Journal of Cleaner Production 372 (2022) 133659

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Life cycle assessment of tomato production for different production strategies in Norway

Muhammad Naseer [a,*], Tomas Persson [a], Anne-Grete R. Hjelkrem [a], Peter Ruoff [b], Michel J. Verheul [a]

[a] NIBIO, Norwegian Institute of Bioeconomy Research, NO-1431, Ås, Norway
[b] Centre for Organelle Research, University of Stavanger, Stavanger, Norway

ARTICLE INFO

Handling Editor: M.T. Moreira

Keywords:
Environmental impact
Global warming potential
Greenhouse
LCA
Renewable energy

ABSTRACT

The availability of fresh vegetables grown in greenhouses under controlled conditions throughout the year has given rise to concerns about their impact on the environment. In high latitude countries such as Norway, greenhouse vegetable production requires large amounts of energy for heat and light, especially during the winter. The use of renewable energy such as hydroelectricity and its effect on the environment has not been well documented. Neither has the effect of different production strategies on the environment been studied to a large extent. We conducted a life cycle assessment (LCA) of greenhouse tomato production for mid-March to mid-October (seasonal production), 20th January to 20th November (extended seasonal) production, and year-round production including the processes from raw material extraction to farm gate. Three production seasons and six greenhouse designs were included, at one location in southwestern and one in northern Norway. The SimaPro software was used to calculate the environmental impact. Across the three production seasons, the lowest global warming (GW) potential (600 g CO_2-eq per 1 kg tomatoes) was observed during year-round production in southwestern Norway for the design $NDSFML_{LED + LED}$, while the highest GW potential (3100 g CO_2-eq per 1 kg tomatoes) was observed during seasonal production in northern Norway for the design NS. The choice of artificial lighting (HPS (High Pressure Sodium) or LED (Light Emitting Diodes)), heating system and the production season was found to have had a considerable effect on the environmental impact. Moreover, there was a significant reduction in most of the impact categories including GW potential, terrestrial acidification, and fossil resource scarcity from seasonal to year-round production. Overall, year-round production in southwestern Norway had the lowest environmental impact of the evaluated production types. Heating of the greenhouse using natural gas and electricity was the biggest contributor to most of the impact categories. The use of an electric heat pump and LED lights during extended seasonal and year-round production both decreased the environmental impact. However, while replacing natural gas with electricity resulted in decreased GW potential, it increased the ecotoxicity potential.

1. Introduction

The availability of fresh agricultural products throughout the year is common in many developed countries. These products include off-season vegetables, which are domestically grown in greenhouses with controlled heating, cooling and supplemental lighting systems, and imported vegetables. There is, however, a growing concern regarding the effects of fresh vegetable production on the environment (Torrellas et al., 2012b). In Norway, tomatoes are a major greenhouse crop. The Norwegian market has seen a significant preference for locally produced tomatoes compared to imported ones (Bremnes et al., 2019). According to Rebnes and Angelsen (2021), Norway imported a total of 24113 tonnes of tomatoes in 2021, of which around 88% were imported from Spain and the Netherlands, and 12720 tonnes were produced domestically.

Greenhouses in northern latitude countries, such as Norway, consume great amounts of heat, often generated from fossil fuels, and electricity for lighting, particularly due to the shortage of light and heat during the winter season. In 2018, the Norwegian commercial greenhouses consumed a total of around 0.56 TWh energy (Statistics Norway,

* Corresponding author.
E-mail address: na.seer@hotmail.com (M. Naseer).

https://doi.org/10.1016/j.jclepro.2022.133659
Received 18 May 2022; Received in revised form 6 July 2022; Accepted 13 August 2022
Available online 17 August 2022

2019) mostly for heating and light. Several studies have shown that in greenhouse production, heating, which to a large extent is supplied by natural gas, has the highest environmental impact, and is the main contributor to global warming (Halberg and Rasmussen, 2006; Davis et al., 2011). The latest available study for Norway, showed that around 95% of greenhouse gas (GHG) emissions from commercial greenhouse tomato production were related to energy use. In addition, smaller emissions originated from artificial CO_2 fertilization. In total, the use of gas, including natural gas and propane for heating and CO_2 fertilization, accounted for almost 93% of GHG emissions while only 2% of GHG emissions were due to the use of hydroelectric energy (Verheul and Thorsen, 2010).

There is an increasing understanding of the effects of climate change among states and citizens alike in Europe, with around 92% of European citizens being of the view that GHG emissions ought to be reduced and the EU economy be made carbon neutral by 2050 (European Commission, 2019). In Norway, around 69.4% Norwegians are of the view that human activity is affecting the climate (Aasen et al., 2019). This view agrees to the Norwegian government's plan to reduce GHG emissions by at least 40% by 2030 compared to 1990 levels (*Rapport fra partssammensatt arbeidsgruppe* 1.7.2019) under the targets set by the Paris agreement (2015). Moreover, Norway produces some of the world's highest amounts of renewable electricity, primarily hydroelectricity, which emits only small amounts of greenhouse gases (The Norwegian Water Resources and Energy Directorate, 2020), creating a possibility to replace fossil fuel in the greenhouse sector with hydroelectricity.

Multiple studies have evaluated effects on the environment and trade-offs in greenhouse and field tomato production by using life cycle assessment (LCA) techniques (Martínez-Blanco et al., 2011). Some of these works have focused on calculating the environmental impact, including abiotic depletion, acidification, eutrophication, global warming and photochemical oxidation, of indoor year-round tomato production in multi-tunnels (Khoshnevisan et al., 2014), while others study the environmental impact of tomato production in both open-fields and greenhouses with a comparison of different types of fertilizers (Martínez-Blanco et al., 2011). Antón et al. (2005) in his study has conducted an environmental impact assessment of three different tomato production systems including soil cultivation and open and closed hydroponic systems and analysed three different waste management scenarios to concluded that composting of biodegradable matter was the best way to manage the waste of biomass. Interest has also grown on the effect of heating systems on the environment (Torrellas et al., 2012b, 2013) some works also focus on the analysing the use of energy and the related greenhouse gas emissions of greenhouse organic farming (Baptista et al., 2017). Other local specific studies including under Spanish (Torrellas et al., 2012a), French (Boulard et al., 2011), Italian conditions (Cellura et al., 2012) have showed that high-tech, soil-less heated greenhouse production have a higher impact than unheated tunnels and greenhouses. Other works focusing on different types of greenhouses under Italian conditions (Russo and Scarascia Mugnozza, 2005) and on studying the carbon and water footprints trade-offs in Sydney, Australia also found similar results (Page et al., 2012). In unheated greenhouses, especially in the Mediterranean region, it has been shown that the structure, auxiliary equipment, fertilizers (Romero-Gámez et al., 2009) packaging and transportation (Hueso-Kortekaas et al., 2021) that contributed to the largest environmental impacts. Verheul and Thorsen (2010) found that heating requirements of greenhouses accounted for almost 93% of the total GHG emissions in greenhouses in Norway. Gjessing (2018) concluded that although GWP from the greenhouse structure was higher due to the higher use of steel and reinforced concrete in greenhouse systems using biogas than the GWP from standard greenhouse during seasonal and year-round production, low emissions associated with the production phase meant that the former system had lower cumulative emissions than standard production systems. However, there is a need to study other impact categories than GWP in order to get a better understanding of greenhouse tomato production in high latitude regions. In addition, LCA of tomato production in greenhouses heated by hydropower are missing.

Previously it has been shown that even within the same location, there is a large difference in the economic performance and resource use between production strategies in seasonal production (Naseer et al., 2021) as well as in extended seasonal and year-round production (Naseer et al., 2022). These studies also showed that greenhouse production with a high economic performance and low energy use was possible for Orre in southwestern Norway with a comparably mild climate, but such an economically favourable and energy-efficient production could not be identified for Tromsø in northern Norway. Therefore, it can be expected that the environmental impact may also differ between production strategies. The present study is aimed at examining the environmental impact of seasonal and off-season greenhouse tomato production in northern climatic conditions for greenhouse designs that have the potential for high economic performance or have a low fossil fuel use.

2. Materials and methods

2.1. Scope and system boundaries

Three production seasons: seasonal production (mid-March to mid-October); extended season (20th January to 20th November); and year-round production were evaluated at Orre in southwestern (SW) Norway (lat. 58.71, long. 5.56, alt. 18 m a.s.l.), and Tromsø in northern (N) Norway (lat. 69.65, long. 18.96, alt. 60 m a.s.l.) (Fig. 1) using a variation in greenhouse designs.

The system boundary included all stages of the products' life cycle from raw material extraction to farm gate (Fig. 2). Transport to the wholesaler and store was not within our boundaries, neither was the production or use of biological and chemical plant protections. Although biological pesticides, and to a relatively lesser extent also chemical pesticides, are used by most producers, previous studies related to heated greenhouses in Netherlands (Antón et al., 2012) and Norway (Verheul and Thorsen, 2010) have shown that pesticide contribution in greenhouse tomato production is negligible with regard to the total contribution of the tomato production. The functional unit (FU), which is the reference unit for expressing environmental interventions, was

Fig. 1. The two selected locations in Norway, for which the production strategies were evaluated.

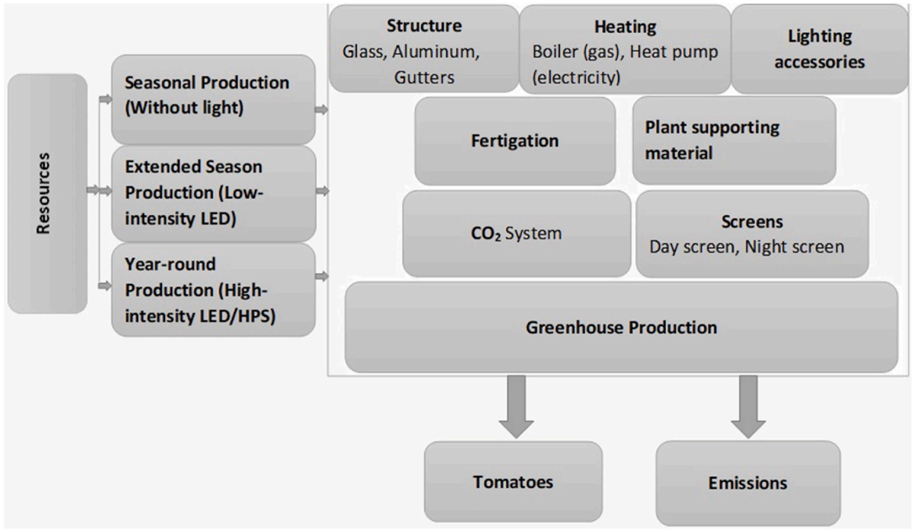

Fig. 2. System boundaries used in this study for greenhouse tomato production.

expressed as 1 kg fresh weight pre-packed 1st class tomatoes.

The marketable yield, i.e., 1st class fruits was considered to be 95% of the total fresh weight yield. Plants were transplanted to the greenhouse with the initial leaf area index (LAI) of 0.3, and the tomatoes were harvested at the light red ripening stage. For seasonal and extended seasonal production, young plants were transplanted in the greenhouse on standard Rockwool slabs with a density of 2.60 plants per m^2 and a row distance of 1.5 m. For year-round production, we considered two inter-plantings of tomato plants. The variable inputs included natural gas, electricity, fertilizer (that were supplied through water and is therefore referred to fertigation), cultivation medium, other production materials (tying hooks, nylon, etc.) and packaging and the fixed inputs included the greenhouse building and fixtures (cultivation slabs, gutters, shading systems, lighting systems etc.).

The seasonal production was carried out without the use of artificial lighting, whereas the extended production took place with fixed capacities of low intensity LED inter-lighting and in the year-round production we varied the type (HPS (High Pressure Sodium) and LED (Light Emitting Diodes)) and capacities of top lighting and constant LED-inter-lighting (see Naseer et al., 2022 for more details).

2.2. Scenarios

We evaluated two heating systems that comprised of a boiler heating system using natural gas, and a heat pump powered by electricity. To save energy within the greenhouse, we used night or day thermal energy screens. CO_2 fertilization was supplied to the greenhouse either by burning of natural gas in the boiler or as pure CO_2 from a tank.

The designs that previously were found to be the most profitable or that had the lowest energy use for seasonal previous (Naseer et al., 2021) and extended season and year-round production (Naseer et al., 2022) were evaluated. In doing so we aimed to assess whether designs that yield profit can also be sustainable considering other environmental loads than GHG emissions from energy use. A brief description of the selected greenhouse designs for the three production seasons is presented below:

2.2.1. Selected designs for seasonal production

1. **Night energy screen (NS):** This design consisted of a gas boiler with 1.16 MW capacity that was used for heating and CO_2 fertilization. A night energy screen consisting of 50% aluminum and 50% polyethylene, which was used for energy-saving purposes whenever the temperature was below 14 °C at night was included. No artificial cooling or fogging system was used. This design yielded the highest NFR for seasonal production out of several designs evaluated in Naseer et al. (2021).
2. **Day and night energy screens with fogging and mechanical cooling and heating (DNSFM)**: This design represents a production where the natural gas is partly replaced by hydroelectric energy. An electrical heat pump with a coefficient of performance (COP) of 3 was used for heating i.e., 1 kWh energy consumed would provide 3 kWh of output heat. There was an activation of mechanical cooling and heat harvest during the day when the temperature in the greenhouse exceeded 25 °C. In addition, CO_2-enrichment was provided by pure CO_2. All electricity was assumed to be generated in a hydro-electrical power plant. This design is a relatively closed design and had the lowest fossil fuel use (Naseer et al., 2021).

2.2.2. Selected designs for extended season production

1. **Night and day thermal screens + light ($NDSL_{LED}$):** This design consisted of the same design elements as NS described above, with the addition of a thermal screen, used during the day, when the temperature reached below 10 °C and the global radiation was below 150 Wm^{-2}, and an LED inter-lighting supplement with a capacity of 125 μmol.
2. **Night and day thermal screens + fogging + mechanical heating + lights ($NDSFML_{LED}$):** This design consisted of two thermal screens: one used during the day (like in design $NDSL_{LED}$) and the other at night (like in design NS), fogging, an electric heat pump with mechanical heating and cooling, and LED as inter-lighting with a capacity of 125 μmol.

2.2.3. Selected designs for year-round production season

1. **Night and day thermal screens + fogging + mechanical heating + lights ($NDSFML_{HPS + LED}$):** This design consisted of two thermal screens: one used during the day and the other at night, fogging, an electric heat pump with mechanical heating and cooling, and HPS with a capacity of 200 and 250 μmol as top light and LED as inter-lighting with a capacity of 125 μmol.
2. **Night and day thermal screens + fogging + mechanical heating + lights ($NDSFML_{LED + LED}$):** This design consisted of two thermal screens: one during the day and the other at night, fogging, an electric heat pump with mechanical heating and cooling, and LED with a capacity of 200 and 250 μmol as top light and LED as inter-lighting with a capacity of 125 μmol.

2.3. Impact assessment

This study used the SimaPro 9 software (www.simapro.com) to perform an LCA of greenhouse tomato production. LCA is well-established and standardized by the International Commission of Standardization ISO 14040 (2006a) and ISO 14044 (2006b). Data related to the background system, i.e., the production of fertilizers, electricity, constructions, etc. was taken from the Ecoinvent v.3 database. The ReCiPe 2016 Midpoint (H) V1.04 method (Huijbregts et al., 2017; Goedkoop et al., 2009) was used for impact assessment for a selection of impact categories (Table 1).

2.4. Data inventory

Values for greenhouse structure and building, fertilizer, culture medium, packaging, other production material, and waste management were taken from Verheul and Thorsen (2010), while values for fossil fuel and electricity use, pure CO_2 fertilization and yield in the seasonal production were taken from Naseer et al. (2021), and the corresponding values in the extended seasonal and year-round production from Naseer et al. (2022). We have chosen to use the values for basic greenhouse structure, fertilizer, culture medium, packaging, other production material, and waste management from 2010 since during the last 12 years, these have not changed significantly in the greenhouses we have evaluated in our study (Milford et al., 2021). The cultivation system was organised into these components: greenhouse structure, greenhouse equipment, climate control systems and fertilizers. Tables 2–4 provide an overview of yield and resources used for different designs, locations, and production seasons.

We used a Venlo type glasshouse with standard glass roofs and natural ventilation (Fernandez and Bailey, 1992). The greenhouse equipment included trolleys, cultivation gutters, shade systems and growing lights. A drip irrigation system was used to grow plants by irrigating standard Rockwool slabs. Bumblebees were used in the greenhouse for pollination. The material and equipment for greenhouse structure are listed in Table 5. CO_2 fertilization was supplied to the greenhouse through the boiler, by burning natural gas, or as pure CO_2 from a tank. The values for CO_2 supplied from the boiler was not recorded by the local growers, while values for pure CO_2 fertilization have been included. The total amounts of fertilizers used (Tables 2–4) were set according to recommendations by advisors at NIBIO. With regards to the waste management, we have assumed that metal and glass were 100% recycled, concrete was 50% recycled, and plastics 50% recycled and 50% incinerated. The estimated life spans of the different materials were: 20 years for metals, glass and concrete, 4–5 years for screens and other equipment, and 1 year for Rockwool.

Table 1
Selected impact categories, their abbreviations, and the measurement units.

Impact category	Abbreviation	Unit
Global warming	GW	g CO_2-eq
Ozone formation, Human health	OzHH	g NO_X-eq
Ozone formation, Terrestrial ecosystems	OzTE	g NO_X-eq
Terrestrial acidification	TA	g SO_2-eq
Freshwater eutrophication	FwEu	g P-eq
Marine eutrophication	MEu	g N-eq
Terrestrial ecotoxicity	TEco	g 1,4-DCB
Freshwater ecotoxicity	FwEco	g 1,4-DCB
Marine ecotoxicity	MEco	g 1,4-DCB
Land use	LU	m^2a crop-eq
Mineral resource scarcity	MiRes	g Cu-eq
Fossil resource scarcity	FRes	g oil-eq

Table 2
Overview of the crop yield and resources used for the selected greenhouse designs for the seasonal production in two Norwegian regions. For an explanation of the design abbreviations, see section 2.2.

Input data used in selected greenhouse designs for seasonal tomato production				
	Orre		Tromsø	
	NS	NDSFM	NS	NDSFM
Crop yield (kg m^{-2}) (Fresh weight)	41.4	40.2	37.2	35.6
Energy use natural gas (kWh m^{-2})	293.9	157.4	380.5	217.9
Electricity use (kWh m^{-2})	0.0	22.1	0.0	22.8
Plant fertilizers				
Nitrate Nitrogen (kg m^{-2})	0.5	0.4	0.4	0.4
Phosphorus (kg m^{-2})	0.1	0.1	0.1	0.1
Potassium (kg m^{-2})	0.8	0.7	0.7	0.7
Magnesium (kg m^{-2})	0.1	0.1	0.1	0.1
Calcium (kg m^{-2})	0.4	0.4	0.3	0.3
CO_2 (Pure) (kg m^{-2})	1.3	1.6	0.6	1.8

Table 3
Overview of the crop yield and resources used for the selected greenhouse designs for extended seasonal production in two Norwegian regions. For an explanation of the design abbreviations, see section 2.2.

Input data used in selected greenhouse designs for extended seasonal tomato production				
	Orre		Tromsø	
	$NDSL_{LED}$	$NDSFML_{LED}$	$NDSL_{LED}$	$NDSFML_{LED}$
Crop Yield (kg m^{-2}) (Fresh weight)	81.2	81.4	76.3	77.0
Energy use natural gas (kWh m^{-2})	550.2	269.3	644.5	340.5
Electricity use (kWh m^{-2})	199.2	272.5	215.7	288.9
Plant fertilizers				
Nitrate Nitrogen (kg m^{-2})	0.9	0.9	0.8	0.8
Phosphorus (kg m^{-2})	0.2	0.2	0.2	0.2
Potassium (kg m^{-2})	1.5	1.5	1.4	1.4
Magnesium (kg m^{-2})	0.2	0.2	0.2	0.2
Calcium (kg m^{-2})	0.7	0.7	0.7	0.7
CO_2 (Pure) (kg m^{-2})	2.8	4.5	2.5	4.7

3. Results

3.1. Seasonal production

The results showed that seasonal greenhouse production had high values for global warming potential and terrestrial ecotoxicity (Table 6). Of the two locations, Tromsø had higher values due to higher energy use. Replacing natural gas with electricity for an electric heat pump reduced most impact categories in both locations, however more so in Tromsø, but increased terrestrial ecotoxicity, while land use potential remained the same. Of the various input factors, natural gas and greenhouse structure had the highest contribution to most impact categories, while packaging had a high contribution to land use potential (Fig. 3). The design NS in Orre was associated with global warming potential of approximately 2200 g CO_2-eq. for 1 kg tomatoes, while the design with the lowest fossil fuel used, NDSFML, had the lowest global warming potential (approx. 1300 g CO_2-eq. for 1 kg tomatoes). Meanwhile, the highest global warming potential was observed in Tromsø (about 3100 g CO_2-eq. for 1 kg tomatoes for the design NS) and of about 1700 g CO_2-eq. for 1 kg tomatoes for the design NDSFML.

3.2. Extended seasonal production

The results showed that extended season production had relatively lower global warming potential and mineral and fossil resource scarcity

Table 4
Overview of crop yield and the resources used for the selected greenhouse designs for the year-round production in two Norwegian regions. For an explanation of the design abbreviations, see section 2.2.

Input factors used in selected greenhouse designs for year-round tomato production	Orre		Tromsø	
	NDSFML $_{HPS+LED}$	NDSFML $_{LED+LED}$	NDSFML $_{HPS+LED}$	NDSFML $_{LED+LED}$
Energy use for HPS 250 μmol				
Natural gas (kWh m^{-2})	129.6	131.9	166.7	166.2
Electricity (kWh m^{-2})	1279.0	955.8	1352	1006
Crop Yield (kg m^{-2}) (Fresh weight)	129.7	129.8	126.6	126.9
Energy use for HPS 200 μmol				
Natural gas (kWh m^{-2})	140.1	140.7	178.4	177
Electricity (kWh m^{-2})	1116.0	857.6	1177	901
Crop Yield (kg m^{-2}) (Fresh weight)	122.6	123.8	119.2	120.4
Plant fertilizers used for both capacities				
Nitrate Nitrogen (kg m^{-2})	1.4	1.4	1.4	1.4
Phosphorus (kg m^{-2})	0.3	0.3	0.3	0.3
Potassium (kg m^{-2})	2.4	2.4	2.3	2.3
Magnesium (kg m^{-2})	0.4	0.4	0.4	0.4
Calcium (kg m^{-2})	1.2	1.2	1.2	1.2
CO_2 (Pure) (kg m^{-2})	5.6	5.9	6.3	6.5

than seasonal production but higher impact for terrestrial, freshwater and marine ecotoxicity and terrestrial acidification (Table 7). Tromsø continued to have higher impact for all categories in this season than Orre for both designs. The greater use of hydroelectricity had a greater contribution to some of the impact categories while the reduction in natural gas use reduced most impact categories. Of the various input factors, natural gas and greenhouse structure had the highest contribution to most impact categories, while electricity had a high contribution to terrestrial, freshwater and marine ecotoxicity and land use potential (Fig. 4). The global warming potential for the design NDSL$_{LED}$ in Orre was about 2100 g CO_2-eq. for 1 kg tomatoes and was highest for the same design in Tromsø (about 2600 g CO_2-eq. for 1 kg tomatoes). However, global warming potential was lowest for the design NDSFML$_{LED}$ in Orre, of about 1100 g CO_2-eq. for 1 kg tomatoes, which was the most energy efficient design in this season (Table 3).

3.3. Year-round production

For the year-round production, the global warming potential for the design NDSFML with 200 μmol HPS as top light and 125 μmol inter-lighting capacities was about 640 g CO_2-eq. for 1 kg tomatoes in Orre (Table 8). When lighting capacities and types of lighting was varied for the same location, the lowest global warming potential was observed for the combination 250 μmol LED as top light and 125 μmol LED as inter-lighting, which was the lowest throughout the two locations (616 g CO_2-eq. for 1 kg tomatoes) (Table 9). Highest global warming potential was observed for the combination HPS as top light with capacity of 200 μmol in Tromsø (766 g CO_2-eq. for 1 kg tomatoes). Electricity, followed by natural gas, had the highest share in almost all impact categories in the two locations except global warming potential and fossil resource scarcity, while the other factors had significantly lower impact (Figs. 5 and 6). When HPS was replaced by LED as top light, regardless of the

Table 5
Materials and quantities for greenhouse structure, auxiliary equipment, lighting equipment and climate system equipment for the Venlo greenhouse.

Greenhouse size	Shape	Type		Reference
5760 (m^2)	90*64 (m)	Venlo		Fernandez & Bailey (1992)
Structure				Verheul and Thorsen (2010) and Antón et al. (2012)
Material	Quantity	Unit	Explanation	
Aluminium	16022	kg	Gutters, ridges, bars, ventilation opening mechanism, screens	
Steel	62601	kg	Roof bars, rails, ventilation opening mechanism, wire system	
Concrete	26.3	m^3	Foundation, side paths	
Glass	67789	kg	Roof, walls	
Polyester	828.2	kg	Screens, floor material	
Greenhouse equipment				Verheul and Thorsen (2010) and Antón et al. (2012)
Polystyrene	523	kg	Substrate layers	
Polyvinyl Chloride	203	kg	Distribution system, distribution equipment	
Steel	46378	kg	Boiler, condensers, pumps, pipes, CO_2 systems equipment	
LDPE	450	kg	Drippers, microtubes, pipes, benches	
Aluminium	4869	kg	Heating pipes, rail pipes	
Polyethylene	32	kg	Tubes, screens	
Nylon	102	kg	Rope, clips	
Polyester	22	kg	Inside tanks	
Lighting equipment				Verheul and Thorsen (2010); Zhang et al. (2017); Dale et al. (2011) and Tuenge et al. (2013)
Aluminium	25650	kg	HPS fixture, LED, fitting parts, brackets, blocks	
Cords	8550	m	power cords	
Copper	239	kg	Wiring	
Diodes	132	kg	LED	
Glass	712	kg	LED glass	

capacities, an overall decrease in all impact categories was observed at both locations, pointing toward the LED as a better choice for supplemental lighting for year-round greenhouse tomato production in Norway.

4. Discussion

This study aimed at conducting an LCA of tomato production under different production strategies at two different locations in Norway. The designs have previously been shown to be economically profitable or associated with low energy use in seasonal (Naseer et al., 2021), and extended seasonal and year-round production (Naseer et al., 2022). Our results showed that, even within one country, the choice of production strategy, including the use of supplemental lighting, choice of heating system and the production season, had a huge influence on the environmental impact of the final production. Moreover, the fact that certain designs that yielded high NFR also resulted in low environmental impact across the three production seasons and selected locations shows that

Table 6
LCA results for seasonal greenhouse tomato production per FU, in Orre and Tromsø in Norway for NS (Night Screen) and NDSFM (Night and Day Screen with Mechanical Heat Pump and Fogging).

		Orre		Tromsø	
Impact category	Unit	NS	NDSFM	NS	NDSFM
Global warming	g CO_2-eq	2203.10	1315.46	3096.97	1757.06
Ozone formation, Human health	g NO_X-eq	1.78	1.23	2.40	1.53
Ozone formation, Terrestrial ecosystems	g NO_X-eq	1.86	1.29	2.51	1.60
Terrestrial acidification	g SO_2-eq	2.06	1.54	2.70	1.86
Freshwater eutrophication	g P-eq	0.14	0.12	0.17	0.14
Marine eutrophication	g N-eq	0.02	0.01	0.02	0.02
Terrestrial ecotoxicity	g 1,4-DCB	1791.84	1896.96	2093.48	2144.22
Freshwater ecotoxicity	g 1,4-DCB	57.33	70.38	67.96	75.12
Marine ecotoxicity	g 1,4-DCB	74.03	88.51	88.46	95.01
Land use	m2a crop-eq	0.01	0.01	0.01	0.01
Mineral resource scarcity	g Cu-eq	6.32	6.23	7.35	6.53
Fossil resource scarcity	g oil-eq	758.57	442.28	1075.00	595.79

economic profitability can be combined, and achieved, together with low environmental impact.

As expected, our results indicate that the greatest environmental burden from the production of greenhouse tomatoes in typical Norwegian systems arises from the large amounts of natural gas used for heating the greenhouse. Other components such as electricity use, structure, fertilizers, and packaging were also significant contributors, yet they were to a relative extent surpassed by heating in most environmental impact categories. This is comparable to findings from similar studies on greenhouse tomato production in Norway (Verheul and Thorsen, 2010; Gjessing, 2018) and other high latitude regions including Canada (Dias et al., 2017a, 2017b; Hendricks, 2012) and Sweden (Bosona and Gebresenbet, 2018).

This study chose 1 kg tomatoes as FU, which is a common unit for measuring tomato yield. A reason for selecting this FU is the possibility of easy comparison with other studies related to greenhouse production. Nonetheless, choosing 1 kg of tomato can be problematic in case tomatoes of different sizes are produced. Tomato types with smaller sizes, for instance cherry tomatoes, often have a lower yield but a higher market value than larger tomatoes. In such cases, it may be relevant to calculate the environmental impact per unit of turnover (Verheul and Thorsen, 2010). This study assumes the production of ordinary round tomatoes. There is a considerable production of this type of tomatoes in greenhouses across Europe. The fact that there is such a large geographical production range, including several European countries (Högberg, 2010) as well as other world regions (Hendricks, 2012), of this type of tomatoes means that results of this study are highly relevant from an international perspective. Comparisons of the results from our study with those from other study designs can help identify environmental advantages and disadvantages with different allocations of greenhouse tomato production across climate conditions, regions, and greenhouse types.

Such comparisons of results also need to consider the system boundaries that have been considered in the LCA calculations. For this study, a system boundary including all processes from raw material extraction to farm gate was set. Hence, the transport from the farm to the consumer has not been considered and the subsequent losses that may occur during the transport phase are also not included. A recent study of greenhouse tomato production in Southern Spain considering the entire production stages, from processing of input materials to the disposal stage, reported that around 77% of its energy demand and carbon emissions arise due to packaging and transport (Hueso-Kortekaas et al., 2021). A previous study assessing the environmental impact of tomato crop in a multi-tunnel greenhouse, with the system boundary from raw materials extraction to farm gate including material disposal showed that under Mediterranean conditions, in the absence of heating requirements for the greenhouse, the structure, auxiliary equipment and fertilizers contributed the most to the environmental impacts (Torrellas et al., 2012a).

Another related aspect to the system boundary is that of the cut-off criteria for the types of emissions that were considered. For instance, in our study, we have not included the biogenic emissions related to the use of irrigation water since water is not a limited resource in Norway and the drainage water is usually recycled. Our study also omits biogenic emissions, including potential nutrient leaching and N2O and NH3 emissions from substrate (Rockwool) to air since N2O emissions from rockwool wrapped in plastic are significantly different from N2O emissions from managed soils. In addition, the nitrogen source is only synthetic (sodium nitrate) and consist of only 5% NH4+ and 95% of the

Fig. 3. Relative contribution to different impact categories for seasonal greenhouse tomato production for NS (Night Screen) (a and c) and NDSFM (Night and Day Screen with Mechanical Heat Pump and Fogging) (b and d), in Orre (a and b) and Tromsø (c and d). The 'other' input category includes plant protection, cultivation medium and other production materials (tying hooks, nylon, etc.). For an explanation of impact categories' abbreviations, see Table 1.

Table 7
LCA results for extended season greenhouse tomato production per FU in Orre and Tromsø in Norway for $NDSL_{LED}$ (Night and Day Screens and LED inter-lighting) and $NDSFML_{LED}$ (Night and Day Screens with Mechanical Heat Pump and Fogging and LED inter-lighting) using 125 μmol LED as inter-lighting.

		Orre		Tromsø	
Impact category	Unit	NDSL	NDSFML	NDSL	NDSFML
Global warming	g CO_2-eq	2127.17	1173.25	2619.99	1510.68
Ozone formation, Human health	g NO_X-eq	1.73	1.15	2.09	1.40
Ozone formation, Terrestrial ecosystems	g NO_X-eq	1.81	1.20	2.18	1.46
Terrestrial acidification	g SO_2-eq	2.25	1.73	2.66	2.03
Freshwater eutrophication	g P-eq	0.19	0.18	0.22	0.21
Marine eutrophication	g N-eq	0.02	0.02	0.02	0.02
Terrestrial ecotoxicity	g 1,4-DCB	4188.23	4549.90	4732.22	5051.11
Freshwater ecotoxicity	g 1,4-DCB	145.27	168.82	164.96	187.95
Marine ecotoxicity	g 1,4-DCB	181.95	209.10	206.83	233.02
Land use	m2a crop-eq	0.01	0.01	0.01	0.02
Mineral resource scarcity	g Cu-eq	5.82	5.71	6.50	6.29
Fossil resource scarcity	g oil-eq	723.45	380.62	894.48	496.71

fertilizer NO3-. Therefore, similar to the findings of Hosono and Hosoi (2008) the indirect N2O emissions will be much less than in a conventional tomato soil-based culture. The indirect N2O emissions are included due to the production of Sodium nitrate.

Our results show that while there was a substantial reduction in most impact categories when natural gas was replaced with electricity in the seasonal and extended seasonal production cycles, an increase in the terrestrial, freshwater and marine ecotoxicity was detected. However, during year-round production season, moving from $NDSFML_{HPS\ +\ LED}$ to $NDSFML_{LED\ +\ LED}$, changed the trend of an increase in terrestrial, freshwater and marine ecotoxicity to an overall reduction for all impact categories. This could be explained by the fact that during seasonal and extended season production and within designs in each season, the use of electricity and natural gas increased, causing an increase in the potential for terrestrial, freshwater and marine ecotoxicity for which electricity was the biggest contributor.

Yet in year-round production, when LED replaced the traditional HPS as top lights and combined with the use of an electric heat pump, a reduction in the terrestrial, freshwater and marine ecotoxicity potential was seen. This could be explained by the fact that in typical glass greenhouses, heating requirements contribute to around 76–82% of terrestrial ecotoxicity potential (Boulard et al., 2011). Moreover, the mercury in HPS lights has also been shown to be a significant contributor to terrestrial ecotoxicity. However, the use of LED lights in design $NDSFML_{LED\ +\ LED}$ had lower environmental impacts than HPS and contributed to saving energy, as has also been shown in other studies (Tähkämö and Halonen, 2015). This puts further weight in the suggestion that in cold climate zones such as Norway, switching to year-round production of greenhouse tomatoes can yield better results, both in terms of economic profitability and environmental sustainability (Milford et al., 2021). The reduction in the environmental impact from seasonal to extended and year-round seasons can be further explained by the following reasons: 1. For the seasonal production, the design with the night screen, which used higher levels of energy, had higher yield. In extended and year-round seasons, the design having the night and day screens and electric heat pump had higher levels of energy saved and high levels of yield; 2. The use of artificial lighting and electric heat pump during extended and year-round seasons had the double effect of not only increasing the yield but also reducing the use of fossil fuel due to the heat produced from the lights (Naseer et al., 2021, 2022). These positive results of using an electric heat pump are a new and important empirical contribution of this study to existing research, especially related to high latitude regions such as Norway, and those which use energy from renewable sources.

Previous studies have shown that the necessity of heating greenhouses, especially in colder climates, and the subsequent reliance on fossil fuels, including oil and natural gas, make imported tomatoes a better choice than locally produced tomatoes (Keskitalo, 2009; Payen et al., 2014). However, the study by Payen et al. (2014) shows that under the conditions they studied, the imported tomatoes performed better with respect to the carbon and energy perspective but from a freshwater resource standpoint, local production of tomatoes under French conditions was better. One exception is the study by Nordenström et al. (2010), who found that bio-fuelled CHP heated greenhouse tomato production in central-Norway performed better environmentally in all impact categories studied including global warming potential, and potentials of abiotic depletion, acidification, eutrophication and ozone layer depletion than open-field tomatoes imported from Spain. While our study did not include a comparison with the environmental impact of imported tomatoes, our results have shown that for greenhouse tomato production in Norway, year-round production has much lower environmental impacts than seasonal and extended seasonal production. In total, our results indicate that the understanding of the difference

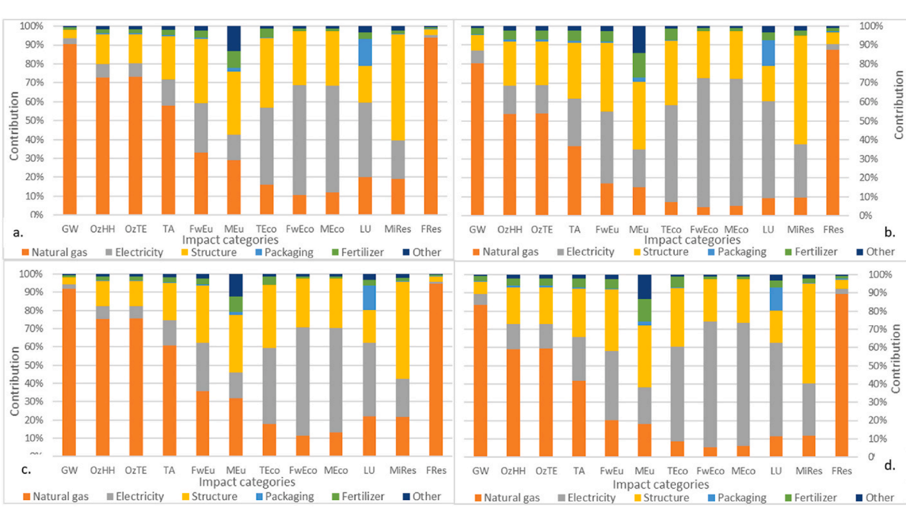

Fig. 4. Relative contribution to different impact categories for extended season greenhouse tomato production for $NDSL_{LED}$ (a and c) and $NDSFML_{LED}$ (b and d), in Orre (a and b) and Tromsø (c and d). NDSL denotes the design with the Night and Day Screens and LED inter-lighting, NDSFM denotes Night and Day Screens with Mechanical Heat Pump and Fogging and LED inter-lighting. The 'other' input category includes plant protection, cultivation medium and other production materials (tying hooks, nylon, etc.). For an explanation of impact categories' abbreviations, see Table 1.

Table 8
LCA results for year-round greenhouse tomato production per FU, in Orre and Tromsø in Norway for $NDSFML_{HPS+LED}$ and $NDSFML_{LED+LED}$ with 200 μmol top light and 125 μmol inter-lighting capacities. NDSFML denotes Night and Day Screens with Mechanical Heat Pump and Fogging and HPS as top lighting and LED as top and inter-lighting.

		Orre		Tromsø	
Impact category	Unit	NDSFML_HPS_LED	NDSFML_LED_LED	NDSFML_HPS_LED	NDSFML_LED_LED
Global warming	g CO_2-eq	642.62	599.71	766.44	711.36
Ozone formation, Human health	g NO_X-eq	0.92	0.82	1.04	0.92
Ozone formation, Terrestrial ecosystems	g NO_X-eq	0.95	0.85	1.07	0.95
Terrestrial acidification	g SO_2-eq	1.85	1.57	2.04	1.72
Freshwater eutrophication	g P-eq	0.26	0.21	0.28	0.23
Marine eutrophication	g N-eq	0.02	0.01	0.02	0.02
Terrestrial ecotoxicity	g 1,4-DCB	7856.23	6250.60	8480.15	6711.44
Freshwater ecotoxicity	g 1,4-DCB	349.72	271.70	378.13	292.63
Marine ecotoxicity	g 1,4-DCB	428.10	332.89	462.93	358.58
Land use	m2a crop-eq	0.02	0.02	0.02	0.02
Mineral resource scarcity	g Cu-eq	7.01	5.88	7.52	6.27
Fossil resource scarcity	g oil-eq	172.39	165.15	211.75	201.45

Table 9
LCA results for year-round greenhouse tomato production per FU, in Orre and Tromsø in Norway for $NDSFML_{HPS+LED}$ and $NDSFML_{LED+LED}$ with 250 μmol top light and 125 μmol inter-lighting capacities. NDSFML denotes Night and Day Screens with Mechanical Heat Pump and Fogging and HPS as top lighting and LED as top and inter-lighting.

		Orre		Tromsø	
Impact category	Unit	$NDSFML_{HPS+LED}$	$NDSFML_{LED+LED}$	$NDSFML_{HPS+LED}$	$NDSFML_{LED+LED}$
Global warming	g CO_2-eq	616.24	570.47	728.74	670.69
Ozone formation, Human health	g NO_X-eq	0.93	0.81	1.03	0.90
Ozone formation, Terrestrial ecosystems	g NO_X-eq	0.95	0.83	1.06	0.93
Terrestrial acidification	g SO_2-eq	1.90	1.58	2.08	1.72
Freshwater eutrophication	g P-eq	0.27	0.22	0.29	0.23
Marine eutrophication	g N-eq	0.02	0.01	0.02	0.02
Terrestrial ecotoxicity	g 1,4-DCB	8304.28	6476.35	8938.21	6935.62
Freshwater ecotoxicity	g 1,4-DCB	373.72	284.79	403.37	305.92
Marine ecotoxicity	g 1,4-DCB	457.22	348.72	493.53	374.63
Land use	m2a crop-eq	0.02	0.02	0.03	0.02
Mineral resource scarcity	g Cu-eq	7.22	5.95	7.72	6.33
Fossil resource scarcity	g oil-eq	159.73	153.38	195.22	185.66

Fig. 5. Relative contribution to different impact categories for year-round greenhouse tomato production for $NDSFML_{HPS+LED}$ (a and c) and $NDSFML_{LED+LED}$ (b and d) respectively with 200 μmol top light and 125 μmol inter-lighting capacities in Orre (a and b) and Tromsø (c and d). NDSFML denotes Night and Day Screens with Mechanical Heat Pump and Fogging and HPS as top lighting and LED as top and inter-lighting. The 'other' input category includes plant protection, cultivation medium and other production materials (tying hooks, nylon, etc.). For an explanation of impact categories' abbreviations, see Table 1.

between imported and locally produced tomatoes, in Norway and in other countries, would benefit from further comparisons of imported and locally produced tomatoes where different designs and production cycles are included. Such comparisons should also include the same system boundaries for all included types of production, other inventory data and assumptions.

Nonetheless, the increased use of electricity resulted in a trade-off between the reduced potential for global warming and the increased potentials for terrestrial, freshwater and marine ecotoxicity during the three production seasons, even though there is an overall reduction in all other impact categories during the year-round production. Moreover, there was an overall reduction in all impact categories between different designs during the same production cycle. This presents a challenge in terms of assessing the environmental impact and economic performance of greenhouse tomato production and can be seen in LCAs of greenhouse tomato production using renewable energy resources in different

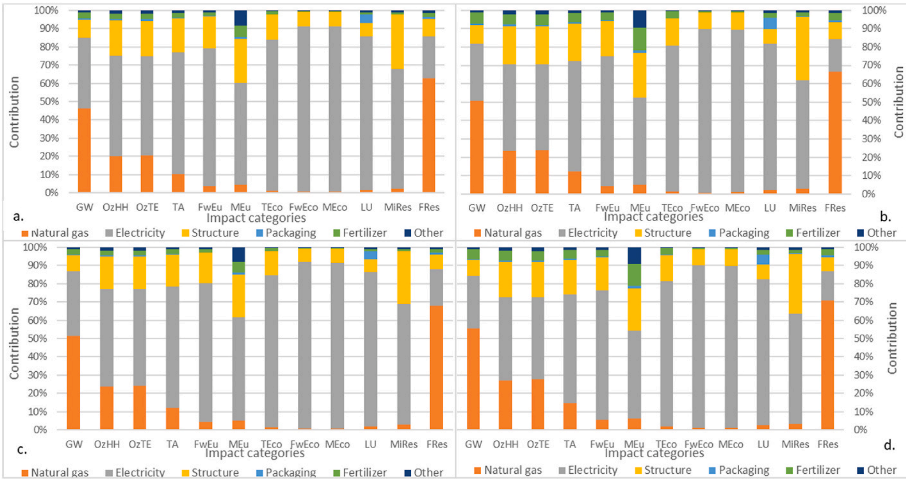

Fig. 6. Relative contribution to different impact categories for year-round greenhouse tomato production for $NDSFML_{HPS + LED}$ (a and c) and $NDSFML_{LED + LED}$ (b and d) respectively with 250 μmol top light and 125 μmol inter-lighting capacities, in Orre (a and b) and Tromsø (c and d). NDSFML denotes Night and Day Screens with Mechanical Heat Pump and Fogging and HPS as top lighting and LED as top and inter-lighting. The 'other' input category includes plant protection, cultivation medium and other production materials (tying hooks, nylon, etc.). For an explanation of impact categories' abbreviations, see Table 1.

regions. For instance, Dias et al. (2017a, 2017b) showed that when natural gas is substituted by wooden biomass for heating greenhouses in Ontario, Canada, although there was an almost 85% reduction in global warming potential relative to the fossil fuels, yet relative to global warming potential, its use had higher impacts in eutrophication and respiratory effects. Similarly, a study on the greenhouse tomato production in Hungary comparing the use of geothermal energy and natural gas for heating found that the former energy source had significantly lower environmental impact than the latter, however, geothermal energy had high financial costs (Torrellas et al., 2012b).

It will be difficult to say what the increase in terrestrial, freshwater and marine ecotoxicity means compared with an increase in greenhouse gas emissions or other categories, as no normalisation or weighting has been carried out (European Commission, 2010). Irrespective of the production cycle, questions related to the environmental impact of different energy sources and the environmental impact of vegetables is complex and highlights crucial issues related to the comparison of impact categories of food products. Payen et al. (2014) showed a trade-off between energy-related impact categories and freshwater use impacts. Their findings highlight the significance of selecting different impact categories and the preference one gives to them. Thus, it is not a simple matter of recommending a specific production strategy but the significance of the impact category one decides to give preference to. Nevertheless, further research is needed to know more about the selection criteria and the trade-offs between individual impact categories.

The study comprised of an LCA for several different greenhouse designs within each of three production cycles. The results for the assessment showed that variation in greenhouse management systems, especially climate control, has a significant impact on the environmental burden associated with the production of the same crop i.e., tomato and even within the same production region. This indicates the benefits of studying different production strategies to further reduce the environmental impact of greenhouse tomato production in Norway and could also benefit other regions with predominant production of greenhouse tomatoes or have similar climate conditions as that of Norway. Nonetheless, as pointed out by Milford et al. (2021), cooperation on measures to reduce the environmental impact among growers within different regions in Norway and elsewhere is necessary for these to achieve positive results.

5. Conclusion

In the present study, an LCA of greenhouse tomato production including processes from raw material extraction to farm gate as system boundary for three production cycles, a selected number of design strategies and two locations in Norway, was conducted. The study showed that there was a significant reduction in most impact categories from seasonal to extended and year-round production, indicating that year-round greenhouse tomato production in southwestern Norway has a lower impact from all evaluated categories than tomato production in northern Norway. Heating requirements of the greenhouse arising from the use of natural gas and electricity comprised the biggest contributor to most of the impact categories. Despite a reduction in most impact categories by using higher levels of electricity than fossil fuel in extended and year-round production, its contribution to terrestrial, freshwater, and marine ecotoxicity was significantly large.

CRediT authorship contribution statement

Muhammad Naseer: Conceptualization, Methodology, Data Acquisition, Software, Writing – original draft, and Subsequent Revisions, Editing. **Tomas Persson:** Conceptualization, Analysis and Interpretation, Drafting Manuscript and Revision. **Anne-Grete R. Hjelkrem:** Analysis and Interpretation, Revision. **Peter Ruoff:** Analysis and Interpretation, Revision. **Michel J. Verheul:** Conceptualization, Analysis and Interpretation, Drafting Manuscript and Revision.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgement

This study is a part of the research project 'Bioeconomic production of fresh greenhouse vegetables in Norway (BioFresh)', which is financially supported by the Bionær program of the Research Council of Norway, project number 255613/E50.

References

Aasen, M., Klemetsen, M., Reed, E.U., Vatn, A., 2019. Folk og klima: nordmenns holdninger til klimaendringer, klimapolitikk og eget ansvar. CICERO: 20, Retrieved on 12th. http://hdl.handle.net/11250/2634149. (Accessed May 2021).
Antón, A., Montero, J., Muñoz, P., Castells, F., 2005. LCA and tomato production in Mediterranean greenhouses. Int. J. Agric. Resour. Govern. Ecol. 4, 102–112.
Antón, A., Torrellas, M., Montero, J.I., Ruijs, M.N., Vermeulen, P.T., Stanghellini, C., 2012. Environmental Impact Assessment of Dutch Tomato Crop Production in a Venlo Glasshouse.

Baptista, F.J., Murcho, D., Silva, L.L., Stanghellini, C., Montero, J.I., Kempkes, F., Munoz, P., Gilli, C., Giuffrida, F., Stepowska, A., 2017. Assessment of energy consumption in organic tomato greenhouse production-a case study. Acta Hortic. 1164, 453–460. https://doi.org/10.17660/ActaHortic.2017.1164.59.

Bosona, T., Gebresenbet, G., 2018. Life cycle analysis of organic tomato production and supply in Sweden. J. Clean. Prod. 196, 635–643.

Boulard, T., Raeppel, C., Brun, R., Lecompte, F., Hayer, F., Carmassi, G., Gaillard, G., 2011. Environmental Impact of Greenhouse Tomato Production in France, 31. Agronomy for Sustainable Development, pp. 757–777.

Bremnes, E., Hansen, J.S., Slimestad, R., Verheul, M., 2019. *Gartneryrket*. NIBIO, NOFIMA. https://nofima.no/publikasjon/1807024/.

Cellura, M., Longo, S., Mistretta, M., 2012. Life Cycle Assessment (LCA) of protected crops: an Italian case study. J. Clean. Prod. 28, 56–62.

Dale, A.T., Bilec, M.M., Marriott, J., Hartley, D., Jurgens, C., Zatcoff, E., 2011. Preliminary comparative life cycle impacts of streetlight technology. J. Infrastruct. Syst. 17, 193–199.

Davis, J., Wallman, M., Sund, V., Emanuelsson, A., Cederberg, C., Sonesson, U., 2011. Emissions of Greenhouse Gases from Production of Horticultural Products. Analysis of 17 Products Cultivated in Sweden. SR 828. Retrieved on. http://www.diva-portal.org/smash/get/diva2:943913/FULLTEXT01.pdf. (Accessed 13 May 2021).

Dias, G.M., Ayer, N.W., Khosla, S., Acker, R.C., Young, S.B., Whitney, S.R., Hendricks, P., 2017a. Life cycle perspectives on the sustainability of Ontario greenhouse tomato production: benchmarking and improvement opportunities. J. Clean. Prod. 140, 831–839.

Dias, G.M., Ayer, N.W., Kariyapperuma, K.A., Thevathasan, N., Gordon, A.M., Sidders, D., Johannesson, G.H., 2017b. Life cycle assessment of thermal energy production from short-rotation willow biomass in Southern Ontario, Canada. Appl. Energy 204, 343–352.

European Commission, 2010. International Reference Life Cycle Data System (ILCD) Handbook. Publications Office of the European Union, Luxembourg.

European Commission, 2019. Climate Change''. *Special Eurobarometer 490*. https://ec.europa.eu/clima/sites/default/files/support/docs/report_summary_2019_en.pdf. https://doi:10.2834/00469.

Fernandez, J.E., Bailey, B.J., 1992. Measurement and prediction of greenhouse ventilation rates. Agric. For. Meteorol. 58 (3–4), 229–245. https://doi.org/10.1016/0168-1923(92)90063-A.

Gjessing, H., 2018. *Livsløpsvurdering Av Tomatproduksjon I Norge: Hvordan Vil Klima-Og Miljøpåvirkninger Endres Ved Bruk Av Biogassressurser?* (Master's Thesis. Norwegian University of Life Sciences, Ås.

Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A. De, Struijs, J., Zelm, R. Van, 2009. ReCiPe 2008, a Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level- First Edition Report I: Characterisation.

Halberg, N., Rasmussen, M.D., 2006. Miljøvurdering af konventionel og økologisk avl af grøntsager. *Arbejdsrapport fra Miljøstyrelsen nr 5*. Danmark.

Hendricks, P., 2012. *Life Cycle Assessment of Greenhouse Tomato (Solanum lycopersicum L.) Production in Southwestern Ontario* (Doctoral Dissertation).

Hosono, T., Hosoi, N., 2008. N2O and NO Emissions during Tomato [Lycopersicon esculentum] Cultivation by Means of Drip Fertigation in a Glasshouse. Bulletin of the National Institute of Vegetable and Tea Science *(Japan)*.

Högberg, J., 2010. European Tomatoes - Comparing Global Warming Potential, Energy Use and Water Consumption from Growing Tomatoes in Sweden, the Netherlands and the Canary Islands Using Life Cycle Assessment (Master Dissertation).

Hueso-Kortekaas, K., Romero, J.C., González-Felipe, R., 2021. Energy-environmental impact assessment of greenhouse grown tomato: a case study in almeria (Spain). World 2 (3), 425–441.

Huijbregts, M.A., Steinmann, Z.J., Elshout, P.M., Stam, G., Verones, F., Vieira, M.D., Zijp, M.C., Hollander, A., Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147. https://doi.org/10.1007/s11367-016-1246-y.

ISO 14040, 2006a. Environmental Management. Life Cycle Assessment. Principles and Framework. ISO, Geneva, Switzerland.

ISO 14044, 2006b. Environmental Management. Life Cycle Assessment. Requirements and Guidelines. ISO, Geneva, Switzerland.

Keskitalo, A., 2009. Environmental Impacts of Conventionally and Year-Round Produced Greenhouse Tomato (Solanum lycopersicum L.) Production Chain in Finland (Master Dissertation).

Khoshnevisan, B., Rafiee, S., Omid, M., Mousazadeh, H., Clark, S., 2014. Environmental impact assessment of tomato and cucumber cultivation in greenhouses using life cycle assessment and adaptive neuro-fuzzy inference system. J. Clean. Prod. 73, 183–192.

Martínez-Blanco, J., Muñoz, P., Antón, A., Rieradevall, J., 2011. Assessment of tomato Mediterranean production in open-field and standard multi-tunnel greenhouse, with compost or mineral fertilizers, from an agricultural and environmental standpoint. J. Clean. Prod. 19, 985–997.

Milford, A.B., Verheul, M., Sivertsen, T., Kaufmann, L., 2021. Klimagassreduksjon i veksthusnæringen: muligheter, barrierer og tiltak. NIBIO Rapp.

Naseer, M., Persson, T., Righini, I., Stanghellini, C., Maessen, H., Verheul, M.J., 2021. Bio-economic evaluation of greenhouse designs for seasonal tomato production in Norway. Biosyst. Eng. https://doi.org/10.1016/j.biosystemseng.2021.11.005.

Naseer, M., Persson, T., Righini, I., Stanghellini, C., Maessen, H., Ruoff, P., Verheul, M.J., 2022. Bioeconomic evaluation of extended season and year-round tomato production in Norway using supplemental light. Agric. Syst. https://doi.org/10.1016/j.agsy.2022.103391.

Nordenström, E., Guest, G., Fröling, M., 2010. LCA of local bio-chp fuelled greenhouses versus mediterranean open field tomatoes for consumption in northern scandinavia. Linnaeus Eco-Tech. 475–484.

Page, G., Ridoutt, B., Bellotti, B., 2012. Carbon and water footprint trade-offs in fresh tomato production. J. Clean. Prod. 32, 219–226.

Paris agreement, 2015. In report of the conference of the parties to the united nations framework convention on climate change (21st session, 2015: Paris). Retrieved on December. In: HeinOnline, 4, 2017.

Payen, S., Basset-Mens, C., Perret, S., 2014. LCA of local and imported tomato: an energy and water trade-off. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2014.10.007. Retrieved on 15th. (Accessed May 2021).

Rapport fra partssammensatt arbeidsgruppe 1.7.2019, 2019. Jordbruksrelaterte klimagassutslipp. Gjennomgang av klimagassregnskapet og vurdering av forbedringer. https://www.regjeringen.no/contentassets/0f1af0ca7efe493e8e48b46b6fba5ffd/rapport-tbu-jordbruk_siste.pdf. (Accessed 13 May 2021).

Rebnes, G., Angelsen, T., 2021. Totaloversikten 2021. https://www.frukt.no/globalassets/materiell/innsikt/310723_frukt–og-grontstatistikk-2021_korr6.pdf. (Accessed 10 April 2022).

Romero-Gámez, M., Anton, A., Soriano, T., Suárez-Rey, E.M., Castilla, N., 2009. Environmental impact of greenbean cultivation: comparison of screen greenhouses vs. open field. J. Food Agric. Environ. 7 (3–4), 132–138.

Russo, G., Scarascia Mugnozza, G., 2005. LCA methodology applied to various typology of greenhouses. Acta Hortic. 691, 837–844. https://doi.org/10.17660/ActaHortic.2005.691.103.

Statistics Norway, 2019. Forbruk av energi i veksthus. [Consumption of energy in greenhouses]. https://www.ssb.no/statbank/table/12834/. (Accessed 11 December 2021).

Tähkämö, L., Halonen, L., 2015. Life cycle assessment of road lighting luminaires–comparison of light-emitting diode and high-pressure sodium technologies. J. Clean. Prod. 93, 234–242.

The Norwegian Water Resources and Energy Directorate, 2020. Kraftproduksjon. https://www.nve.no/energiforsyning/kraftproduksjon/?ref=mainmenu. (Accessed 22 March 2020).

Torrellas, M., Antón, A., Lopez, J., Baeza, E., Parra, J.P., Muñoz, P., Montero, J.I., 2012a. LCA of a tomato crop in a multi-tunnel greenhouse in Almeria. Int. J. Life Cycle Assess. 17, 863–875.

Torrellas, M., Antón, A., Ruijs, M., Victoria, N.G., Stanghellini, C., Montero, J., 2012b. Environmental and economic assessment of protected crops in four European scenarios. J. Clean. Prod. 28, 45–55.

Torrellas, M., Antón, A., Montero, J.I., 2013. An environmental impact calculator for greenhouse production systems. J. Environ. Manag. 118, 186–195.

Tuenge, J.R., Hollomon, B., Dillon, H.E., Snowden-Swan, L.J., 2013. Life-cycle Assessment of Energy and Environmental Impacts of LED Lighting Products, Part 3: LED Environmental Testing (No. PNNL-22346). Pacific Northwest National Lab. (PNNL), Richland, WA (United States).

Verheul, M.J., Thorsen, S.M., 2010. Klimagassregnskap for norske veksthusprodukter. Bioforsk Rapp. 5 (135).

Zhang, H., Burr, J., Zhao, F., 2017. A comparative life cycle assessment (LCA) of lighting technologies for greenhouse crop production. J. Clean. Prod. 140, 705–713.