thus it is transferred to national electricity grid. Therefore, CO<sub>2</sub> emissions for tomato production can in some instances be halved by using such offsets in both conventional and organic systems (Vermeulen and Lans, 2011; Raaphorst *et al.*, 2019). Further, the use of biomass energy for heating can also reduce the generation of CO<sub>2</sub> emissions, reaching up to an 86% reduction in an organic, high-tech greenhouse in Canada (Dorais *et al.*, 2014).

### **SDG 12-Responsible Consumption and Production**

To achieve SDG12 (responsible consumption and production), three targets were identified to be highly relevant to greenhouse production. As already assessed for SDG2

(zero hunger), achieving the efficient use of natural resources (Target 12.2), such as freshwater and land, is also essential for attaining SDG12. We already noted that water and land use efficiency were the highest in conventional, high-tech greenhouses (Table 5.2). There are strong linkages between SDG12 and SDG6 (clean water and sanitation), with both aiming to achieve sustainable and efficient water use (Target 12.2, Target 6.4), and sustainably manage chemicals and reduce their emissions to the environment (Target 12.4, Target 6.3). As demonstrated for SDG3 and SDG6, conventional, high-tech greenhouses with soil-less cultivation resulted in the lowest N emission to water systems (Table 5.3), owing to the recirculating nutrient management and wastewater treatment (Voogt *et al.*, 2013).

In addition to chemical release, reducing waste generation is also an important objective (Target 12.5) in achieving SDG12. In general, waste generation was the lowest in organic, high-tech greenhouses due to the long-lasting material with high recycling potential used in greenhouse infrastructure (glass) and no substrate waste. Conversely, waste generation from conventional, high-tech greenhouses was highest, owing to the used substrate and their bags (plastics), and soil coverage with plastic, that is applied in soilless cultivation systems. In terms of waste management, practices vary considerably from grower to grower, depending on various factors, such as costs and convenience. In a comparative study by Montero *et al.* (2011), both high- and low-tech systems showed the same recycling proportions of metals (100%), concrete (50%) and green biomass (50%). With respect to plastic waste, a large proportion (90%) was reported to be collected and recycled from low-tech systems (Montero *et al.*, 2011), indicating a better performance compared to that (50%) for conventional, high-tech systems. However, with the information only reported from one study, more information is required to objectively rank the performance of waste management between systems. Moreover, absolute values regarding the quantities of each type of waste are needed for better understanding of waste management. Used substrates like stone wool can be collected and recycled by substrate companies into raw material. In the Netherlands, it has been reported that around 90% of used stone wool is collected and recycled (Diara *et al.*, 2012). Likewise, this rate cannot represent the average situation of substrate recycling in the Netherlands.

### **SDG 14-Life below Water**

One of the aims under SDG14 (life below water) is to conserve the oceans, seas, and marine resources. To achieve this, marine pollution from land-based activities needs to firstly be reduced (Target 14.1). Leached irrigation water from soil-based systems or

discharges from soilless cultivation contain high concentrations of fertilisers (primarily P and N), which is one of major sources of nutrient losses to aquatic systems (Carpenter, 2005; Kalkhajeh *et al.*, 2017). This may cause excessive algal growth and anoxic events, called eutrophication, a persistent environmental problem in freshwater and marine systems (Mugnozza *et al.*, 2007; Torrellas *et al.*, 2012a). To assess this issue, “eutrophication potential” modelling using the CML2001 method (Guinée, 2001) was selected as an indicator to estimate the potential effects of N and P fertilisation on both freshwater and marine systems. “N emission to water systems” was additionally used to indicate other potential impacts on marine systems than eutrophication. Furthermore, the rapid increase in anthropogenic atmospheric CO<sub>2</sub> concentration has directly led to declining ocean pH that in turn affects ocean chemistry from the surface water. Such a series of alterations causes ocean acidification (Guinotte and Fabry, 2008). As contributors to CO<sub>2</sub> emissions, greenhouse production systems must also minimise their impacts on ocean acidification (Target 14.3). Hence, CO<sub>2</sub> emission generated from the greenhouse production was taken as the indicator to assess ocean acidification potential, which has been indicated under SDG7 (affordable and clean energy).

We already addressed the issue of N emission via drainage water or SDG3 (good health and well-being), SDG6 (clean water and sanitation) and SDG12 (responsible consumption and production). Conventional, high-tech greenhouses with soilless cultivation systems resulted in the lowest N emission (Table 5.3). Further, conventional, high-tech systems (without use of CHP) showed a lower eutrophication potential (ca. 0.63 g PO<sub>4</sub><sup>3-</sup> eq kg<sup>-1</sup> tomatoes), being 20% lower than in conventional, low-tech systems (Torrellas *et al.*, 2012b). In organic, high-tech systems, the eutrophication potential was estimated to be higher than in conventional, high-tech systems, due to lower yields (Tittarelli *et al.*, 2017) and higher nutrient losses (Voogt *et al.*, 2011).

### **SDG 15-Life on Land**

SDG15 (life on land) is relevant to greenhouse systems as it mentions that intensive use of water and land in agricultural activities is becoming a threat to our ecosystems, resulting in rising freshwater depletion (Target 15.1), increased deforestation, soil degradation, desertification (Target 15.3) and loss of biodiversity (Target 15.5). Water use in each system was again used to evaluate the sustainability of using terrestrial and inland freshwater ecosystems and their services (Target 15.1). Next to water use, efficient land use could also help conserve and restore water in the environment, thus potentially combating desertification (Target 15.3). SDG15 presented connections with SDG2 (zero

hunger) and SDG12 (responsible consumption and production), all aiming to achieve efficient water and land use. Results on water and land use have been presented in Table 5.2.

The emission of PPPs could also potentially affect the loss of biodiversity (such as insects) and was therefore used to assess Target 15.5. As indicated under SDG3 (good health and well-being), greenhouses with organic cultivation had near zero use of synthetic PPPs (Table 5.3) and thus performed better in terms of maintaining the biodiversity compared with conventional greenhouse systems.

## 5.4. Discussion

### *Current performance of four greenhouse production systems*

This study proposes a framework that enables a more holistic evaluation of the performance of greenhouse production systems against rigorous sustainability indicators. Our framework includes environmental impacts as well as social aspects of the SDGs (SDG2-zero hunger and SDG3-good health and well-being). Social components often lack attention in environmental studies on greenhouse production systems (Torrellas *et al.*, 2012a,b; Khoshnevisan *et al.*, 2014; Dias *et al.*, 2017). Here we applied a scoring system that awards positive scores when performing best out of the four greenhouse production systems through an SDG lens (Table 5.6). Among all systems, conventional, high-tech greenhouse systems obtained positive scores on eight indicators of the 14 assessed, showing the best performance overall for achieving sustainable development. This is followed by organic, low-tech systems (positive scores on four indicators). Conventional, low-tech and organic, high-tech systems were found to contribute less towards achieving the SDGs (positive scores on two indicators).

**Table 5.6.** Summary of scores on indicators for four greenhouse systems. Plus (+) denotes the system(s) where the best performance was observed at corresponding indicators.

SDGs	Indicators	Conventional		Organic	
		High-tech	Low-tech	High-tech	Low-tech
2	Length of harvest season (weeks)	+			
2	Market price (€ kg <sup>-1</sup> )		+		
2	Yield (kg m <sup>-2</sup> )	+			
2, 12, 15	Land use (m <sup>2</sup> 100 kg <sup>-1</sup> )	+			
2, 6, 12, 15	Water use (L kg <sup>-1</sup> )	+			
3, 6, 12, 14	N emission to water systems (kg ha <sup>-1</sup> year <sup>-1</sup> )	+			
3, 15	PPPs (kg active ingredients ha <sup>-1</sup> year <sup>-1</sup> )			+	+
6	Share of recycling water used (%)	+			
6, 12	Treatment on discharges	+			
7	Share of renewable energy use (%)		+		+

7	Energy use (MJ kg <sup>-1</sup> )				+
7, 14	CO <sub>2</sub> emissions at farmgate (g CO <sub>2</sub> eq kg <sup>-1</sup> )				+
12	<i>Waste generation</i>			+	
14	Eutrophication potential (g PO <sub>4</sub> <sup>3-</sup> eq kg <sup>-1</sup> )	+			
<b>Total number of obtained best scores</b>		<b>8</b>	<b>2</b>	<b>2</b>	<b>4</b>

In high-tech greenhouses with soilless cultivation, the higher yields and higher resource use efficiencies are guaranteed due to the advanced technologies adopted (Marcelis *et al.*, 2019). The high productivity in such systems has been documented in several studies (Antón *et al.*, 2012; Torrellas *et al.*, 2012b; Page *et al.*, 2014; Dias *et al.*, 2017). Compared to soilless systems, organic, high-tech greenhouses result in lower yields, which is in agreement with a number of comparative studies between conventional and organic production systems (De Ponti *et al.*, 2012). Note that here organic cultivation implies that the cultivation was soil-based as in many countries soilless would not be considered organic. Yield gaps between conventional and organic cultivation are caused by multiple factors, including crop variety and management practices (Marcelis and Heuvelink, 2019). The ban of synthetic pesticides for use in organic greenhouses makes a positive contribution towards meeting SDG3 (good health and well-being) and SDG15 (life on land) goals. Furthermore, application of recirculating nutrient management leads to higher water and nutrient use efficiencies and can even result in zero nutrient emissions through 100% recirculation (Putra and Yuliando, 2015; Ruffi-Salís *et al.*, 2020). This shows that significant contributions towards improving environmental sustainability are achievable (Marcelis and Heuvelink, 2019). It is worth noting that these advanced climate control and cultivation systems require high capital investment and operating costs (Vermeulen, 2010, 2016; Torrellas *et al.*, 2012b; Dorais *et al.*, 2014), resulting in a higher production cost compared to low-tech systems (Marcelis and Heuvelink, 2019). In light of the large energy consumption of the construction of greenhouses, we recommend that this impact be included in any further research (Antón *et al.*, 2012).

In addition to benefits, we identified that the use of fossil-based energy for heating and the associated high CO<sub>2</sub> emissions in high-tech production systems have negative impacts on the performance measures for energy use (SDG7) and marine ecosystems (SDG14). In life-cycle studies of greenhouse production, the potential environmental impacts on marine systems, via for instance, ocean acidification, were barely assessed and discussed (Antón *et al.*, 2012; Dias *et al.*, 2017). However, based on SDG14 (life below water), high-tech greenhouses show a big impact on potential ocean acidification due to the higher CO<sub>2</sub> emissions. In comparison with conventional systems, organic, high-tech greenhouses resulted in higher environmental impacts per unit of tomatoes, such as CO<sub>2</sub> emission and

eutrophication, suggesting a lower contribution for achieving sustainability. This is contrast to the perception of consumers (Aldanondo-Ochoa and Almansa-Sáez, 2009) and possibly even producers and other actors along the food value chain. The meta-analysis study by Tuomisto *et al.* (2012) found that organic farming systems showed benefits in regard to environmental sustainability per unit of area, but not necessarily per unit of product. However, our study (Table 5.3) shows that N emissions per unit of area as well as per unit of produce in organic, high-tech systems were much higher than in conventional, high-tech systems.

We found that the composition of waste generation is associated with the level of technology adopted in the greenhouse. High-tech greenhouses generally produce more types of waste (e.g. substrate) than low-tech systems. This disadvantage might be tackled by making use of this waste after minimal processing, as inputs for other production systems. For conventional, high-tech systems, yearly waste generation of, for instance, used stone wool ( $2 \text{ t ha}^{-1} \text{ year}^{-1}$ ) (Stanghellini *et al.*, 2003) needs to be reduced by either extending its life span or increasing the availability of its recycling service regionally and globally (Kool and Blonk, 2011). In some cases, the environmental impact of recycling used stone wool may be even greater than that of disposing of it in landfill (Kool and Blonk, 2011). This suggests that recycling is not always the best solution for waste management.

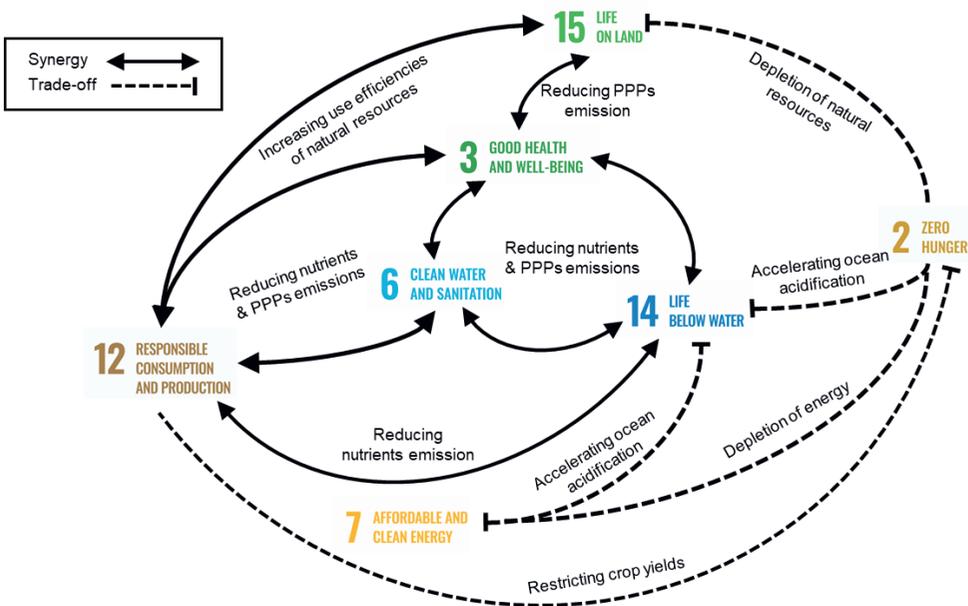
For greenhouses with soil-based cultivation systems, improving water use efficiency and reducing nutrient losses are the main challenges for attaining most of the relevant SDG goals. This is especially important in areas where freshwater is scarce, e.g. Almeria in the south of Spain (Muñoz *et al.*, 2010). In Spain, eutrophication due to nutrient losses is a serious problem caused by over-application of fertilisers and unmitigated, free drainage associated with irrigation in soil-based cultivation systems (Torrellas *et al.*, 2012b). As a consequence, local water bodies are heavily polluted by nitrates (European Commission, 2018) and the entire greenhouse production area around Almeria in Spain has been classified as a Nitrate Vulnerable Zone by the European Union.

Although 90% of plastics used in conventional, low-tech greenhouses can be reused (Torrellas *et al.*, 2012a), the amount of plastics used in these systems is still very high ( $2.4 \text{ t ha}^{-1} \text{ year}^{-1}$ ; Montero *et al.*, 2011). Further, plastic used for mulching is more difficult to recycle than plastic covers due to dirt contamination. In fact, only 30% of this type of plastic is recycled (Montero *et al.*, 2011), resulting in large quantities of plastic waste from greenhouses being dumped in the coastal areas near Almeria and the Mediterranean Sea,

endangering marine species and negatively impacting fisheries and even human health (Cózar *et al.*, 2015).

### Synergies and trade-offs between SDGs

SDG2 (zero hunger) is fundamental to achieve all SDGs (Food and Agriculture Organisation, 2016). However, trade-offs amongst goals and sub-goals are inevitable and require informed and deliberate choices by decision-makers (Figure 5.1). Antle and Valdivia (2020) point out that the scale, scope, and complexity of agri-food systems and their linkages to natural and human systems mean that as societies strive to achieve SDGs, there will be inevitable trade-offs among and between key impact areas such as, for instance, nutrition and food security; gender equality, youth, and social inclusion or climate adaptation, GHG emissions reduction; environmental health and biodiversity. For example, in some areas, food production needs to be substantially increased to meet consumer needs. This, however, also increases the use of natural resources and drives GHG emissions (SDG14: life below water and SDG15: life on land) (Nilsson *et al.*, 2016; Pradhan *et al.*, 2017; Singh *et al.*, 2018), which is also showed in the current study (Figure 5.1).



**Figure 5.1.** Identified synergies and trade-offs between seven selected SDGs in the case of greenhouse tomato production. Solid line with arrows denotes synergies, dense dash line with single block end indicates trade-offs. For example, synergies were identified among SDG3 (good health and well-being), SDG6 (clean water and sanitation), SDG14 (life below water) and SDG12

(responsible consumption and production), owing to common aim of reducing the emissions of either nutrient or plant protection products (PPP). Trade-offs were found between SDG2 (zero hunger) and SDG7 (affordable and clean energy), SDG12, SDG4, SDG15. For example, the achievement of SDG12 may lead to the reduction in crop yields that is central target under SDG2; meeting SDG2 consumes natural resources, which therefore causes negative impacts on nature and biodiversity.

In the current study, SDG12 (responsible consumption and production) is a prerequisite for achieving the sustainable development of greenhouse production, due to its positive associations with other SDGs (Figure 5.1). For example, efficient use of natural resources and reducing and managing chemical emissions are two main components to achieve SDG12 (Figure 5.1). These also are the keys for maintaining good health (SDG3), freshwater ecosystems (SDG6, SDG15) and marine systems (SDG14), and achieving a land degradation-neutral world (SDG15). However, the achievement of SDG12 may restrict the crop productivity which is the core of eliminating hunger (SDG2). Some researchers have stated that interactions between SDGs differ with the context of the evaluation (Pradhan *et al.*, 2017), a finding supported by Antle and Valdivia (2020).

### **Reviewing selected indicators**

The results of our evaluation are based on an a priori choice of the indicators we selected. The selection of different indicators influences results as mentioned also by Miola and Schiltz (2019) who measured SDG-based performance at country level. It is also worth noting that our method of scoring indicators represents only one, preliminary assessment of the comparison between the four systems. The summary scores in Table 5.6, for instance, provide no indication on whether alternative systems performed marginally or substantially below the standard set by the highest ranked system. Such an analysis should be conducted before making investment or policy decisions based on this information.

The present study provides useful, actionable information and evidence for the greenhouse production sector that can be used to inform decision making at policy as well as management levels. We identified that data availability is the most limiting factor for indicator selection. Most data sources for indicator quantification were from studies based on life-cycle approaches, suggesting it would be useful to integrate life cycle assessment into the performance evaluation of the SDGs framework. Due to data limitations, we had to use a descriptive indicator to assess Target 12.5 (waste generations), mainly because the quantities of each waste generation are not available for greenhouse production. Moreover, a few indicators may deviate from those originally proposed by the UN. For

instance, to evaluate the improvement in energy efficiency for SDG7 (affordable and clean energy), the changes in energy use efficiencies over time should be used as an indicator. However, such data are only available for high-tech greenhouses in the Netherlands, making it impossible to compare with the systems in Spain. An implicit assumption in this evaluation is that each SDG and indicator is of equal importance to meet the sustainability of greenhouse production systems. Hence, we did not attempt to weigh the chosen indicators as this is ultimately the responsibility of the decision-makers as the key stakeholders and end users of this study (Ahi *et al.*, 2018) and opinions about the importance of various trade-offs will inevitably differ (Allen *et al.*, 2019). For example, for greenhouse growers are likely to prioritise yield and productivity improvements over the health of marine ecosystems. To accommodate specific applications, our methods could be suitably adapted. However, our study, and trade-off analyses more generally, can help with building cooperation and trust amongst diverse stakeholders and decision-makers, who often have very divergent objectives (Antle and Valdivia, 2020). It would be helpful if future research would explicitly build monitoring and evaluation into their project design so that the appropriate data are collected that will allow for quantitative assessments of progress against SDGs. This will require the involvement of staff trained in the use of these tools (Ahi *et al.*, 2018).

### **Outlook to 2030**

Based on current technological trends, high-tech greenhouse systems will remain the most efficient systems for water and land use. Their ability to substantially extend the harvest season can make an important contribution towards achieving SDG2 (zero hunger), SDG12 (responsible consumption and production) and SDG15 (life on land). Since yields are already very high in conventional, high-tech systems (at present up to about 90 kg tomatoes per m<sup>2</sup>; Marcelis *et al.*, 2019), there is more potential for low-tech systems to substantially increase their productivity. To comply with the Dutch regulation targeting zero emissions of nutrients and PPPs from greenhouses by 2027, growers have actively reduced N emission (Beerling *et al.*, 2017), and are expected to reduce the N emission to zero by 2030. It has been shown that through using advanced techniques (ozone and UV treatment; Voogt *et al.*, 2013), residues of PPPs can be removed with 98% effectiveness (Van Ruijven *et al.*, 2017). For soil-based greenhouses, the most effective way of reducing N emissions is to apply nutrients and water with more precision. However, it is very unlikely that N emissions from soil-based cultivation systems can be eliminated. Both zero emission of nutrient and pesticide residue can be achieved through 100% re-use of drain

water in conventional, high-tech greenhouses (Beerling *et al.*, 2017). In the Netherlands, conventional, high-tech greenhouse technologies have considerable potential of contributing towards achieving SDG3 targets (good health and well-being), SDG6 targets (clean water and sanitation) and some targets under SDG12 (responsible consumption and production). However, fossil fuel-based energy use for greenhouse heating will remain an environmental concern in high-tech systems regardless of the application of artificial lighting, even with possible increases in the use of renewable energy (e.g. all electric greenhouses; Ministry of Economic Affairs of the Netherlands, 2016).

### **5.5. Conclusions**

Our study comprehensively assesses the sustainability of greenhouse production systems through the lens of SDGs. Water use and N emissions are the most frequently used sustainability indicators in measuring progress towards achieving several SDGs. Based on seven SDGs and 14 indicators, we conclude that high-tech greenhouses with soilless cultivation, where recirculation of drain water is obligatory, substantially contribute to achieving SDGs. High fossil-based energy use is the major environmental burden in high-tech systems, and high water use and N losses are the main contributors to environmental impacts of soil-based greenhouse systems. High-tech systems with organic cultivation present limited environmental benefits, which should be considered for future innovations in organic food production. There are clear synergies identified between SDG12 (responsible consumption and production) and other SDGs. SDG2 (zero hunger) shows trade-offs with most SDGs. This study provides method and a baseline to evaluate the sustainability performance of greenhouse production systems against the SDGs, which adds to the scientific evidence for decision making in greenhouse production sector; the study might also be helpful for other agri-food systems in addressing the SDGs. Future studies are encouraged to collaborate with experts from other disciplines and different stakeholders to collect sufficient information for further implementation of SDGs.

# **CHAPTER 6**

## **General discussion**

Dianfan Zhou

*“Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs.”*

*Brundtland Report, 1987*

## **6.1. Introduction**

A wide range of approaches, consisting of various frameworks, methods, indicators and metrics have been proposed and discussed for sustainability assessment in the agri-food sector over the past decades (Binder *et al.*, 2010; Arulnathan *et al.*, 2020; Chopin *et al.*, 2021). This thesis explores new insights derived from these existing approaches and proposed and implements an integrated analytical framework, to evaluate their suitability for assess sustainable development (SD) in greenhouse production systems, in terms of comprehensiveness and thus usefulness (e.g. sustainability dimensions and themes covered, system boundaries) and ease for potential end users.

In this thesis, four studies, described in four chapters, were conducted to gain a comprehensive understanding of the sustainability of greenhouse tomato production. Firstly, in Chapter 2, I reviewed the literature on existing approaches that have been applied in sustainability evaluation of either greenhouse production systems or open-field agriculture for their potential application specifically for assessing the SD of greenhouse production systems. The review highlights a lack of thorough, quantitative assessments for sustainability in greenhouse production systems. Specifically, there is limited coverage of social dimension and a consensus on indicators for such assessments is lacking. However, environmental sustainability and resource use have attracted considerable attention from researchers in the field of greenhouse production systems. Therefore, in Chapter 3, I employed a quantitative synthesis to study the effects of water management and nitrogen (N) fertiliser supply in greenhouse (primarily soil-based) and field production systems through compiling data on tomato yield, water use efficiency (WUE) and N fertiliser use efficiency (NUE) from 46 studies at a global scale.

In Chapter 4, I conducted a cradle-to-farmgate life cycle assessment (LCA) on three high-tech, heated, small-scale, commercial greenhouses in Australia. The aim was to evaluate and compare the environmental sustainability of fresh tomatoes produced from different systems, with a special focus on the use of different energy sources for greenhouse heating and impacts of water use on the condition of local freshwater resources.

In support of the outcomes from Chapter 3 and Chapter 4, I devised an integrated framework (Chapter 5) to assess the SD of greenhouse production systems from environmental, economic and social aspects, aligning with the Sustainable Development Goals (SDGs) of the United Nations (UN).

In the following sections, I discuss the main results obtained in my studies (Section 6.2) and compare the usefulness of different methods of assessing SD (Section 6.3). Additionally, I explore the practical implications for greenhouse management (Section 6.3) and policy making (Section 6.4). Furthermore, I highlight the main scientific contributions and limitations of this thesis work in Section 6.5, then provide recommendations for future research (Section 6.6). This is complemented by the final conclusions of this thesis (Section 6.7).

## **6.2. Approaches for sustainability assessments**

### ***Critical themes and system boundaries for sustainability assessment***

Management of water and nitrogen (N) are major determinants of SD in intensive greenhouse production, influencing environmental, economic, and social dimensions of sustainability. In this thesis, the effective use of resources such as water and N fertiliser was applied as an indicator for sustainability assessments and was therefore evaluated across three different approaches in Chapters 3–5 (Table 6.1). The quantitative synthesis in Chapter 3 evaluated the effects of water management and N fertiliser use with most data derived from soil-based greenhouse systems at a global scale. Datasets derived from 34 field and 12 greenhouse systems were analysed and this revealed that greenhouse cultivation resulted on average in a 45% higher tomato yield, 104% higher WUE and 45% higher NUE compared with field production (Chapter 3). Regarding water-saving practices, the analysis in Chapter 3 indicated that on average 32% lower total water input required for producing per unit of tomatoes in greenhouse systems than in field production. A further analysis on the effects of deficit irrigation within a range of 70–100% crop evapotranspiration (ET) indicated more profound responses of tomato yield and WUE to changes in the degree of deficit irrigation under greenhouse cultivation than field production (Chapter 3).

In comparison with the quantitative synthesis on WUE and NUE at farm level (Chapter 3), the LCA study (Chapter 4) provides a more comprehensive understanding of environmental sustainability with an expanded study boundary including activities both on-site and off-site greenhouses. For the impact of water use For the impact of water use I

assessed not only the quantity of water used for irrigation but also the potential effects, such as freshwater scarcity, over the life cycle of tomatoes on associated watersheds and river basins. For instance, the LCA revealed that use of 1 kg freshwater in water-scarce regions (e.g. South Australia) could aggravate the scarcity of local watersheds compared to freshwater-abundant regions (e.g. the Netherlands). This suggests that the environmental impact of water use is contingent on both the quantity of water use and the geographical location where the water was extracted (Pfister *et al.*, 2009).

In addition to the impact on water quantity, LCA approach provides estimation of potential impacts on water quality, such as marine and freshwater eutrophication. These impacts are directly associated with losses of fertiliser, particularly N and P fertilisers. In the indicator-based framework proposed in Chapter 5, water and nutrient management were assessed by the indicators adapted from the quantitative synthesis (water use) and LCA (N emissions to aquatic systems, potential eutrophication) combined with management practices, such as use of recycling water and treatment on discharges (Table 6.1).

Comparing four types of greenhouse systems where cultivation type (conventional or organic) and the level of technologies adopted were considered (Table 6.1), it was found that conventional, high-tech, soilless greenhouse cultivation with recirculation performs better in terms of water and nutrient management than the three soil-based greenhouse systems (Table 6.1) (Chapter 5).

**Table 6.1.** Comparative assessment of water and nitrogen fertiliser use across different greenhouse tomato production systems.

Approaches & system boundaries	Critical themes	Types of greenhouse system assessed
<p><b>Chapter 3-</b>Quantitative synthesis: During production at greenhouse site</p>	<p><b>Water</b> <u>Water use efficiency (kg m<sup>-3</sup>):</u> kg tomatoes per m<sup>3</sup> total water input (sum of irrigation and rainfall)</p>	<p><b>N fertiliser</b> <u>N fertiliser use efficiency (kg kg<sup>-1</sup> N):</u> kg tomatoes per kg N fertiliser supplied</p> <p>Low-tech greenhouses with soil-based cultivation</p>
<p><b>Chapter 4-</b>Potential environmental impact categories/indicators: From pre-production to post-production</p>	<p><u>Water use (L kg<sup>-1</sup>):</u> Freshwater use for irrigation per kg tomatoes</p> <p><u>Water scarcity footprint (L H<sub>2</sub>O eq kg<sup>-1</sup>):</u> Impact of freshwater use on sourced watersheds and river basins over the life cycle of per kg tomatoes</p>	<p><u>Eutrophication (kg N eq kg<sup>-1</sup>):</u> Dissolved inorganic N increase in marine water cause potential marine eutrophication per kg tomatoes</p> <p>High-tech, heated greenhouses with soilless cultivation</p>
<p><b>Chapter 5-</b>Indicator-based framework based on UNSDGs: During production at greenhouse site</p>	<p><u>Water use (L kg<sup>-1</sup>):</u> Water use for irrigation per kg tomatoes</p> <p><u>Share of recycling water used (%):</u> Proportion of recycling water used in the cultivation system</p>	<p><u>N emissions to aquatic systems (kg N ha<sup>-1</sup> year<sup>-1</sup>):</u> kg N losses via leaching and drainage to water system per hectare greenhouse per year</p> <p><u>Treatment on discharges (yes/no):</u> Whether or not purification treatment is applied before discharges released to the environment</p> <p>Conventional high-tech, heated greenhouses with soilless cultivation</p> <p>Conventional low-tech greenhouses with soil-based cultivation</p> <p>Organic high-tech, heated greenhouse with soil-based cultivation</p> <p>Organic low-tech greenhouses with soil-based cultivation</p>

In addition to water and N fertiliser use, several other sustainability themes were identified, such as energy use, greenhouse infrastructure and waste disposal, that are also critical for the SD of greenhouse production. For example, waste generation and disposal are important themes in greenhouse production as relevant issues being increasingly outlined in various types of greenhouse systems (Sayadi-Gmada *et al.*, 2020; Castillo-Díaz *et al.*, 2021; Van Tuyll *et al.*, 2022). Whereas high-tech, heated greenhouses require more raw materials and energy for their construction than low-tech plastic greenhouses, and substantially more energy for heating, particularly in cool climatic regions, such as the Netherlands and North America. For my thesis, I selected multiple themes to obtain comparisons of sustainability performance between different greenhouse systems, providing a comprehensive picture of this performance for greenhouse production in general. With the LCA approach in Chapter 4 and the indicator-based SDGs framework in Chapter 5, multiple themes and their interconnections can be assessed. In line with previous studies (Page *et al.*, 2012, 2014; Torrellas *et al.*, 2012b; Dias *et al.*, 2017), the LCA showed that greenhouse heating, fertiliser production, and greenhouse structure were major burdens to multiple environmental impacts in heated greenhouse production systems (Chapter 4). With respect to the use of renewable energy sources for greenhouse heating, the LCA showed that using wood biomass can be a feasible solution for mitigating GHG emissions but meanwhile increases the risk of air pollutants, such as fine particle matter (e.g. PM<sub>2.5</sub>).

By defining new indicators and adapting the indicators included in the quantitative synthesis and LCA analysis, I proposed an analytical framework based on the UN SDGs to evaluate the SD from multiple dimensions (Table 6.2). In addition to resource use and their impacts, the indicators within the proposed SDGs framework incorporate practice management (e.g. reuse of drainage water) in analysing the overall performance of greenhouse production. Also, additional themes, such as land use and application of pesticides, have been used to expand the scope of the assessment, allowing a system-wide comparison of various cultivation systems (e.g. organic farming) across a range of geographical and temporal scales (e.g. climate). However, limited data is available to assess the social dimensions of greenhouse production, as highlighted in Chapter 2. This gap makes it challenging to incorporate crucial themes, including working conditions and labour sources, which are essential pieces of information needed for decision-making, especially in the context of subsidies.

**Table 6.2.** Critical themes and related indicators and metrics that were incorporated for assessing the contributions of greenhouse tomato production to the achievements of relevant Sustainable Development Goals in Chapter 5.

<b>Critical themes</b>	<b>Indicators and metrics</b>	<b>Sources</b>	<b>Sustainability coverage</b>
Productivity	Length of harvest season (weeks) Yield (kg m <sup>-2</sup> )	Proposed in this thesis Proposed in this thesis	Economy & society Economy & society
Land occupation	Land use (m <sup>2</sup> 100 kg <sup>-1</sup> )	Adapted from LCA <sup>1</sup>	Economy & environment
Water use	Water use (L kg <sup>-1</sup> ) Share of recycling water used (%)	Adapted from QS <sup>2</sup> indicators Proposed in this thesis	Economy & environment Economy & environment
Energy use for heating	Energy use (MJ kg <sup>-1</sup> ) CO <sub>2</sub> emissions at farm gate (g CO <sub>2</sub> eq kg <sup>-1</sup> ) Share of renewable energy use (%)	Adapted from LCA Adapted from LCA Proposed in this thesis	Economy & environment Environment Environment
Nitrogen fertiliser use	N emissions to water system (kg N ha <sup>-1</sup> year <sup>-1</sup> ) Treatment on discharges (yes/no):	Adapted from LCA Proposed in this thesis	Environment Environment & society
Phosphorus fertiliser use	Eutrophication potential (g PO <sub>4</sub> <sup>3-</sup> eq kg <sup>-1</sup> )	LCA	Environment
Plant protection products use	Application rate of plant production products (kg active ingredients ha <sup>-1</sup> year <sup>-1</sup> )	Proposed in this thesis	Environment & society
Disposal of waste	Composition of waste generation and its management	Adapted from LCA	Environment

<sup>1</sup> Life cycle assessment; <sup>2</sup> Quantitative synthesis.

### ***Ease and usefulness of different indicators and methods for assessing SD***

All three approaches assessed in this thesis provide valuable information covering a broad range of perspectives. However, when balancing the ease of use with the usefulness associated with the complexity of the method, trade-offs inevitably occur (De Olde *et al.*, 2018; Arulnathan *et al.*, 2020; Talukder *et al.*, 2020).

For this work the ease of sustainability assessment was primarily constrained by data acquisition for the quantitative synthesis (Chapter 3) and LCA (Chapter 4). I did not foresee that this data acquisition would become the most time-consuming phase of my entire thesis research (Table 6.3), although it is consistent with reports on time constraints and data availability for sustainability assessments in agri-food systems (Schader *et al.*, 2014; Kelly *et al.*, 2018). The nature of a quantitative synthesis necessitates a large quantity of data to be extracted from publications at the farm level, requiring the application of multiple statistical techniques. Hence, these approaches are not commonly used outside of a research environment. Regarding the proposed indicator-based SDGs framework (Chapter 5), the time needed for data collection was relatively low, as a considerable amount of data was collected from previous chapters. Nonetheless, in practice, implementations of sustainability assessment can consume much time of both investigators and farmers, being up to 9 hrs for one single farm (De Olde *et al.*, 2016). This is widely considered as a main barrier hindering the implementation of sustainability assessment at the farm level (De Olde *et al.*, 2016; Whitehead *et al.*, 2020; Chopin *et al.*, 2021).

**Table 6.3.** Ease and usefulness of three approaches adopted for sustainability assessment in greenhouse tomato production. Plus (+) and minus (-) denote a high (relatively easier or useful) and low degree (relatively less easy or useful) of corresponding aspects, respectively.

Methods	Ease			Usefulness			Groups involved
	Data sources	Data acquisition	Complexity of analysis	Scalability	Sustainability coverage	Themes included	
<b>Chapter 3-</b> quantitative synthesis on yield, WUE <sup>1</sup> and NUE <sup>2</sup>	Published studies	+	+	+	Economy & environment	Water Nutrients	Researchers
<b>Chapter 4-LCA</b> <sup>3</sup>	Interviews with commercial greenhouse growers & upstream suppliers	-	+	-	Environment	Water Nutrients Energy GHG <sup>5</sup> emissions Air pollution Waste	Researchers Stakeholders involved in the supply chain
<b>Chapter 5-SDGs</b> <sup>4</sup> framework	Published studies Government papers Company reports	+	+	+	Economy, environment & society	Land Water Nutrients Energy GHG <sup>5</sup> emissions PPPs <sup>6</sup> Waste	Researchers Stakeholders involved in the supply chain

<sup>1</sup> Water use efficiency; <sup>2</sup> Nitrogen fertiliser use efficiency; <sup>3</sup> Life cycle assessment; <sup>4</sup> Sustainable Development Goals; <sup>5</sup> Greenhouse gas; <sup>6</sup> Plant protection products.

The data sources used in sustainability assessment play a crucial role in determining the usefulness of the adopted approach. The quantitative synthesis in Chapter 3 mainly made use of data derived from studies focusing on optimisation of crop yield, water and N use. Such experimental-based data may not reflect the actual crop productivity and efficiencies of water and N use in commercial greenhouses but can provide science-based evidence on potential interactions between water and N use for a type of greenhouse system (Chapter 3).

WUE and NUE are quantitative indicators of resource use efficiency for production systems and can serve as efficient indicators in sustainability assessment in practice. With a large amount of data available for calculations, and simplicity in terms of definition and calculation (and hence ease in communication), resource use efficiency presents great potential in sustainability-relevant assessment across a range of scale and societal groups (Franke *et al.*, 2011; Steyn *et al.*, 2016; Antille and Moody, 2021). In contrast to the quantitative synthesis, LCA is highly reliant on high-resolution, on-site data and background information, with emphasis on LCA as a tool for reaching consensus across a diverse range of stakeholders. A rigorous LCA can provide comprehensive information on the environmental dimension of sustainability. This has received considerable popularity across industries and has been adopted by some larger businesses to obtain and maintain their societal licence (Matos and Hall, 2007). However, the high complexity in data processing and analysis requires specific technical knowledge and results cannot be readily interpreted by potential end users (e.g. stakeholders, policy makers), because they require interpretation by LCA experts. This potentially limits the application of LCA.

It is widely accepted that sustainability assessment should address multiple sustainability dimensions and trade-offs, although this increases complexity, thus risking lower rates of implementation (De Olde *et al.*, 2018; Talukder *et al.*, 2020; Chopin *et al.*, 2021). To reach a balance between applicability and complexity, I include land and water use efficiency in combination with simplified indicators from LCA in the proposed SDGs framework. This framework is sufficiently user-friendly for a wide range of stakeholders to gain specific insights into some aspects of the overall operation, while maintaining the comprehensiveness of the information provided. In addition, the involvement of a wide range of stakeholders throughout the greenhouse production supply chain in the current framework design provides additional perspectives. This addresses a major shortfall in stakeholder engagement that has been identified in most ex-post sustainability assessment methods (Binder *et al.*, 2010; De Olde *et al.*, 2018; Arulnathan *et al.*, 2020;

Chopin *et al.*, 2021). I consider the proposed indicator-based SDGs framework in Chapter 5 as a starting point for future work and an opportunity to reflect on the optimisation of greenhouse production with high scalability to specific operating environments and business models.

### **6.3. Practical relevance to SD in greenhouse management**

#### ***Improvements for water and nutrient management***

Improper irrigation and fertilisation occur in both soil-based and soilless greenhouse systems, damaging soil health, polluting aquatic systems (Incrocci *et al.*, 2020) and leading to additional GHG emissions (e.g. N<sub>2</sub>O) (Qasim *et al.*, 2021, 2022). For soil-based greenhouse systems improvement measures for optimising water and nutrient use at farm-level should consider local context rather than just providing generic recommendations for management practices. The quantitative synthesis (Chapter 3) revealed that there are large variations in yields, WUE and NUE across soil-based greenhouse systems even within the same region, suggesting a high variability in local practices. To prevent further promulgation of the negative impacts due to water and nutrient use in greenhouses with soil-based cultivation, measurements on the water status and soil properties, especially the available nutrients in soils before fertilisation, must be implemented in order to avoid excess irrigation and fertilisation (Incrocci *et al.*, 2020). Compared to soil-based cultivation, greenhouse systems with soilless cultivation have a higher potential to mitigate and even eliminate excess nutrient leakages through the reuse of drain water and wastewater (Chapter 5).

#### ***Considerations for adopting renewable energy***

Climate change is the most urgent challenge of our time (United Nations, 2015). To combat climate change burning fossil fuels must be reduced as it is responsible for primary CO<sub>2</sub> emissions that is one of major GHG emissions (IPCC, 2023). For fossil-heated greenhouse systems, urgent actions are needed to reduce the energy use. More practically, adoption of locally, readily available renewable energy is a prudent strategy for sustaining stable greenhouse production, particularly for heated greenhouses. However, availability (e.g. infrastructure for renewable energy generation) and access to renewable energy is largely determined by geography, socio-economic and political factors (i.e. the location of greenhouses versus the nearest location of energy generating infrastructure; Soltani *et al.*, 2021). This can be an obstacle to adopting renewable energy for some existing greenhouses but could also be an opportunity for others. For future expansion in

energy-intensive greenhouses, the availability and abundance of renewable energy sources should be considered together with climate, markets and logistics as key factors in the selection of greenhouse locations in regions or countries with significant geographical heterogeneity, such as Australia, China and North America. Nonetheless, generation and/or use of renewable energy also comes with environmental costs, which should be clearly recognised and accounted for by all stakeholders, including regulators and government agencies. For example, as discussed in the Chapter 4, the use of wood biomass reduced GHG emissions, but increased PM<sub>2.5</sub> generation. Consequently, the harmful health impacts might outweigh environmental gains. In addition to impacts derived from consumption stages, production of renewable energy can also be associated with negative environmental impacts. Forests, for example, play a vital role for carbon storage and are also an important source of biofuel. A recent published study by Peng *et al.* (2023) estimated that world wood harvests could release 3.5–4.2 Gt CO<sub>2e</sub> annually between 2010 and 2050 to meet rising demand for wood products. Among these demands the projected increase in wood fuel is the largest (91%). Moreover, several studies have revealed that wind turbines increased birds and bats mortality in various regions (Rydell *et al.*, 2010; Arnett *et al.*, 2011; Zimmerling and Francis, 2016; Marques *et al.*, 2020; Perold *et al.*, 2020). Hence, from a life-cycle perspective, the use of renewable energy, such as solar, hydro and wind, might enhance other unintended environmental impacts (e.g. pollution, habitat losses) caused by renewable energy generation systems (manufacturing, construction, installation) (Rabaia *et al.*, 2021; Sayed *et al.*, 2021). Moreover, the supply of some types of renewable energy (e.g. hydropower) can be unstable due to climate change, such as drought (Solaun and Cerdá, 2019). To enhance the resilience of energy consumption in greenhouse production requires a rigorous trade-off analysis and the consideration of multiple energy sources.

### ***Waste management in greenhouse production systems***

Waste generation derived from greenhouse production should be reduced and corresponding waste management needs to be improved. To reduce the amount of waste generation, options to increase the lifespan of materials (e.g. plastics) used in greenhouse structures should be considered. However, trade-offs may occur between extending greenhouse lifespan and the degradability of the subsequent waste products. Approaches based on the concept of a circular economy may lead to better waste management (Sayadi-Gmada *et al.*, 2019; Castillo-Díaz *et al.*, 2021; Van Tuyl *et al.*, 2022). For example, in Dutch greenhouses, circularity has been applied on several aspects, such as

reuse of drainage water for irrigation. Apart from farm-level application, the concept of circularity can also be applied at larger scales, involving collaboration between different industries. For example, technology converting used stone wool insulation materials from buildings into bricks for the building industry has involved collecting the used substrate from greenhouse industry. However, processes making used substrate ready for brick production is also energy intensive, generating large amounts of greenhouse gas emissions (Chapter 5). Therefore, sustainability assessment is necessary to compare the current waste management (e.g. landfill) with alternative strategies such as use as input for another process. Moreover, recycling options are often due to infrastructure availability and logistics etc., which requires involvement of local and regional municipalities.

#### **6.4. Implication for policy making towards SD**

Geographic location of greenhouses can be a major constraint limiting growers' choices of sustainable practices and thus the sustainability of greenhouse systems. These choices must be underpinned by well-informed policies. This highlights the importance of objective evaluations of the sustainability of greenhouse production at farm level and regional level. Formulating reasonable legislation and regulations that enhances sustainability and profitability of greenhouse production must be based on such objective evaluations. For example, the results of the LCA in Chapter 4 revealed that the greenhouse location determines which renewable energy sources (e.g. biomass, geothermal heat) are readily available for use and the abundance of local freshwater resources. The greenhouse systems assessed in Tasmania used wood biomass as an alternative fuel for greenhouse heating due to their local availability. This is the most suitable renewable energy source for this location. However, the greenhouse system in South Australia relied heavily on fossil fuels due to lack of access to thermal energy generated from renewable energy sources for greenhouse heating. In fact, changes in government policy means that the use of wind and solar now accounts for 70% of the electricity generation in South Australia (Government of South Australia, Energy & Mining, 2022), a considerable increase from when the LCA described in Chapter 4 was conducted. However, to fully utilise this resource, growers still require infrastructure for integrating electric heating from renewable energy sources into their greenhouse heating systems (Van't Hoog, 2022). Given the high capital investment, such infrastructure transferring renewable energy readily for greenhouse heating may require multi-stakeholder involvement ranging from growers to local or national governments (Van't Hoog, 2022). This also increases the difficulty for greenhouse growers in transiting to sustainable greenhouse production.

Appropriate regulations, legislation and incentives can facilitate adoption of sustainable practices in agriculture production (Tilman *et al.*, 2002). This thesis recognises that adoption of targeted technological innovations is critical in improving the sustainability of greenhouses. A recent study (Moons *et al.*, 2022) on greenhouse growers' adoption intentions of technologies identified financial constraints as one of the main barriers. Appropriate financial and non-financial incentives and a supportive policy framework could help with addressing this bottleneck. Verburg *et al.* (2022) investigated the sustainable transition to organic dairy farming and found that Dutch farmers have been facing strong pressure in terms of adoption of sustainable practices due to the current policies that were designed to deliver single outcomes (i.e. substantial reduction in GHG emissions). Verburg *et al.* (2022) pointed out that policies should target longer term transformations rather than radical changes, and explicitly support the adoption of sustainable practices by farmers. This may be also crucial for the policy making in greenhouse production. Additionally, in a study assessing incentives for land conservation for waterbirds in paddy fields (Herring *et al.*, 2022) found that effective incentives did not have to be just monetary and could range from direct financial support to actions that help rice growers to gain and maintain their societal licence to operate (e.g. by improving the image of rice production or by awarding environmental certificates). Developing and implementing such support mechanisms in combination with follow-up evaluation provides opportunities to establish farm-level, practice-relevant databases which have been identified as a big gap in greenhouse production research and industries in several production areas, such as Australia and Spain (Castro *et al.*, 2019).

## **6.5. Scientific contributions and challenges of this thesis**

The main scientific contributions are:

**I.** Quantitative evidence of the importance of incorporating greenhouse production into the agenda of achieving SDGs and the Paris agreement. Greenhouse production plays an important role in our food systems, given its high productivity and resource use efficiency (SDG2-end hunger, achieve food security and improved nutrition and promote sustainable agriculture). Greenhouse production has far-reaching, transboundary impacts (e.g. N losses from greenhouse production could undermine sources of drinking water) on environments and ecosystems, which in turn, affect human well-being.

**II.** A quantitative analysis at a global scale provides baseline data on tomato yields, WUE, NUE of field and soil-based greenhouse production systems and demonstrates

considerable differences in the use of water and N fertiliser between field and greenhouse production. Tomato yield was significantly affected by water use and N fertiliser supply as well as their interactions. In comparison to field production, efficacy of mild deficit irrigation (70–100%ET) was higher for greenhouse systems. This study contributes by: 1) providing scientific evidence and datasets on the resource use of tomato production in different systems; and 2) offering essential implications for future land planning in food production to meet rising demand for fresh produce, and guiding agronomists to differentiate the optimisation strategies for water and nutrient management between field and greenhouse cultivation systems.

**III.** An LCA analysis provides a comprehensive understanding on the environmental sustainability of high-tech, heated greenhouses in Australia and sound sustainable choices by the growers. The results highlight a clear trade-off in use of wood biomass for greenhouse heating between mitigating different emissions and emphasise that location-bounded resources, such as fresh water and infrastructure of renewable energy, are vital criteria for the selection of future greenhouse locations in meeting environmental requirements.

**IV.** A tailored analytic framework with measurable indicators was proposed and applied to assess the SD of greenhouse production systems, considering economic, environmental and social aspects simultaneously. This analysis offers both a method and a baseline for evaluating the sustainability performance of greenhouse production systems in alignment with SDG goals. This contribution enhances the scientific evidence available for decision-making within the greenhouse production sector.

The major challenge was data collection from various stages of greenhouse production and related research, which limited the comprehensiveness of this research. These challenges include:

**1.** The availability of current data on water and nutrient management in high-tech, soilless greenhouses is limited, which hampers the inclusion of high-tech greenhouse systems in quantitative analyses. Existing analyses heavily rely on empirical data, which typically do not prioritise maximising production. Consequently, empirical yield data exhibit significant variations and differ considerably from those observed in commercial greenhouses.

**2.** Inventory data collection from commercial greenhouses for LCA was the biggest difficulty encountered during this research. To provide comprehensive information based on an LCA study, a considerable amount of data is required, which is generally very time-

consuming for all parties involved. This, together with legitimate concerns about commercial confidentiality, often discourages the involvement of growers.

3. Data is lacking for assessing some key components in greenhouse production, such as quantities of waste generation, phosphorus fertiliser losses and the nutrients stored in the soils in soil-based greenhouse cultivation.

4. Data is lacking for assessing the economic aspect of the SD for greenhouse production systems because of confidentiality concerns from growers.

5. In the design of the proposed SDGs framework in Chapter 5, methods for aggregation and weighting of the indicators were not explored, due to the lack of a consensus in the scientific community on how to do this.

## **6.6. Recommendations for future research**

### ***A systems approach with expanded scales is needed***

Greenhouse production holds promise for securing more nutritious food, but it can also have adverse effects on the environment and ecosystems, impeding progress towards achieving multiple Sustainable Development Goals (SDGs). In addition to acknowledging the interconnections among sustainability themes related to greenhouse production such as energy, water, and nutrients, there is a pressing need for a comprehensive systems approach that explicitly considers system boundaries in assessing its sustainability. This includes assessments at farm and regional scale as well as using LCA as a means of engaging stakeholders in building consensus. By adopting this approach, valuable insights can be generated to inform decision-making and policy formulation in the realm of greenhouse production.

There are two main reasons why we need to consider a much larger system scale in sustainability assessment of greenhouse production: (i) To meet the future increasing adoption of innovation based on circular economy in the life cycle of greenhouse production, the overall sustainability of greenhouse production systems will be very much dependent on the sustainability of other sectors which can be based locally or even a globally. (ii) For countries, such as Germany, whose vegetable and fruit supply highly relies on imports of greenhouse produce from the Netherlands and Spain (Van Grinsven *et al.*, 2019), the share of GHG emissions derived from this type of food trade may play an important role in achieving domestic goals of GHG emissions mitigation, and future

increases in such trades may hinder progress in mitigating GHG emissions in exporting countries and even in the region (e.g. Europe).

### ***Importance of incorporating economic and social dimensions***

For any meaningful assessment of sustainability, besides environmental aspects, it is essential to understand economic and social dimensions of sustainability. Previous sustainability assessment tools for agri-food production show that there is no consensus on the indicators and themes that need to be included for a valid assessment of both economic and social aspects of sustainability (Chopin *et al.*, 2021). A recent review on the sustainability of controlled environment agriculture (e.g. greenhouse cultivation) pointed out that the social and cultural dimensions were often neglected in the sustainability assessment of the production systems (Gan *et al.*, 2022). However, coverage of social aspects in sustainability assessment is pivotal in decision making towards sustainability and should be incorporated in future research.

My thesis highlights the difficulty in obtaining essential data for thorough SD assessments. Due to legitimate concerns about confidentiality, I was unable to obtain much needed economic data. Hence, I used surrogate, secondary data such as crop productivity (yield), water use efficiency and energy use as proxies to estimate the economic performance of greenhouse production (Table 6.2). However, analysis using these indicators is insufficient in guiding decision making. For future studies it would be desirable to have access to real economic indicators, such as profit per unit land or produce. Furthermore, cost-benefit analysis can be helpful to assess the economic feasibility of adopting new technologies (Torrellas *et al.*, 2012b). Likewise, to address the social dimension, I used indicators in relation to potential residues of N fertiliser and plant protection products (Table 6.2) as proxies to indicate potential risks to human health which is an important theme of the social dimension. Due to a lack of data for other important themes, such as social contribution and involvement, working conditions, and the image of greenhouse production (Chopin *et al.*, 2021), these were not assessed in the current thesis work but are highly suggested to be incorporated in future research as they are also related to the economic viability and stability.

### ***Impacts on biodiversity from greenhouse production***

Land use for intensive agriculture can lead to profound impacts on local or regional biodiversity and ecosystem services (Willett *et al.*, 2019). To date, a limited number of studies assessed the biodiversity losses associated with the land use change due to

greenhouse production (Antón *et al.*, 2007; Benito *et al.*, 2009; Messelink *et al.*, 2021). Better indicators are needed to evaluate their impacts. In this thesis, the impacts on biodiversity were indirectly assessed via the application rate of production inputs (Chapter 5). However, explicit understanding of biodiversity losses due to greenhouse production systems is necessary and direct indicators are required in future assessment. For example, the benefits and limitations of organic greenhouse production systems when it comes to sustainability are still unclear. The value proposition of organic greenhouse cultivation is the avoidance of synthetic plant protection products and chemical fertilisers. The former is responsible for the widespread impression that organic greenhouses enhance biodiversity. However, studies by Tschardt *et al.* (2021) and Torre *et al.* (2018) pointed out that use of “natural” pesticides in organic greenhouse production, such as copper compounds, can be equally damaging for the environment as a result of high Cu accumulation in the soils. Tschardt *et al.* (2021) demonstrated that the enhancement in biodiversity in comparison to conventional farming is very limited in terms of species composition. Overall, exploring and implementing rational indicators associated with land use impacts is important to further demonstrate differences between different cultivation methods, which is essential for understanding the sustainability of greenhouse systems at various spatial scales.

In addition to the impacts at farm level, evaluation on the land use impacts by greenhouse production at larger scales is essential to achieve SD at national or regional levels. For example, greenhouse production may lead to low on-site biodiversity, but could potentially spare land in other regions for biodiversity conservation at landscape scale, owing to high yields per area of land obtained from greenhouse systems. Such indirect and often unnoticed effects are usually beyond the assessment or even spatial/administrative boundaries and are referred to as “spillovers” (Balmford *et al.*, 2018; Bastos Lima *et al.*, 2019). Such spillovers receive increasing attention when it comes to evaluating the impact of ongoing land use changes (Bastos Lima *et al.*, 2019). In the case of greenhouse production, effects due to spillovers have rarely been captured in assessments on sustainability performance but may play a crucial role in understanding the net sustainability performance of greenhouse production at larger scales (e.g. regional, national, continental). For example, in regions such as Almeria in South-eastern Spain, Westland in the Netherlands and Shouguang in Shandong province in China, where greenhouse production is dominating and has become part of a socially accepted landscape, the vegetable production from these regions is sufficient to meet the domestic and even partly the international (European countries) demand. This potentially spares

land on other locations which might be set aside for nature conservation or forests, with benefits for biodiversity. Therefore, gaining insights at larger scales are important for comprehensively understanding the sustainability performance. This has important implications for the science-policy interface and plays a vital role in developing successful policies to aid a sustainable transition towards increased greenhouse production.

## 6.7. Final conclusions

This thesis explores methods for the sustainability assessment of greenhouse production systems. I assessed the sustainability of greenhouse production systems by using various approaches, starting from simple agronomic indicators via a comprehensive environmental assessment, to an analytic framework that considers the environmental, economic, and social dimensions of sustainability.

The main conclusions that can be drawn from this thesis are:

- I. Greenhouse production plays an important role in providing fresh tomatoes (Chapter 2–5) but has far-reaching impacts on local and even much bigger scale environments and ecosystems (Chapter 2–5).
- II. Considerable improvements in terms of crop productivity, resource use efficiency and sustainability of greenhouse production are possible (Chapter 3 and 4).
- III. The current sustainability assessment for greenhouse production largely focuses on specific themes (i.e. energy, water, nutrients) and/or dimensions (i.e. environmental), neglecting the potential interconnections between them (Chapter 2). Rather than focusing on single-factor solutions, a systems approach can gain a much better understanding of how the various components of the system interact, including the socio-environmental-economic dynamics within which greenhouse production is embedded (Chapter 4 and 5).
- IV. The sustainability of greenhouse production systems is highly context-specific, requiring a sound understanding of the broader systems implications. This includes how local circumstances impact on greenhouse production and, conversely how greenhouse production impacts on local and even regional systems, encompassing factors such as environment, geography, climate, socio-economic conditions. (Chapter 4 and 5).
- V. The analytical framework outlined in Chapter 5 serves as a valuable starting point, functioning as an operational tool for a comprehensively assess the role of greenhouse production in advancing sustainable development, with a particular emphasis on capturing transboundary interconnections. This framework not only enables a holistic understanding

of the contributions made by greenhouse production but also facilitates the identification of trade-offs between different SDGs across various scales, ranging from individual farms to regional and global levels. By considering these dimensions, the framework provides a robust means of evaluating the broader impacts and implications of greenhouse production on sustainable development.

# APPENDIX I

## Studies for data extraction used in the Chapter 3.

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## Appendix I

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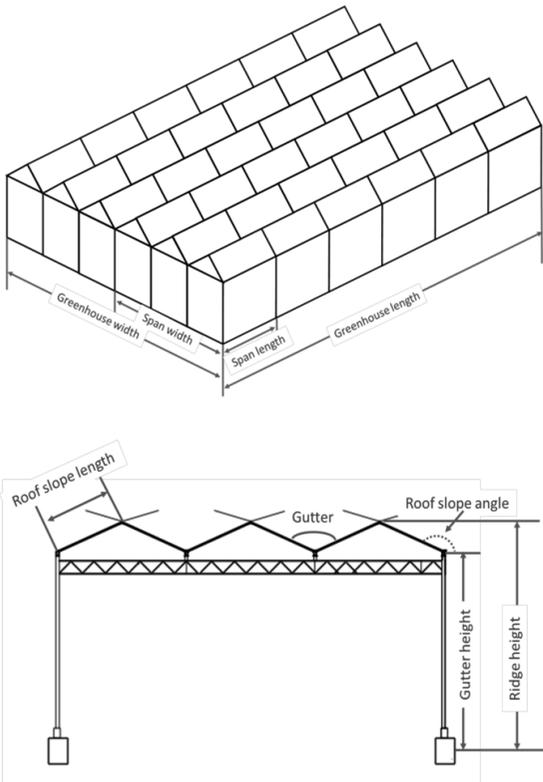
# APPENDIX II

Copy of survey used for the data collection of life cycle inventory analysis of greenhouse tomato production systems

1. Main characteristics of greenhouse		
Characteristics	Information	Comments
Type of greenhouse	<input type="checkbox"/> Venlo <input type="checkbox"/> multi-tunnel <input type="checkbox"/> wide-span	
Size (m <sup>2</sup> )		
Location	Latitude:	
	Longitude:	
	Greenhouse orientation:	
Cover material	<input type="checkbox"/> Plastic <input type="checkbox"/> Glass	
Water source	<input type="checkbox"/> Fresh water	
	<input type="checkbox"/> Rainwater	
	<input type="checkbox"/> Recycle water	
Energy source	<input type="checkbox"/> Fossil fuels, please specify:	
	<input type="checkbox"/> Biomass	
	<input type="checkbox"/> Renewable, specify:	
Inside equipment	<input type="checkbox"/> Soil-based <input type="checkbox"/> Soilless	
	<input type="checkbox"/> Fertigation system	
	<input type="checkbox"/> Cooling system	
	<input type="checkbox"/> Heating system	
	<input type="checkbox"/> CO <sub>2</sub> enrichment	
	<input type="checkbox"/> Thermal screen	
	<input type="checkbox"/> Shade screen	
2. Crop production		
Characteristics	information	Comments
Cultivars		
Source of tomato seedlings: <input type="checkbox"/> Self-supplying <input type="checkbox"/> Nursery, please specify the supplier, location and transport type		
Crop period (weeks per year)		
Planting density (no. of plants m <sup>-2</sup> )		
Annual yield (kg m <sup>-2</sup> )		
No. of rows		
No. of plants per row		
No. of stems per plant		
3. Greenhouse dimensions (Figure 1)		

**Appendix II**

<i>Element</i>	<i>Size</i>	<i>Unit</i>	<i>Comments</i>
Number of spans		u	
Span width		m	
Span length		m	
Greenhouse width		m	
Greenhouse length		m	
Gutter height		m	
Ridge height		m	
Roof slope length		m	
Roof slope angle		°	
Number of window ventilator		u	
Ventilator dimensions		m	
Insect proof screen		u	
Side window ventilators		u	



**Figure 1. Description of Venlo type greenhouse dimensions**

**4. Materials used for greenhouse construction**

<i>Material</i>	<i>Quantity</i>	<i>Approx. cost</i>	<i>Supplier &amp; location</i>
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Aluminium			
Concrete			
Glass			
Steel			
<b>5. Resource consumption during production</b>			
<b>Type of resources</b>	<b>Quantity</b>	<b>Approx. cost</b>	<b>Supplier &amp; location</b>
Water use: <input type="checkbox"/> Fresh water <input type="checkbox"/> Rainwater <input type="checkbox"/> Recycled water			
Heating fuels: <input type="checkbox"/> Natural gas <input type="checkbox"/> Wood biomass <input type="checkbox"/> Others, please specify:			
Electricity			
Labour use: <input type="checkbox"/> Crop management <input type="checkbox"/> Packaging			
Fertiliser use			
<input type="checkbox"/> Inorganic fertiliser:			
Potassium nitrate			
Calcium nitrate			
Potassium Phosphate			
Epsom Salt			
<input type="checkbox"/> Organic fertiliser, please specify:			
Pesticides application, please specify:			

<b>6. Growing substrate (Figure 2):</b> <input type="checkbox"/> Stone wool <input type="checkbox"/> Perlite <input type="checkbox"/> Other, please specify:					
<b>Element</b>	<b>Dimensions e.g. length, width and thickness</b>	<b>Quantity (no. of per growing season)</b>	<b>Approx. cost</b>	<b>Supplier and location</b>	<b>Transport type</b>
Cubes					
Slabs					

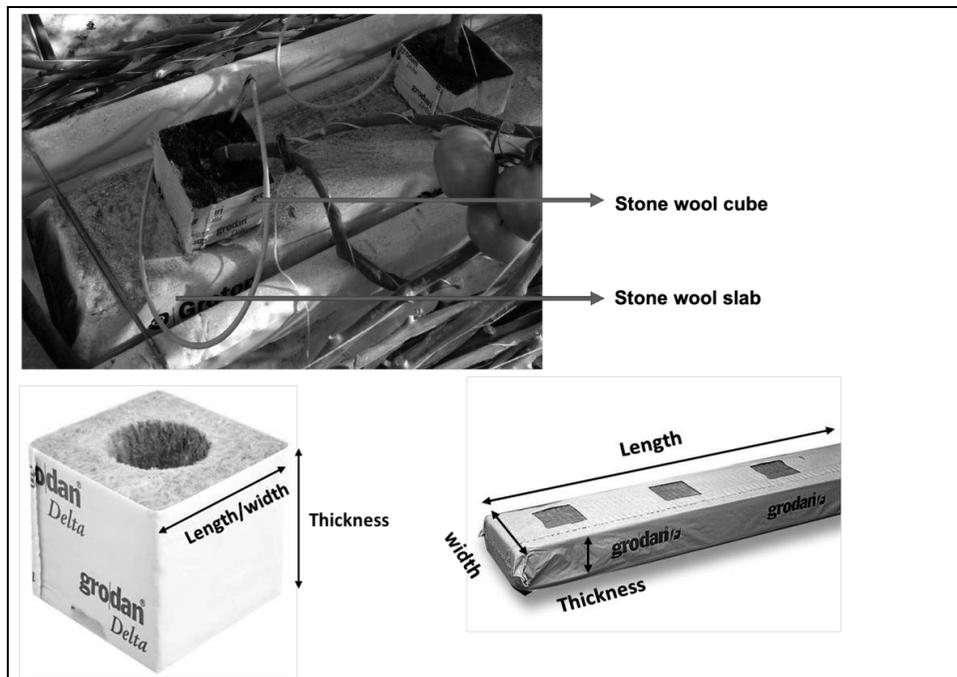


Figure 2. Example of stone wool soilless cultivation in greenhouse.

7. Fertigation system					
Element	Dimensions	Quantity	Approx. cost	Supplier and location	Transport type
Drippers					
Pipes					
Pumps					
Emitters					
Injectors					
Benches					
Tanks for water and fertilisers					
8. Heating system					
Element	Dimensions	Quantity	Approx. cost	Supplier and location	Transport type
Pipes					
Boilers					
Pumps					
Emitters					
Injectors					
Distributors					
Water tanks					
9. Cooling system					
Element	Dimensions	Quantity	Approx. cost	Supplier and location	Transport type

Fans: <input type="checkbox"/> Circular fan <input type="checkbox"/> Forced fan					
<b>10. CO<sub>2</sub> enrichment</b>					
<b>Element</b>	<b>Dimensions e.g. length, width and thickness</b>	<b>Quantity (no. of per growing season)</b>	<b>Approx. cost</b>	<b>Supplier and location</b>	<b>Transport type</b>
Pure CO <sub>2</sub>					
No. of containers of pure CO <sub>2</sub>					
Tubes of CO <sub>2</sub> distribution: <input type="checkbox"/> Plastics <input type="checkbox"/> Rubber					
Exhaust CO <sub>2</sub>					
<b>11. Other equipment</b>					
<b>Element</b>	<b>Dimensions</b>	<b>Quantity</b>	<b>Approx. cost</b>	<b>Supplier and location</b>	<b>Transport type</b>
Thermal screen					

<b>12. Waste and management</b>						
<b>Type of waste</b>	<b>Quantity (kg y<sup>-1</sup>)</b>	<b>Recycling (%)</b>	<b>Incineration (%)</b>	<b>Landfill (%)</b>	<b>Compost plant (%)</b>	<b>Other, please specify</b>
Green biomass						
Substrate						
Plastics						
Wood ash						

# APPENDIX III

## Datasets and sources of background processes for life cycle inventory analysis of the three greenhouses assessed in Chapter 4

### Tomato production in the greenhouse using wood biomass for heating in Tasmania (GH1-TAS).

Material/processes	Quantity	Unit	Data sources	Geographic region
<b>Greenhouse structure</b>				
Aluminium	0.00146	kg	AusLCI	Australia, average
Aluminium coating	1.98E-5	m <sup>2</sup>	AusLCI	Australia, average
Glass	0.00505	kg	Ecoinvent	Global, average
Steel	0.00757	kg	AusLCI	Australia, average
Zinc coating	0.000397	m <sup>2</sup>	AusLCI	Australia, average
Transport, transoceanic freight ship	0.221	tkm	AusLCI	Australia, average
<b>Energy use for greenhouse heating and operation</b>				
Electricity mix production and transmission	0.184	KWh	AusLCI	Tasmania
Heat with hardwood chips at furnace 300KW	13.6	MJ	AusLCI	Tasmania
<b>Seedling and substrate</b>				
Seedling production	0.0305	p	Ecoinvent	Global, average
Seedling transport via van <3.5t	0.000177	tkm	AusLCI	Australia, average
Seedling transport via aircraft freight	0.00192	tkm	AusLCI	Australia, average
Stone wool	0.0161	kg	Ecoinvent	Global, average
Plastic sleeve of stone wool	0.000323	kg	Ecoinvent	Global
Substrate transport via transoceanic freight ship	0.165	tkm	Ecoinvent	Global
<b>Climate control systems</b>				
Steel (heat distribution pipes, heat storage tanks)	0.0111	kg	AusLCI	Australia, average
Polyester (Thermal screen)	0.000111	kg	Ecoinvent	Global
Aluminium (Thermal screen)	0.00027	kg	Ecoinvent	Global

Liquid CO <sub>2</sub> production	0.000258	kg	Ecoinvent	Switzerland
Rubber tubes of CO <sub>2</sub> distribution in greenhouses	0.000174	kg	Ecoinvent	Europe
Paint (heat distribution pipes)	0.00021	kg	Ecoinvent	Global
Transport via transoceanic tanker	0.000377	tkm	AusLCI	Australia, average
Transport via transoceanic freight ship	0.0237	tkm	Ecoinvent	Global
Transport via van <3.5t	0.000237	tkm	AusLCI	Australia, average
<b>Fertiliser production</b>				
Calcium nitrate – Ca(NO <sub>3</sub> ) <sub>2</sub>	0.0101	kg	Ecoinvent	Global
Potassium nitrate – KNO <sub>3</sub>	0.00405	kg	Ecoinvent	Global
Magnesium sulphate – MgSO <sub>4</sub>	0.00382	kg	AusLCI	Australia
Monopotassium – phosphate KH <sub>2</sub> PO <sub>4</sub>	0.00225	kg	AusLCI	Australia
Potassium sulphate – K <sub>2</sub> SO <sub>4</sub>	0.00428	kg	Ecoinvent	Europe, average
<b>Water and distribution</b>				
Town supply water	44.7	kg	AusLCI	Tasmania
<b>Waste management</b>				
Landfill of wood ash mixture	0.0348	kg	AusLCI	Australia
Landfill of polyethylene	0.000323	kg	AusLCI	Australia
Landfill of stone wool	0.0161	kg	AusLCI	Australia
Composting of green biomass	0.12	kg	AusLCI	Australia
Transport via Lorry 20–28t	0.005	tkm	AusLCI	Australia

*Tomato production in the greenhouse using multiple types of fuels for heating in Tasmania (GH2-TAS).*

Material/processes	Quantity kg <sup>1</sup> tomatoes	Unit	Data sources	Geographic region
<b>Greenhouse structure</b>				
Aluminium	0.00298	kg	AusLCI	Australia, average
Aluminium coating	4.04E-5	m <sup>2</sup>	AusLCI	Australia, average
Glass	0.00921	kg	Ecoinvent	Global, average
Steel	0.0148	kg	AusLCI	Australia, average
Zinc coating	0.000791	m <sup>2</sup>	AusLCI	Australia, average
Transport, transoceanic freight ship	0.417	tkm	AusLCI	Australia, average
<b>Energy use for greenhouse heating and operation</b>				
Electricity mix production and transmission	0.376	kWh	AusLCI	Tasmania
Electricity generated from 3 kWp roof photovoltaic	0.107	kWh	AusLCI	Tasmania
Heat with sawdust at furnace 300 kW	28.3	MJ	AusLCI	Tasmania
Heat with liquefied petroleum gas at 100 kW furnace	0.0266	MJ	AusLCI	Tasmania
Heat with waste oil at industrial furnace	0.333	MJ	Ecoinvent	Global
<b>Seedling and substrate</b>				
Seedling production	0.0437	p	Ecoinvent	Global, average
Seedling transport via van <3.5t	0.000111	tkm	AusLCI	Australia, average
Seedling transport via aircraft freight	0.000199	tkm	AusLCI	Australia, average
Stone wool	0.0029	kg	Ecoinvent	Global, average
Coco coir	0.0546	kg	Agri-footprint 1.0	India
Plastic sleeve of stone wool and coco coir	0.000527	kg	Ecoinvent	Global
Substrate transport via transoceanic freight ship	0.677	tkm	Ecoinvent	Global
Substrate transport via transoceanic tanker	0.0467	tkm	AusLCI	Australia, average
<b>Climate control systems</b>				
Steel (heat distribution pipes, heat storage tanks)	0.0286	kg	AusLCI	Australia, average
Polyester (Thermal screen)	0.000225	kg	Ecoinvent	Global

Aluminium (Thermal screen)	0.00055	kg	Ecoinvent	Global
Paint (heat distribution pipes)	0.00037	kg	Ecoinvent	Global
Transport via transoceanic tanker	0.000389	tkm	AusLCI	Australia, average
Transport via transoceanic freight ship	0.0305	tkm	Ecoinvent	Global
Transport via van <3.5t	2.14E-7	tkm	AusLCI	Australia, average
<b>Fertiliser production</b>				
Calcium nitrate – Ca(NO <sub>3</sub> ) <sub>2</sub>	0.0163	kg	Ecoinvent	Global
Potassium nitrate – KNO <sub>3</sub>	0.0149	kg	Ecoinvent	Global
Magnesium sulphate – MgSO <sub>4</sub>	0.00256	kg	AusLCI	Australia
Monopotassium – phosphate KH <sub>2</sub> PO <sub>4</sub>	0.0031	kg	AusLCI	Australia
<b>Water and distribution</b>				
Town supply water	38.1	kg	AusLCI	Tasmania
<b>Waste management</b>				
Landfill of wood ash mixture	0.0047	kg	AusLCI	Australia
Landfill of polyethylene	0.0005	kg	AusLCI	Australia
Landfill of stone wool	0.003	kg	AusLCI	Australia
Composting of coco coir (40%)	0.022	kg	AusLCI	Australia
Incineration of green biomass and coco coir (60%)	0.373	kg	AusLCI	Australia
Transport via Lorry 20–28t	0.01	tkm	AusLCI	Australia

*Tomato production in the greenhouse using natural gas for heating in South Australia (GH3-SA).*

<b>Material/processes</b>	<b>Quantity</b>	<b>Unit</b>	<b>Data sources</b>	<b>Geographic region</b>
<b>Greenhouse structure</b>				
Aluminium	0.00298	kg	AusLCI	Australia, average
Aluminium coating	4.04E-5	m <sup>2</sup>	AusLCI	Australia, average
Glass	0.00921	kg	Ecoinvent	Global, average
Steel	0.0148	kg	AusLCI	Australia, average
Zinc coating	0.000791	m <sup>2</sup>	AusLCI	Australia, average
Transport, transoceanic freight ship	0.417	tkm	AusLCI	Australia, average
<b>Energy use for greenhouse heating and operation</b>				
Electricity mix production and transmission	0.198	kWh	AusLCI	South Australia
Heat with natural gas at 100 kW furnace	30.9	MJ	AusLCI	South Australia
<b>Seedling and substrate</b>				
Seedling production	0.0407	p	Ecoinvent	Global, average
Seedling transport via lorry 3.5–16t	0.00384	tkm	AusLCI	Australia, average
Stone wool	0.0129	kg	Ecoinvent	Global, average
Plastic sleeve of stone wool	0.000468	kg	Ecoinvent	Global
Substrate transport via transoceanic tanker	0.313	tkm	AusLCI	Australia, average
<b>Climate control systems</b>				
Steel (heat distribution pipes, heat storage tanks)	0.014	kg	AusLCI	Australia, average
Polyester (Thermal screen)	0.000105	kg	Ecoinvent	Global
Aluminium (Thermal screen)	0.000257	kg	Ecoinvent	Global
Paint (heat distribution pipes)	0.000198	kg	Ecoinvent	Global
Transport via lorry 3.5–16t	0.00029	tkm	AusLCI	Australia, average
Transport via transoceanic freight ship	0.0398	tkm	Ecoinvent	Global
<b>Fertiliser production</b>				
Calcium nitrate – Ca(NO <sub>3</sub> ) <sub>2</sub>	0.0098	kg	Ecoinvent	Global

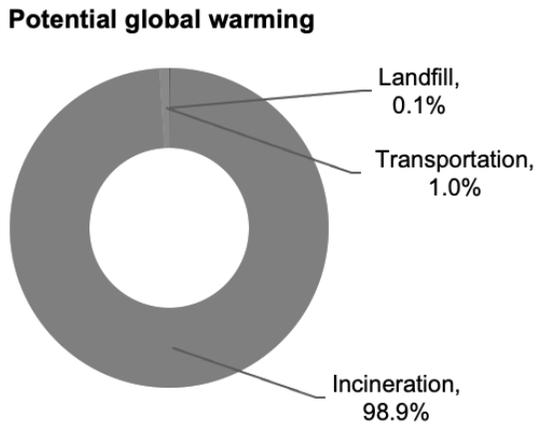
Potassium nitrate – KNO <sub>3</sub>	0.005	kg	Ecoinvent	Global
Magnesium sulphate – MgSO <sub>4</sub>	0.00714	kg	AusLCI	Australia
Monopotassium – phosphate KH <sub>2</sub> PO <sub>4</sub>	0.00219	kg	AusLCI	Australia
<b>Water and distribution</b>				
Rainwater	11.4	kg	AusLCI	Australia
Town supply water	45.4	kg	AusLCI	Murray, South Australia
<b>Waste management</b>				
Landfill of polyethylene	0.001	kg	AusLCI	Australia
Landfill of stone wool	0.03	kg	AusLCI	Australia
Composting of green biomass	0.113	kg	AusLCI	Australia
Transport via Lorry 20–28t	0.0036	tkm	AusLCI	Australia

# APPENDIX IV

## Assumptions made on lifespan of equipment and materials in Chapter 4.

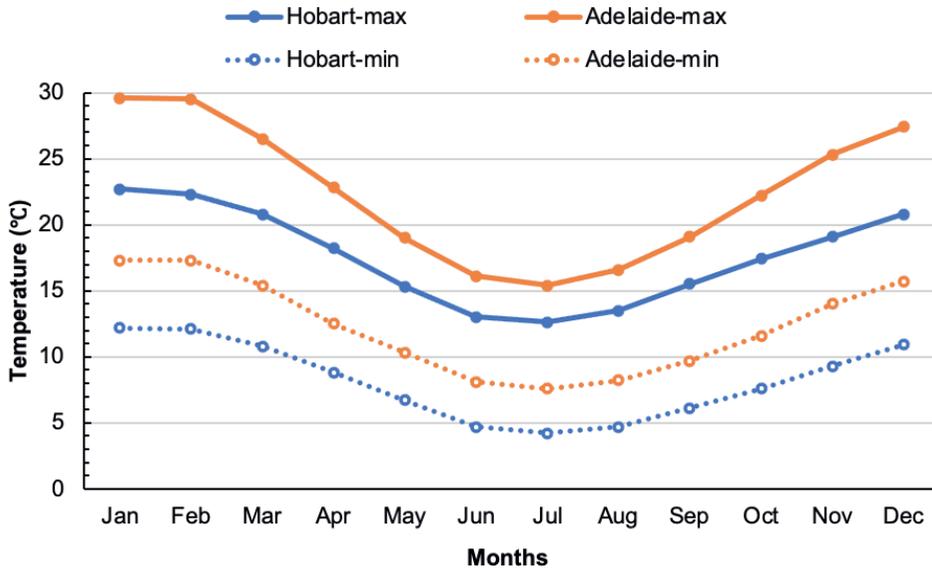
Material	Lifespan (years)
Greenhouse structure	30
Biomass boiler	20
Gas boiler	20
Substrate	1
Steel	15
LDPE	3
PVC	10
Thermal screen	7
Polyester	5
Rubber	7

# APPENDIX V



Contributions (%) of components of waste management to potential global warming in the cherry tomato greenhouse production system in Tasmania (GH2-TAS) in Chapter 4.

# APPENDIX VI



Monthly mean temperature recorded by weather stations proximate to the three greenhouses studied: two in Tasmania (Hobart) and one in South Australia (Adelaide) in Chapter 4. Dots with solid line denote the maximum temperatures with the trend and circles with dash line denote the minimum temperatures with the trend. Data were retrieved from the Australian Government Bureau of Meteorology (2023).



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# SUMMARY

Estimates show that an increase of 50–150% in global production of vegetables and fruit will be required to meet the demand of 10 billion people by 2050. Greenhouse production will play an increasingly important role in meeting this demand by providing year-round, high-quality produce. In some countries, such as China, the Netherlands and Australia, greenhouse production is already regarded as a promising solution in response to either increasing demand for fresh produce or to address several biophysical constraints such as limited arable land, freshwater scarcity and climate change. However, this has also increased environmental concerns about the impact of greenhouse production systems and any further expansion of the greenhouse sector will require sound regulatory guidelines to ensure its environmental and social sustainability. This should include oversight of the latest greenhouse technologies when upgrading existing facilities. Robust scientific evidence and comprehensive assessments of the sustainability of greenhouse production systems and their management could provide valuable insights for decisions makers, enabling them to identify critical actions that can improve performance against a wide range of sustainability indicators. One of the most commonly grown crops in greenhouses is tomato. Hence, in this thesis I evaluated the performance of various greenhouse tomato production systems by identifying, proposing and implementing suitable assessment methods, frameworks, indicators and metrics. The intended outcome of this thesis is to facilitate the progression towards increased sustainability of the greenhouse production sector.

I started this research by reviewing existing methods, indicators and metrics that have been developed and applied in agri-food production and discussing their potential application for the sustainability assessment of greenhouse production systems (Chapter 2). This review identified critical sustainability themes (water, nutrients and energy) for greenhouse production, and interconnections between different themes. I observed that resource use efficiency (e.g. water use efficiency) and life cycle assessment (LCA) have been extensively used for indicating sustainability of greenhouse production systems. To provide a comprehensive understanding, a systems approach considering multiple sustainability dimensions is needed. Given the great comprehensiveness of sustainability themes covered, I chose the Sustainable Development Goals (SDGs) of the United Nations as guidelines for proposing an analytical framework for sustainability assessment of greenhouse production systems.

## Summary

Chapter 3 provides a quantitative synthesis on tomato yields, water use efficiency (WUE) and nitrogen (N) fertiliser use efficiency (NUE). Through analysing 430 yields, 296 WUE and 348 NUE data points of field and greenhouse tomato production systems, the study offers essential baseline data and highlights differences between two production systems in terms of water and N fertiliser use, along with their interactions. Greenhouse systems obtained on average lower water use (32%), however with higher yield (45%), WUE (104%) and NUE (45%), compared with field production. Tomato yield as a function of total water input presented very different trends between systems, being linear for greenhouse studies and with an optimum relationship for field studies. In comparison to field production, effects of deficit irrigation within a range of 70–100% crop evapotranspiration (ET) were larger on the tomato yield and WUE in greenhouse production. In greenhouse studies, the highest mean yield, WUE and NUE were found at 80–90% ET. Large variations were observed on tomato yield as a function of N fertiliser supply, which is likely attributed to the lack of accuracy in the information on the total N availability in soils in the original studies. A significant interaction between water and N fertiliser use was observed for tomato yield. This interaction was positive for field production with mulching and greenhouse production but negative for field production without mulching. Considerable differences were observed between field and greenhouse tomato production in terms of yield, WUE and NUE. At the same deficit irrigation treatment (70–100% ET), significant effects were observed in greenhouse studies but not for field studies, suggesting that water-saving measures should be designed based on the production system and local climate. Understanding the interactive effects between water and N use is key for simultaneously improving WUE and NUE without compromising tomato yields.

To understand the environmental sustainability of growers' choices on sound sustainable practices for greenhouse production within a young industry context, I employed an LCA for assessing three Australian high-tech, heated greenhouse production systems in South Australia and Tasmania (Chapter 4). The study identified that geographic-bounded resources, such as freshwater and availability of renewable energy, are critical factors for the location selection of future greenhouse expansion, especially for energy-intensive greenhouses in large regions or countries, such as Australia. In comparison to WUE used in Chapter 3, the water-scarcity footprint based on LCA can additionally indicate the impact by freshwater use which largely depends on the scarcity status of sourced watersheds and river basins. Use of wood biomass as substitute to fossil fuels for greenhouse heating showed a clear trade-off between different environmental impacts: on the one hand a reduction of 67–88% in global warming potential, on the other hand 200% higher impact

related to air pollution. The estimates of environmental impacts from the use of coco coir as growing substrate depend on whether coco coir is treated as waste or as a by-product of coconut plantations in the original production regions. When coco coir is considered a by-product, environmental impacts stemming from coconut production should be allocated to coco coir from a life-cycle perspective. This LCA reveals a 30% reduction in marine eutrophication when coco coir is treated as a type of waste rather than a by-product. This chapter demonstrates that LCA provides a system perspective that enables decision makers to comprehend transboundary environmental issues (e.g. use of coco coir in greenhouse production in Australia could contribute to marine eutrophication in India) and identify synergies and trade-offs between achieving different mitigation goals.

Chapter 5 builds on the outcomes of the previous two chapters. With adapted indicators and approaches from Chapters 3 and 4, I proposed and applied an integrated analytical framework on the basis of the SDGs, to analyse and interpret the sustainability of greenhouse production systems from multidimensions. I identified seven SDGs as most relevant to greenhouse production. I devised an analytical framework incorporating 14 indicators to assess the sustainability of four representative greenhouse systems: low-tech, unheated plastic greenhouses in Spain, and high-tech, heated greenhouses in the Netherlands, combined with two cultivation methods (conventional and organic).

Conventional, high-tech greenhouses in the Netherlands showed the greatest potential for positive contributions towards four of the SDGs. However, their relatively high energy use makes it difficult to achieve SDG7 on affordable and clean energy, where low-tech systems perform better due to lower energy use from relatively cleaner sources. Lower water use efficiency and higher nutrient losses in all soil-based cultivation systems are barriers to achieving some targets under most of the selected SDGs. Organic cultivation systems show relatively high water and land use. This analytical framework allows potential users to identify the existence of substantial synergies, but also considerable trade-offs between SDGs, which are crucial for making good policy, investment and management decisions related to greenhouse production.

In conclusion, this thesis demonstrates that a systems approach is needed for sustainability assessment in greenhouse production and highlights important synergies and trade-offs between achieving different sustainability goals. I identified that water, nutrients and energy use are the most critical sustainability themes that predominantly determine the overall sustainability of greenhouse production. In high-tech, heated greenhouse systems, reducing fossil-based energy use is the most critical challenge for

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attaining sustainability. In soil-based greenhouses, management of water and nutrients is a central topic to further optimising the systems towards sustainable development. This thesis proposes an analytical framework comprising suitable indicators tailored for greenhouse production. This framework did not attempt to weigh the chosen indicators and identified SDGs, but was designed to allow end-users, such as policy makers and stakeholders, to make decisions on their priority of actions towards sustainability.

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Lastly, to my stepbrother Siyan, you are forever in our hearts. Rest in peace.

# ABOUT THE AUTHOR

Dianfan Zhou was born in the Gansu province of Northwest China. She obtained her bachelor's degree in horticulture at Nanjing Agricultural University. Her interest in greenhouse production was sparked by conducting experiments in a plastic greenhouse with temperatures reaching up to 45–50°C in the summer season in Nanjing. Wishing to



delve deeper into this field, she moved to Wageningen to study greenhouse horticulture. During her MSc study, she worked with Dr. Elias Kaiser to study the photosynthetic induction of tomato plants in response to fluctuating light conditions and raising CO<sub>2</sub> concentrations. The intriguing findings in photosynthesis research ignited her academic curiosity, leading her to a joint PhD program between the University of Tasmania in Australia and Wageningen University.

Dianfan started her PhD in Tasmania in 2016, initially focusing on evaluating the environmental performance of commercial greenhouse production systems in Australia. With gaining multi-dimensional understanding of greenhouse production and refined research questions, she broadened the research to include the sustainability of greenhouse production systems, aiming to establish a framework for evaluating the sustainability of different greenhouse production systems across varied environmental and socio-economic contexts. This work involved collaboration with Australian greenhouse growers, stakeholders engaged in upstream processes of greenhouse production, and external researchers.

Beyond academics, Dianfan's passion for nature flourished in Tasmania's rich environment. She spent most of her free time exploring its beautiful landscape. After moving back to China during the pandemic period she has developed a newfound hobby of bird-watching.



## **PE&RC Training and Education Statement**

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)



### **Review/project proposal (6 ECTS)**

- Opportunities for greenhouse horticulture in temperate climatic regions of Australia

### **Post-graduate courses (4.5 ECTS)**

- Uncertainty propagation in spatial environmental modelling; Wageningen University (2016)
- Introduction to R for statistical analysis; University of Tasmania (2018)

### **Deficiency, refresh, brush-up courses (1.5 ECTS)**

- Training in SimaPro software; Australian Life Cycle Assessment (2018)

### **Laboratory training and working visits (4.2 ECTS)**

- Data collection at research greenhouses; Western Sydney University, Australia (2017)
- Research collaboration with external experts; Institute of Agrifood Research and Technology, Barcelona, Spain (2019)

### **Invited review of journal manuscripts (2 ECTS)**

- Agriculture systems: optimizing regional cropping systems with a dynamic adaptation strategy for water-sustainable agriculture in the Hebei Plain of China (2018)
- Irrigation science: the effects of amount and distribution of supplemental water on wheat yield and water use efficiency (2018)

### **Competence, skills and career-oriented activities (2.7 ECTS)**

- Communicating research; University of Tasmania (2016)
- Writing clear science; University of Tasmania (2018)
- Industry engagement training; University of Tasmania (2018)
- Competence assessment; Wageningen University (2019)
- Searching and organising literature for PhD candidates; Wageningen University (2019)

### **Scientific Integrity/Ethics in science activities (0.6 ECTS)**

- Introduction to higher degree by research; University of Tasmania (2016)

### **PE&RC Annual meetings, seminars and PE&RC weekend/retreat (1.8 ECTS)**

- PE&RC First year weekend (2016)
- PE&RC Day (2016)
- PE&RC Last year weekend (2019)

### **Discussion groups/local seminars or scientific meetings (9.7 ECTS)**

- FLOP; Wageningen University (2016)
- Biological sciences seminar series; University of Tasmania (2016)

## **PE&RC Training and Education Statement**

- Tasmanian Institute of Agriculture seminar; University of Tasmania (2016)
- Centre for food safety and innovation seminar; University of Tasmania (2018)

### **International symposia, workshops and conferences (4.8 ECTS)**

- Food politics conference; Hobart, Australia (2016)
- Greensys; Beijing, China (2017)
- Vertical farm workshop; Wageningen, the Netherlands (2019)

### **Societally relevant exposure (4.3 ECTS)**

- Agricultural festival (2016, 2018)
- Vegetables Australia an industry magazine by AUSVEG (2018)
- Local newspaper the advocate (2018)
- Local radio interview by ABC in Hobart (2019)

### **Lecturing/supervision of practicals/tutorials (1.8 ECTS)**

- Crop ecology; Wageningen University (2016)
- Farming systems and business management; University of Tasmania (2019)

### **BSc/MSc thesis supervision (2.5 ECTS)**

- Effects of different irrigation regimes and nitrogen fertiliser treatments on growth and quality of Herb plants

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