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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 showed 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.

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 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 and Heuvelink, 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 (Almeida et al., 2014; Antón et al., 2012, 2005; Bojacá et al., 2014; Boulard et al., 2011; Dias et al., 2017; Page et al., 2012; Torrellas et al., 2012a, 2012b).

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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_2 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_2 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 (UN, 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.

2. Methods

2.1. 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 1.

Table 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_2 enrichment	Yes	No	Yes	No
Artificial lighting	Yes/no[1]	No	Limited[2]	No
Fertigation system	Recirculating[3]	Free drainage	Free drainage	Free drainage
Main pest control	Natural enemies	Synthetic pesticides	Natural enemies	Natural enemies
Restriction for fertiliser	No	No	Yes[4]	Yes[4]

[1] Artificial lighting may be used in greenhouses to secure fruit production at times when sunlight is insufficient (Marcelis and Heuvelink, 2019).
[2] 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).
[3] Collection and reuse of drain nutrient solution;
[4] Maximum manure application of 170 kg N ha^{-1} $year^{-1}$ (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).

2.2. 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 Section 3.1–3.7.

2.3. 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 re-formulated 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.

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.

3.1. 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 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 (Clark et al., 1999; Kaiser and Ernst, 2011; Pimentel, 1993). 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 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 2). The tomato yield was 50-90 kg m^{-2} in high-tech glasshouses where no supplementary light was used (Heuvelink et al., 2020; Raaphorst et al., 2019). However, yield was substantially higher when supplementary lighting was applied (90-100 kg m^{-2}) (Heuvelink et al., 2020; Raaphorst et al., 2019), 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 2), indicating the highest land use efficiency. In conventional, low-tech greenhouses, tomato yield was ca. 9-17 kg m^{-2} (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^{-2} in the Netherlands (Tittarelli et al., 2017) and 6-15 kg m^{-2} in Spain (Tittarelli et al., 2017). The largest land use was observed in organic, low-tech greenhouses (7-17 m^2 are required to produce 100 kg tomatoes; Tittarelli et al., 2017). For organic production in high-tech greenhouses water use (22 L kg^{-1}; Pronk et al., 2007) was slightly higher than in conventional, high-tech greenhouses but still much lower

Table 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 [1])	High-Tech (with SL)	Low-Tech	High-Tech	Low-Tech
2.1 By 2030, ensure access by all people to safe, nutritious and sufficient food all year round	Harvest season (weeks)	40-41 [a] +	48 [a] +	12-36 [b]	25-33 [c]	12 [c]
	Market price (€ kg^{-1})	0.83 [d]	0.83 [2]	0.76 [e] +	1.5 [f]	1.07 [e]
2.3 By 2030, double the agricultural productivity **2.4** By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production	Yield (kg m^{-2} $year^{-1}$)	50-90 [a] +	90-100 [a] +	9-17 [b]	50 [c] +	6-15 [c]
	Land use (m^2 100 kg^{-1})	1.1-2 +	1-1.1 +	5.9-11	2 +	6.7-16.7
	Water use (L kg^{-1})	14-16 [g] +	14-16 [3] +	29 [h]	22 [i]	> 29 [4]

[1] SL: Supplementary Lighting;
[2] Prices of tomatoes from conventional, high-tech greenhouses with SL was assumed to be same to that from greenhouses without SL.
[3] Water use from conventional, high-tech greenhouses with SL was assumed to be same to that from greenhouses without SL.
[4] Estimation was based on the lower yield in organic low-tech systems.
[a] Heuvelink, 2018; Raaphorst et al., 2019;
[b] Valera-Martínez et al., 2016;
[c] Tittarelli et al., 2017;
[d] European Commission, 2020;
[e] Fresh Plaza, 2016;
[f] Albert Heijn, 2020; Amsterdam Tips, 2020;
[g] Pronk et al., 2007; van Kooten et al., 2008;
[h] Torrellas et al., 2012b;
[i] Pronk et al., 2007.

Table 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 andair, water and soil pollution and contamination	N emission to water system (kg N ha^{-1} $year^{-1}$)	64-107 [a] +	234-262 [b]	709 [c]	—
	PPPs (kg active ingredients $ha^{-1}year^{-1}$)	10 [d]	32 [d]	Near zero +	Nero Zero +

[a] Pronk et al., 2007;
[b] Soto et al., 2015;
[c] Voogt et al., 2011;
[d] Montero et al., 2011.

Table 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
6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimising release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling andsafe reuse globally	Proportion of recycling water used (%)	85 [a] +	0	0	0
	Treatment on discharges (yes/no)	Yes [b] +	No	No	No

[a] Pronk et al., 2007;
[b] Voogt et al., 2013.

than for low-tech systems (Torrellas et al., 2012b).

3.2. 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 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^{-1} $year^{-1}$ (Pronk et al., 2007), and can be completely eliminated when 100% of drain water is reused (Pronk et al., 2007). According to Soto et al. (Soto et al., 2015), N emissions from low-tech greenhouses were about 2-4 times more than 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^{-1} $year^{-1}$ (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^{-1} (mainly fungicides; Montero et al., 2011). The use of PPPs was substantially higher in low-tech systems, with 32 kg ha^{-1} (Montero et al., 2011).

3.3. 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 3), the share of drain water re-used, and whether or not waste water was treated before being released to the environment (Table 4).

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 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.

Table 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 [1])	High-Tech (with CHP)	Low-Tech	High-Tech (without CHP)	High-Tech (with CHP)	Low-Tech
7.2 By 2030, increase substantially the share of renewable energy in the global energy mix	Share of renewable energy use in greenhouse systems (%)	8.6 [a]	0	17.4 [b] +	8.6	0	17.4 +
7.3 By 2030, double the global rate of improvement in energyefficiency	Energy use [2] (MJ kg^{-1})	24 [c]	13 [3; c]	4 [d]	33 [e]	15 [4]	< 4 [5] +
	CO_2 emissions at farmgate[6] (kg CO_2 eq kg^{-1})	1.2 [c]	0.7 [7; c]	0.3 [d]	1.9 [f]	0.8 [7; f]	0.1 [g] +

[1] Combined heat and power;
[2] 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, taking into account the lifespan of a greenhouse structure.
[3] Net energy use for tomato production, deducting the energy use for the excessive electricity transferred to national electricity grid;
[4] Net energy use for tomato production. Estimation was based on (Dorais et al., 2014; Vermeulen and Lans, 2011);
[5] Estimation was based on (Baptista et al., 2017);
[6] CO_2 emissions caused by greenhouse construction were only included in low-tech systems, not in high-tech ones. Methods for calculating CO_2 emissions were based on PAS 2050 (Blonk et al., 2010) for high-tech systems and CML 2001 (Guinée, 2002) for low-tech systems;
[7] Net CO_2 emissions for tomato production, deducting the CO_2 emissions of the excessive electricity transferred to national electricity grid.
[a] Statistics Netherlands, 2020;
[b] Red Eléctrica, 2018;
[c] Raaphorst et al., 2019;
[d] Torrellas et al., 2012a;
[e] Dorais et al., 2014;
[f] Vermeulen and Lans, 2011;
[g] Baptista et al., 2017.

3.4. 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). Table 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. The majority 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.

The energy required to produce 1 kg tomatoes was used to assess energy use efficiency (Target 7.3). Equivalent CO_2 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_2 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_2 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 Vaneeckhaute, 2020). For example, 1-10 kg CO_2 eq per kg is generated to produce of synthetic N fertiliser, but 1-850 kg CO_2 eq per kg may be emitted to produce of compost N fertiliser (Walling and Vaneeckhaute, 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_2 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_2 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^{-1} (without CHP) in the Netherlands (Dorais et al., 2014) and 97 MJ kg^{-1} 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_2 emissions for tomato production can in some instances be halved by using such offsets in both conventional and organic systems (Raaphorst et al., 2019; Vermeulen and Lans, 2011). Further, the use of biomass energy for heating can also reduce the generation of CO_2 emissions, reaching up to an 86% reduction in an organic, high-tech greenhouse in Canada (Dorais et al., 2014).

3.5. 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 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 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.

3.6. 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 enviromental 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, 2002) 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_2 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_2 emissions, greenhouse production systems must also minimise their impacts on ocean acidification (Target 14.3). Hence, CO_2 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 3). Further, conventional, high-tech systems (without use of CHP) showed a lower eutrophication potential (ca. 0.63 g PO_4^{3-} eq kg^{-1} 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).

Table 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^{-1})		+		
2	Yield (kg m^{-2})	+			
2, 12, 15	Land use (m^2 100 kg^{-1})	+			
2, 6, 12, 15	Water use (L kg^{-1})	+			
3, 6, 12, 14	N emission to water systems (kg ha^{-1} $year^{-1}$)	+			
3, 15	PPPs (kg active ingredients $ha^{-1}year^{-1}$)			+	+
6	Share of recycling water used (%)	+			
6, 12	*Treatment on discharges*	+			
7	Share of renewable energy use (%)		+		+
7	Energy use (MJ kg^{-1})				+
7, 14	CO_2 emissions at farmgate (kg CO_2 eq kg^{-1})				+
12	*Waste generation*			+	
14	Eutrophication potential (g PO_4^{3-} eq kg^{-1})	+			
Total number of obtained best scores		8	2	2	4

3.7. 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 fresh water 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 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 3) and thus performed better in terms of maintaining the biodiversity compared with conventional greenhouse systems.

4. Discussion

4.1. 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 (Dias et al., 2017; Khoshnevisan et al., 2014; Torrellas et al., 2012b, 2012a). 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 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).

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; Dias et al., 2017; Page et al., 2014; Torrellas et al., 2012b). 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; Ruff-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 (Dorais et al., 2014; Torrellas et al., 2012b; Vermeulen, 2016, 2010), 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_2 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_2 emissions. In comparison with conventional systems, organic, high-tech greenhouses resulted in higher environmental impacts per unit of tomatoes, such as CO_2 emission and eutrophication, suggesting a lower contribution for achieving sustainability. This is in 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 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 t ha^{-1} $year^{-1}$) (Stanghellini et al., 2003)

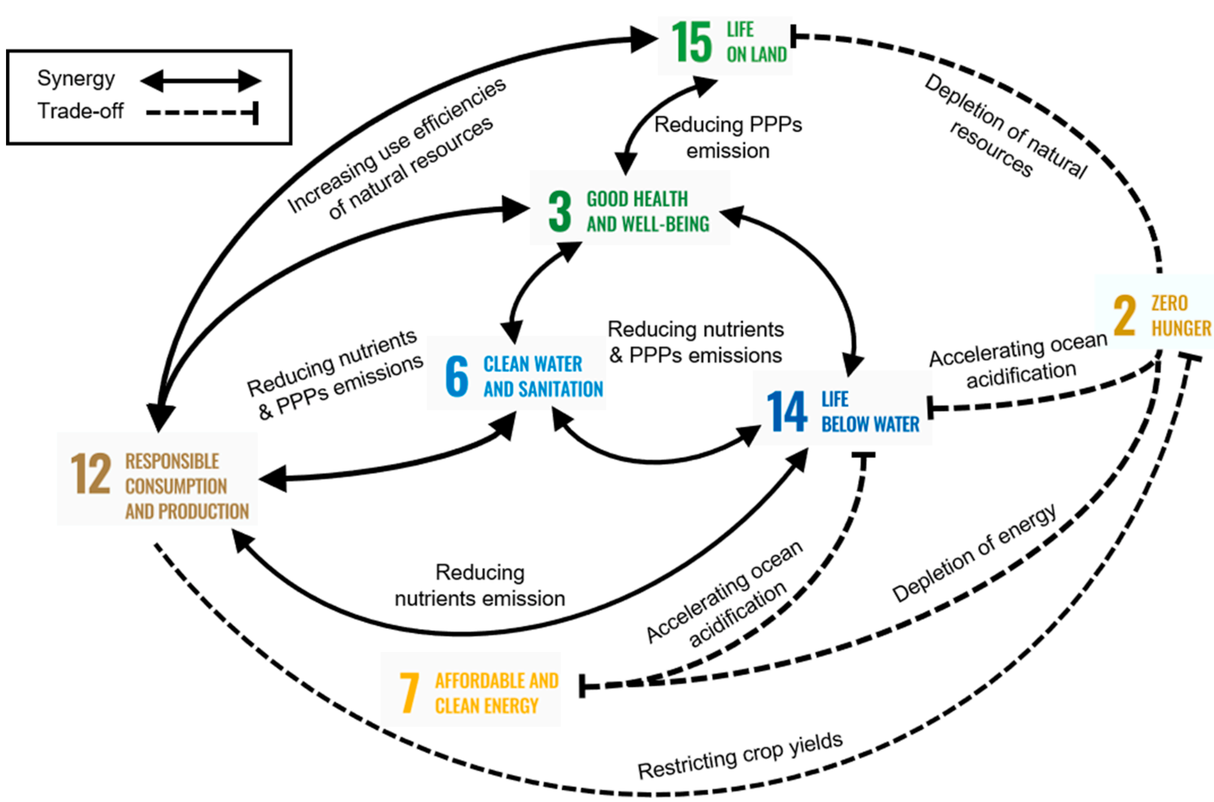

Fig. 1. Identified synergies and trade-offs between seven selected SDGs in the case of greenhouse vegetable production. Solid line with arrows denotes synergies, dense dash line with single block end indicates trade-offs. For example, synergies were identified among SDG3 (good health and well-being), 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.

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 t ha^{-1} $year^{-1}$; 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).

4.2. Synergies and trade-offs between SDGs

SDG2 (zero hunger) is fundamental to achieve all SDGs (FAO, 2016). However, trade-offs amongst goals and sub-goals are inevitable and require informed and deliberate choices by decision-makers (Figure 1). Antle and Valdivia (2020) pointed 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, greenhouse gases (GHG) 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 emission (SDG14: life below water and SDG15: life on land) (Nilsson et al., 2016; Pradhan et al., 2017; Singh et al., 2018).

SDG12 (responsible consumption and production) is a prerequisite for achieving the sustainable development of greenhouse production, due to its positive associations with other SDGs. For example, efficient use of natural resources and reducing and managing chemical emissions are two main components to achieve SDG12 (Figure 1). These also are the keys for maintaining good health (SDG3), fresh-water 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).

4.3. 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 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, 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).

4.4. 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^2; 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. 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 a starting point of understanding the contributions of greenhouse horticulture in attaining SDG goals; 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.

CRediT authorship contribution statement

Dianfan Zhou: Conceptualization, Methodology, Data curation, Formal analysis, Writing - original draft. **Holger Meinke:** Writing - review & editing, Supervision. **Matthew Wilson:** Writing - review & editing, Supervision. **Leo F.M. Marcelis:** Conceptualization, Methodology, Writing - review & editing, Supervision. **Ep Heuvelink:** Conceptualization, Methodology, Data curation, Writing - review & editing, Visualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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