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LCA FOR AGRICULTURE

Assessment of climate change impact and resource-use efficiency of lettuce production in vertical farming and greenhouse production in Finland: a case study

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Abstract

Purpose Our aim in this study was to examine lettuce production in vertical farming or in conventional greenhouse production in Northern European conditions from the perspective of climate change impact and environmental sustainability. Further, the goal was to identify practices and choices that could mitigate adverse effects and increase resource-use efficiency, allowing the development of more sustainable production systems.

Methods This article provides new information of the environmental impacts of lettuce production in greenhouses and vertical farming in Finland, compared using the life cycle assessment (LCA) methodology. The impact categories used were climate change impact, cumulative energy demand, resource use of fossil energy sources, resource use of minerals and metals, land use, and water scarcity. The system boundaries covered the production chains from cradle to farmgate, including inputs in production, as well as direct emissions caused by fertiliser use and the onsite composting of organic waste. The environmental impacts of the two production systems with different energy scenarios were assessed: (1) a greenhouse either with average or renewable energy; and (2) vertical farming either with average or renewable energy and with or without waste heat recovery. The data for vertical farming were based on one Finnish production site and supplementary data for the construction materials. The greenhouse data were based on a previous LCA investigation of average Finnish lettuce production.

Results The climate change and all other impact categories were lowest for lettuce produced in vertical farming with renewable energy and waste heat recovery. The climate change impact was largest for lettuce produced in greenhouse with average energy use. For energy use and energy resource use, the impacts of vertical farming were lower than greenhouse production, but for mineral and metal use and water scarcity, the impact of vertical farming was higher for average energy use without heat recovery. Direct land and irrigation water use on the production sites in Finnish circumstances represented only a small share of total land-use and water-use impacts on both production methods.

Conclusion Paying attention to the energy source and heat recovery, the environmental sustainability can be advanced in both vertical and greenhouse production systems.

Keywords Greenhouse production · Vertical farming · Controlled environment agriculture · Life cycle assessment · LCA · Renewable energy

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Highlights

- This is the first primary data–based LCA (life cycle assessment) investigation of vertical farming in Finland and the Nordic countries.
- If renewable energy and waste heat recovery are used, vertical farming seems to perform better in lettuce production in the studied impact categories (climate change, cumulative energy demand and resource use, water use) compared with greenhouse production.
- Using renewable energy sources and improving energy-use efficiency were both important measures for decreasing the climate change impact in both vertical farming and the greenhouse production of lettuce.

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1 Introduction

In Finland, lettuce and fresh herbs are produced in open fields, greenhouses, and today also in vertical farming. The greenhouse area used for the production of lettuces and herbs in Finland increased by 38% between 2011 and 2022 (Natural Resources Institute Finland Statistics 2021). During the last 3 years (2019–2021), lettuce and fresh herbs were produced on 70 ha in greenhouses and 380 ha in open fields. The total yield was ca. 16 million kg in greenhouses and 4 million kg in open fields. There are still no official statistics on the production areas or yields of lettuce and fresh herbs produced in vertical farming.

Vertical farming is an evolving technology. As a concept, vertical farming (VF) is protected from adverse weather conditions and can offer a way to cultivate plants unsuitable for outdoor or even greenhouse production. Using vertical space and reducing the need for additional land for food production contribute to the interest in VF in large cities. Per land area, VF can produce more yield—according to some scenarios, up to 600 times more than in traditional farming (Asseng et al. 2020). VF offers numerous possibilities to grow plants with desired attributes and guaranteed quality (SharathKumar et al. 2020). VF can be considered a sustainable concept regarding water, nutrient, and pesticide use. However, improvements in energy efficiency and profitability are needed (van Delden et al. 2021). Currently, commercial VF production consists mainly of lettuce and herbs.

The greenhouse horticulture market is expected to grow globally from around 32.3 billion USD in 2021 to 65 billion USD by 2030. In Europe, the market is expected to reach 28 billion USD in 2030, with an annual growth rate of 7% (Neha and Vitika 2022). The market value of the global VF market is expected to increase from 5.5 billion USD in 2020 to 20 billion USD by 2026 (Statista 2022).

Although the differences with more traditional production methods are recognised, it is not well known how they affect the environmental impacts of production. Climate change impact has been the main focus in previous studies because the production of vegetables, especially in heated greenhouses, is known to cause greater GHG emissions than production in open fields (Hospido et al. 2009; Boulard et al. 2011), and improvements in management practices can significantly help in decreasing the climate change impact. The efficient use of resources (water and land) has also been of interest in controlled production systems.

Previous LCA studies concerning greenhouse production of lettuce in Finland have included the environmental impact categories climate change (Yrjänäinen 2011; Yrjänäinen et al. 2013; Räsänen et al. 2014; Silvenius et al. 2019; Silvenius and Katajajuuri 2021), eutrophication (Räsänen et al. 2014), and water-use impact (Silvenius et al. 2019).

Environmental impacts such as eutrophication and acidification have received less attention because unlike in open fields, only minimal direct leaching or volatilisation of nutrients is expected to occur in controlled production systems, as irrigation water and nutrients are recycled. According to one Finnish study (Räsänen et al. 2014), the eutrophicating emissions were small in lettuce production in greenhouses, and these were derived mainly from transport and energy production.

Avgoustaki and Xydis (2020) and Graamans et al. (2018) have previously directly compared the environmental sustainability of greenhouse with the vertical farming production of lettuce. According to Avgoustaki and Xydis (2020), the climate change impact, land area, and water use were smaller, but direct energy use was greater in vertical farming production, whereas Graamans et al. (2018) found that both water and energy use were smaller. However, both studies included only the direct resource use in the primary production phase, excluding the production of input materials. A large part of the previous studies of vertical farming are based on literature data or modelling (Graamans et al. 2018; Hallikainen 2019; Avgoustaki and Xydis 2020; Wildeman 2020), and only a few included data from operative production units (Shiina et al. 2011; Kikuchi et al. 2018; Blom et al. 2022). A literature review of sustainability issues of vertical farming and greenhouses concludes that if renewable energy is used, climate change impact can be lower for vertical farming than in open field cultivation and greenhouse (Vatistas et al. 2022).

In relation to the system boundary of the studies, the production of infrastructure (greenhouse or vertical farm structures and materials) has been included in many of the studies (Hospido et al. 2009; Bartzas et al. 2015; Kikuchi et al. 2018; Romero-Gámez and Suárez-Rey 2020; Wildeman 2020). However, none of the previous studies regarding Finnish production has included greenhouse structures in their system boundaries.

Our aim in this study was to examine how lettuce production in vertical farming or in conventional greenhouse systems in Northern European conditions differs from the perspective of environmental sustainability, impact on climate change, and resource-use efficiency. Greenhouse production was selected to comparison, since the amount of open field cultivation of lettuce is less relevant in Northern conditions. In addition, our aim was to identify practices and choices that could increase resource-use efficiency and mitigate climate change to guide the development and planning of future vertical farming systems. The climate change and the resource-use-related impact categories this study considered were climate change, cumulative energy demand, resource use of fossil energy sources, resource use of minerals and metals, land use, and water scarcity.

2 Materials and methods

2.1 Goal and scope

The assessment included the inputs used in the production of lettuce (seeds, fertiliser, pesticides, substrate, energy, irrigation water, CO_2 enrichment, pots), and packing and temporary refrigerated storage of lettuce on the production site (packaging materials, refrigerant, energy) (Fig. 1), as well as construction materials and equipment used in both vertical farming and greenhouse structures. The direct and indirect N_2O emissions from the soil due to nitrogen input and CO_2 emissions from lime application were also included, as well as emissions caused by peat and plant residue decomposition

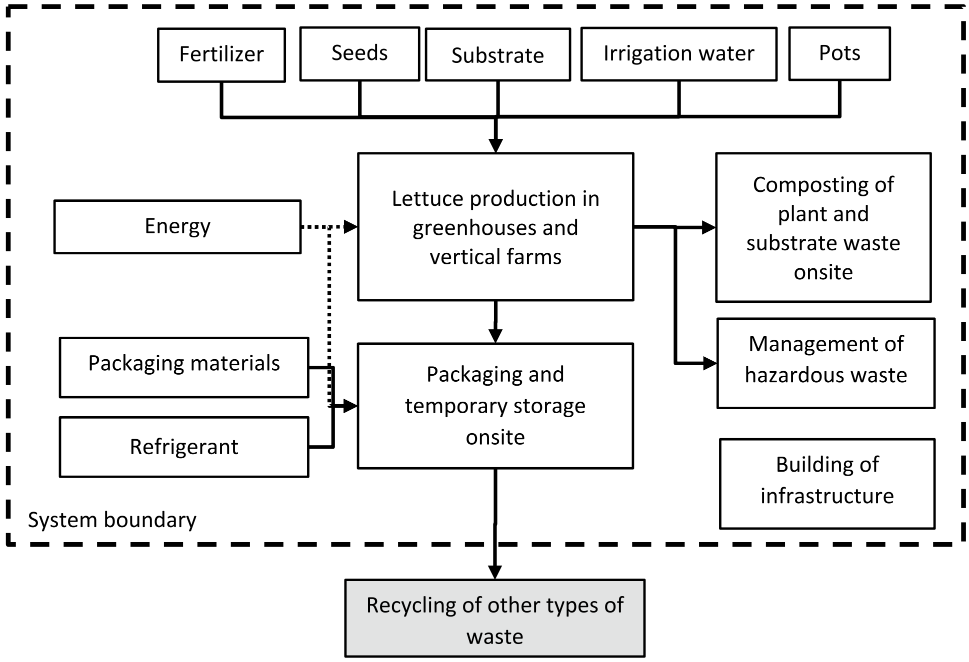

Fig. 1 System boundaries of lettuce production in greenhouses and vertical farms

during onsite composting of substrate and plant waste. The transport of inputs and construction materials to the production site, as well as of waste to recycling plants, was included in the system boundary, but the management and recycling of waste materials were excluded, except for the management of hazardous waste, which was assumed not to be recycled into new products.

Because lettuce production in greenhouses and in vertical farming is energy and resource intensive compared to for example open field vegetable production, impact categories related to climate change, resources use (water, land, minerals, metals), and cumulative energy demand were selected as impact categories to be studied. Climate change, resource use (fossils and minerals and metals), and water scarcity were assessed according to the EF method (EU environmental footprint 3.0) (European Commission 2021), cumulative energy demand, and land use based on Cumulative Energy Demand 1.11 method and Selected LCI results—method in SimaPro (Hischier et al. 2010). The functional unit was 1 kg of fresh lettuce (edible part of the plant).

To analyse the effects of different choices on environmental impacts, six scenarios were formulated and compared (Table 1). The energy choices included the average and renewable electricity production. The selection between renewable and average electricity is a realistic choice for a producer in Finland. In addition to electricity, heating is needed in both vertical farming and greenhouses. The fixtures used for lighting and other electric devices produce waste heat, and can be utilised, but if not, additional heating is applied. Scenarios including the option to utilise or not utilise waste heat were assessed for vertical farming. Unfortunately, no data was available to make a corresponding assessment for greenhouse production. Scenarios for vertical farming (VF) were (1) baseline with renewable energy profile and waste heat utilisation (BAE), (2) renewable energy with no utilisation of waste heat (NAE), (3) average energy with utilisation of waste heat (BRE), and (4) average energy with no utilisation of waste heat (NRE). Scenarios for greenhouse (GH) were (1) average energy production profile (AE) and (2) renewable energy (RE).

Table 1 The different scenarios used in analysing the effect of different management choices on the environmental impacts

Lettuce production system		**A**verage **e**nergy production profile used in average Finnish lettuce production	Only **r**enewable **e**nergy used
Vertical farming	**B**aseline: utilisation of waste heat	**VF BAE**	**VF BRE**
	No utilisation of waste heat	**VF NAE**	**VF NRE**
Greenhouse		**GH AE**	**GH RE**

VF vertical farming, *BAE* baseline utilisation of waste heat and with average energy production profile, *NAE* no utilisation of waste heat and with renewable energy, *BRE* baseline utilisation of waste heat and with renewable energy, *NRE* no utilisation of waste heat and with renewable energy, *GH* greenhouse, *AE* average energy production profile, *RE* renewable energy

The potential to additionally reduce environmental impacts by increasing the life expectancy of production site structures and equipment by 10% and increasing the yield by 10% was studied for VF lettuce produced with renewable electricity utilising waste heat (scenario VF BRE+). The utilization of waste heat from electric devices was assumed to reduce heat produced by electricity with ratio 1:1.

2.2 Inventory analysis

Production data for the lettuce produced in VF were collected from a commercial vertical farming unit in Southern Finland producing lettuce and fresh herbs, considering the years 2018–2020. For the greenhouse production of lettuce, we used data from a previous project studying the environmental impacts of the production of greenhouse vegetables in 2017 in Finland (Silvenius et al. 2019; Silvenius and Katajajuuri 2021). The data on yield and inputs used are presented in Table 2. The impacts of the production of the inputs and the treatment of plant residues and hazardous waste were assessed using the data from the Ecoinvent 3.7 database (Wernet et al. 2016). APOS processes were used in the calculations and a comprehensive list of Ecoinvent 3.7 processes and other data sources used in the calculation is presented in the Supplementary Material (Table S1). The carbon in the peat-based growing media was assumed to decompose completely after use. The resulting CO_2 emissions were calculated based on the data on peat chemical characteristics presented in Pohjala (2014).

Data on the construction materials and equipment used in the vertical farming production unit and greenhouses were collected from the site, another vertical farming facility elsewhere in Finland, literature sources, and the Ecoinvent 3.7 database (Table 3). The vertical farming units were both

Table 2 Input use in lettuce production in vertical farming and greenhouse production in the studied scenarios

	Vertical farm		Greenhouse[a]
Yield, number of plants/m²/year	550		333
Weight of one product, g, edible part of the crop	120		150
Number of seeds, pcs/pot	1		1[b]
Nitrogen fertiliser kg/m²/year	0.05		0.06
Phosphorus fertiliser kg/m²/year	0.01		0.03
Type of substrate	Peat moss		Peat 30% and stone wool 70%
Substrate use kg/m²/year	7		3
Irrigation water l/m²/year	1584		367
Source of irrigation water	Own well 30%, tap water 70%		Tap water
CO_2 enrichment kg/m²/year	6.5		0.04
Pots kg/m²/year[c]	0.09		1.0
Package plastic bag kg/m²/year	1.1		0.7
Package corrugated board box kg/m²/year	11		7
Refrigerant g/m²/year	3		2
Biowaste own composting kg/m²/year	0.3		-
Hazardous waste g/m²/year	0.6		-
Energy use for heating kWh/m²/year	636		310
Source of heating energy	Wood chips		100% wood chips OR 67% wood chips, fossil energy sources 33%[d]
Total electricity consumption kWh/m²/year Source of electricity: Renewable sources and nuclear 100% OR Renewable sources and nuclear 31%, Finnish average 69%	656		551
	Waste heat utilisation	No waste heat utilisation	
Utilisation of waste heat in other production kWh/m²/year	478	-	-
Net electricity consumption kWh/m²/year	178	656	551

[a]Data from Silvenius et al. (2019)

[b]Assumed to be similar to vertical production, not included in the assessment in Silvenius et al. (2019)

[c]Paper pots in vertical and plastic pots in greenhouse production

[d]Including light fuel oil, wood chips, heavy fuel oil, natural gas, and peat

Table 3 Background information on the construction materials and equipment used in the vertical and greenhouse production units

Structure/material	Amount used	Life expectancy, years	Data source
Frame and foundation, greenhouse and vertical farm (steel and concrete)	Vertical farm 45 kg/m^2 Greenhouse 55 kg/m^2	25	Ecoinvent 3.7 database, based on Boulard et al. (2011)
	11 kg/m^2	25	Ecoinvent 3.7 database, based on Boulard et al. (2011)
Insulated roof and wall panels, vertical farm	Total wall and roof area 6.3 m^2/m^2, weight 12 kg/m^2	25	Total area: production site data, weight: manufacturer[a], life expectancy assumed to be same as for other structures
Steel frame support structure for luminaires, etc., greenhouse and vertical farm	Vertical farm 7.5 kg/m^2 Greenhouse 2.5 kg/m^2	25	Weight: vertical farming facility, life expectancy assumed to be same as for other structures, LCA process data from Ecoinvent 3.7 database
Cables, greenhouse and vertical farm	Length, vertical 0.8 m/m^2, greenhouse 0.3 m/m^2 Weight 0.12 kg/m	20	Length: vertical farming facility, weight: electricity equipment wholesaler[b], life expectancy: expert opinion, LCA process data from Ecoinvent 3.7 database
Lettuce gutters, PVC, greenhouse and vertical farm	Length, vertical 6.7 m/m^2, greenhouse 2.2 m/m^2 0.6 kg/m	20	Length: vertical farming facility, weight: Helle Oy, life expectancy: expert opinion, LCA process data from Ecoinvent 3.7 database
Luminaires, greenhouse and vertical farm	HPS, 13 kg/piece, LED 10 kg/piece	15	Zhang et al. (2017)

[a]Manufacturer Kingspan, material tin plate PU (Polyisocyanurate) tin plate sandwich

[b]https://www.finnparttia.fi/MMJ-3x15-S

new, purpose-built buildings. The installation power for lighting was assumed to be 100 W/m^2 in greenhouse production with high-pressure sodium (HPS) luminaires (Anderson 2010) and 65 W/m^2 in vertical production with LED luminaires (production site data). The weight of the steel frame structures, greenhouse glass cover, and luminaires was checked against those used in Finland by a wholesaler of greenhouse structures and accessories (Helle Oy, Jesse Helle, 13.9.2021). The assumed amount of greenhouse structures and materials corresponds with data from the literature (Zabeltitz 2010; Antón et al. 2012). The direct and indirect N_2O emissions from fertilisation due to nitrogen input and CO_2 emissions from lime application were assessed according to the IPCC (2019) guidelines.

The data on the transport distances of inputs to the production sites were calculated using Google Maps, based on the assumed location of the input production. The production location was assumed to be in Central Europe for the construction materials of greenhouse and vertical structures, the Netherlands for seeds, Denmark for the paper pots, and Finland for the other inputs. The direct emissions during transport, as well as fuel consumption, were calculated using the Lipasto database maintained by the Technical Research Centre of Finland (VTT) (2017). The transport vehicles were assumed to be a full trailer in road transport and a container ship in marine transport. The transport distances of the waste materials were assumed to be 20 km with a lorry and 50 km with a full trailer. The impacts caused by the production of the fuel used in transport were assessed based on data from the Ecoinvent 3.7 database.

The sources of electricity in vertical farming were wind and hydroelectricity, and their modelling was made according to the Ecoinvent 3.7 database. The inventory data of different electricity energy sources was based on Ecoinvent 3.7 processes and the distribution of the energy sources produced in Finland between 2016 and 2020 was based on the statistics of Finnish Energy (2023), and imported energy was added to the models.

Using LED luminaires instead of HPS luminaires in greenhouses can decrease electricity consumption but concomitantly increase energy consumption for heating (Katzin et al. 2021). In areas comparable with Southern Finland in terms of latitude (Anchorage, Alaska, and St Petersburg, Russia, in the study of Katzin et al. (2021)), the decrease in electricity use for lighting was 40%, and the increase in heating energy use was ca. 22%, resulting in a decrease of 16% of total energy use. In this study, considering this transition in greenhouses from traditional HPS luminaires to LED luminaires, we made an additional calculation example assuming a similar decrease in energy use when only LEDs were used for lighting (Table 4).

Table 4 The decrease in LCA results for lettuce production in greenhouses when changing from HPS to LED luminaires in greenhouse lighting, or if waste heat could be utilised in greenhouses, with either average energy or renewable energy scenarios

	Average energy		Renewable energy only	
	HPS-LED scenario %	GH waste heat utilisation scenario %	HPS-LED scenario %	GH waste heat utilisation scenario %
Climate impact change	−19	−59	−27	−66
Cumulative energy demand	−27	−54	−28	−67
Resource use, fossil energy sources	−31	−60	−36	−67
Resource use, minerals and metals	−25	−57	−25	−53
Land use	−15	−52	−11	−63
Water scarcity	−32	−56	−34	−45

Waste heat utilisation in greenhouses has not been a commonly used practise in Finland. Hence, we had no data on waste heat utilisation in greenhouses, like we did for the vertical farming case. However, the situation with waste heat utilisation will change in the future, as the rising energy prices are forcing greenhouse growers to adapt new methods and practises. Anticipating these future changes, we included additional calculations assuming that the same part of the energy inputs goes to waste heat utilisation for GH as for VF (Table 4).

3 Results

Considering the climate change impact, the optimal scenario was vertical farming production, assuming the utilisation of waste heat and using electricity from renewable sources. This resulted in a climate change impact of 1.0 kg CO_2-eq/kg (Fig. 2A). When waste heat was not utilised, and average electricity was used, the climate change impact was 150% higher. When using conventional energy sources, greenhouse production had a greater climate change impact than VF production, 3.3 kg CO_2-eq/kg, but the impact decreased by 40% to 2.0 kg CO_2-eq/kg when renewable energy was used. VF production using average electricity and not utilising waste heat had a greater impact than greenhouse production using renewable energy.

VF with waste heat utilisation accompanied by electricity from renewable sources was also the optimal scenario considering the resource-use impact categories (Fig. 2B–F). The majority of the cumulative energy demand and the use of fossil energy sources resulted from the direct energy use onsite (Fig. 2B–C). The use of minerals and metals was mainly due to direct energy use and the production of structures (Fig. 2D). The use was smallest in vertical farming when waste heat was utilised, but the source of energy only had a minor impact.

The direct use of electricity and heat was the main reason for land use, except for VF production using renewable energy (Fig. 2E). In heat production, the impact was caused mainly by heat produced from wood chips. Greenhouse production using only renewable energy sources had even greater land-use impacts than greenhouse production using average energy, because heat was produced only from wood-based resources, which require more land area than heat production in the average energy scenario, in which 3% of heat was produced using fossil energy resources. In vertical farming, the renewable energy sources were wind and hydro power, which require less land area. The water scarcity impact was caused mainly by energy production (Fig. 2F).

The share of direct land use on the production site of the total cumulative land use impact of the whole production chain was only 0.5–2.8% in vertical and 0.3–0.4% in greenhouse production. The share of direct water use as irrigation water of the total water scarcity impact was only 1.4–3.0% in vertical production and 1.0–1.4% in greenhouse production.

All the studied impacts apart from the use of minerals and metals were mainly due to direct energy consumption. The climate change impact was reduced by using renewable energy sources, but the energy source was less important for the other impact categories.

The impact of changing from HPS to LED luminaires in greenhouse lighting would decrease the climate change impact by up to 27%, and resource-use efficiency would affect the category results by 11 to 36%, depending on the energy use scenario (Table 4). In addition, the potential to further reduce the environmental impacts by increasing the life expectancy of production site structures and equipment and yield by 10% was studied for the VF lettuce produced with renewably sourced electricity and with the utilisation of waste heat (VF BRE+). However, the impact reduction was only 4% for the climate change impact and between 0.5 and 5% for the resource-use-efficiency impact categories (data not shown).

Based on our additional calculation related to waste heat utilisation in GH, the impact of utilisation of waste heat in greenhouses would decrease the climate change impact by up to 66%, and resource-use efficiency would

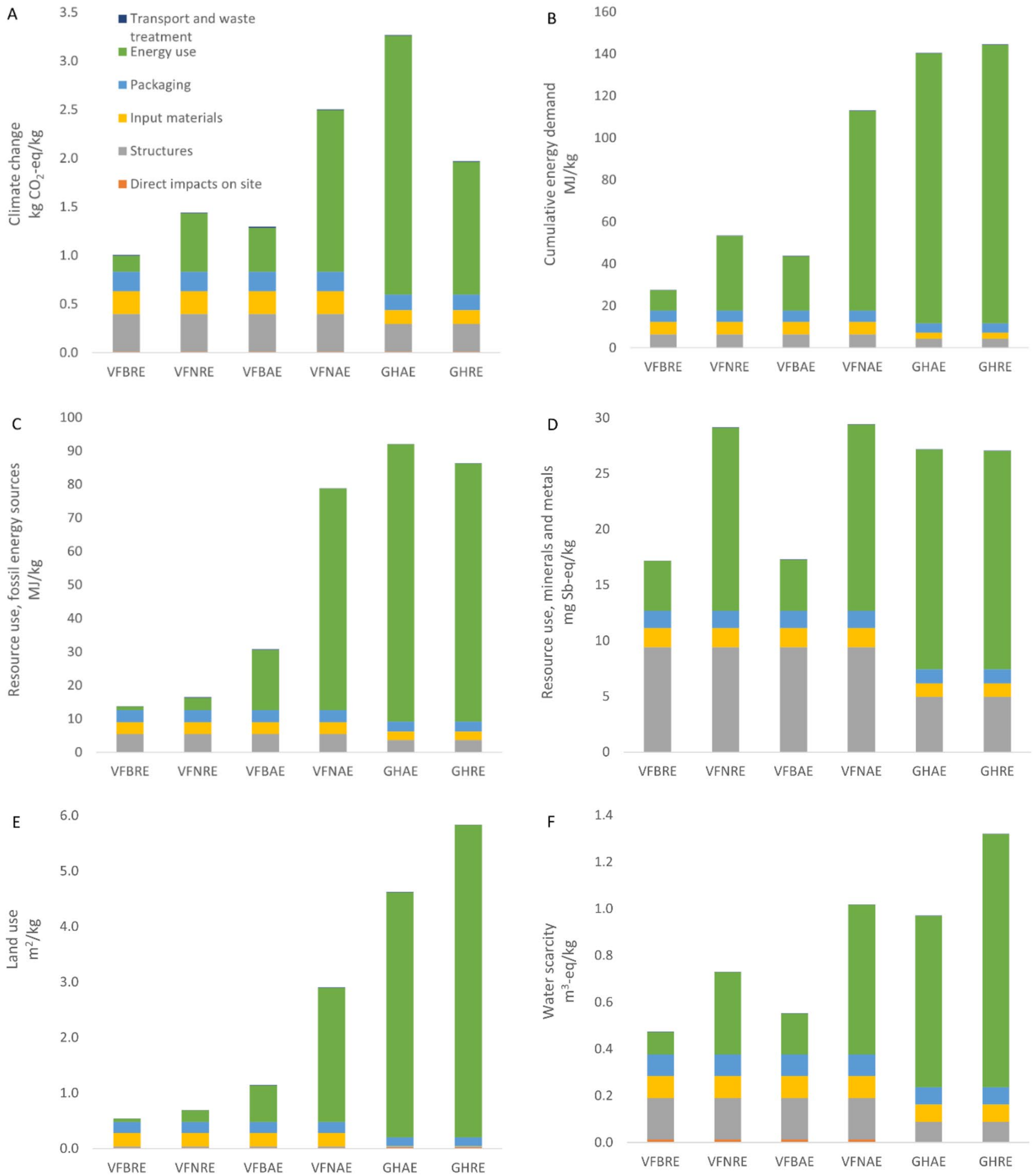

Fig. 2 **A**–**F** LCA results of the lettuce production in vertical farming and greenhouse scenarios. VF vertical farming, BAE baseline utilisation of waste heat and with average energy production profile, NAE no utilisation of waste heat and with renewable energy, BRE baseline utilisation of waste heat and with renewable energy, NRE no utilisation of waste heat and with renewable energy, GH greenhouse, AE average energy production profile, RE renewable energy. Note that the "Transport and waste treatment" and "Direct impacts onsite" categories have a smaller effect than other categories, so they are poorly visible in the graphs

affect the category results by 53 to 67%, depending on the energy use scenario (Table 4). There would be no clear differences between VF and GH in climate impact and for cumulative energy use (data not shown). This additional calculation concerning the waste heat utilisation in GH is highly speculative and computational, since we did not have any kind of data of waste heat utilisation in greenhouses in Finland.

4 Discussion

For all the studied impact categories, VF production using renewable electricity and utilising waste heat was the optimal scenario. Considering climate change, using renewable energy was beneficial, but for the resource-use impact categories, improving energy-use efficiency seemed more important. Direct land and irrigation water use onsite in Finnish circumstances only represented a small share of the total land use and water scarcity impact in both production chains. Most of these impacts were derived from input production. On the other hand, cumulative energy use, as well as the use of fossil energy sources, was mainly due to direct energy use on the production site.

Our results are in line with the climate change impact results obtained in previous studies (Table 5). Typically, lettuce production in unheated greenhouses has had a smaller climate change impact than production in heated greenhouses. For VF, a few studies (Kikuchi et al. 2018; Hallikainen 2019; Avgoustaki and Xydis 2020; Li et al. 2020; Martin et al. 2023a) have reported a smaller climate change impact for certain production systems compared to our results, from 0.1 to 1.0 kg CO_2-eq./kg, but also a much greater climate change impact has been reported for other systems, from 6 to up to 32 kg CO_2-eq./kg (Shiina et al. 2011; Hallikainen 2019; Wildeman 2020; Blom et al. 2022).

In greenhouse lettuce production, the most important cause of GHG emissions was the direct use of energy, as in previous studies focusing on lettuce production in heated greenhouses (Table 5). However, for VF, the share of direct energy use was smaller in our study than in some previous studies, where it has been reported to be close to 100% (Shiina et al. 2011; Kikuchi et al. 2018; Li et al. 2020; Wildeman 2020). However, Martin et al. (2023a) in their study regarding lettuce production in VF in Sweden, reported that electricity contributed less than half (46%) of the climate impact. Of the studies of VF, only Kikuchi et al. (2018), Wildeman (2020), Blom et al. (2022), and Martin et al. (2023a) included the production of structures. Kikuchi et al. (2018), Wildeman (2020), and Blom et al. (2022) reported the share of the structures of the total climate change impact to be less than 1%, much smaller than in our results (16–39%) while Martin et al. (2023a) reported the share of the structures to be 7%. As also discussed by Martin et al. (2023a), this could partly be explained by the longer life expectancy of the vertical farm structures (60 vs 25 years) in the study of Wildeman (2020). In the study of Kikuchi et al. (2018), the life expectancy of the structures was lower, only 15 years, but the yield level was three times higher than in our study, which also explains their lower climate change result. In the study of Blom et al. (2022), the life expectancy of the VF components was estimated to be only 8–10 years, but in their study, VF was assumed to be integrated within an existing building, thus excluding the construction of a large part of the structures. These differences also indicate that long-lasting structures in greenhouse production may have a potential to decrease products' environmental impacts. In all, structures should be taken into account in environmental impact calculations, because their contribution to the climate change impact of production can be large, as shown in our research.

In many of the previous studies, energy use has been reported as direct energy use during lettuce production, excluding life cycle impacts (Table 5). According to Avgoustaki and Xydis (2020), the direct energy use was greater in VF than in greenhouse production, but Graamans et al. (2018) presented opposite results. The direct energy-use levels calculated in this study were relatively small (lettuce produced in a greenhouse 120–133 MJ/kg and lettuce produced in vertical farming 10–95 MJ/kg). On the other hand, Bartzas et al. (2015) and Romero-Gámez and Suárez-Rey (2020) reported considerably lower life cycle cumulative energy use for lettuce production in unheated greenhouses (3 and 4 MJ/kg) than our results was for lettuce produced in heated greenhouse (140–144 MJ/kg). The difference is explained by the fact that in unheated greenhouses supplemental light is not used either, so the total energy consumption is lower.

In addition, land and water use were reported in many of the previous studies as direct land use or direct irrigation water use during production, excluding life cycle impacts (Table 5). The highest values for direct land use in lettuce production were reported for greenhouse production (0.02 m^2/kg, Avgoustaki and Xydis 2020), and the lowest values for lettuce in VF (0.002 m^2/kg, Hallikainen 2019). The direct water use was reported to be from 1 to 20 l/kg lettuce, and there seems to be no clear difference between greenhouse and vertical farming production. Two of the previous studies (Hallikainen 2019; Wildeman 2020) reported water footprint results according to the method by Hoekstra et al. (2011), but reported somewhat contradictory results, 1 l/kg lettuce (Hallikainen 2019) and 22 l/kg lettuce (Wildeman 2020). These results are not comparable with the results in this study because of the different methods used. In our study, direct land use at the production site represented only a small part of the total impacts of land use on the production chain (0.3–2.8%).

Table 5 Comparing results of this study with previous studies, considering only the primary production stage of the production chain

Source	Country and greenhouse type	Yield, t/ha/year	Climate change, kg CO_2-eq./kg yield FW	Share of climate change impact, %			Resource use, direct			Resource use, life cycle		
				Energy use	Infra/ greenhouse structure	Other	Energy use, MJ/kg yield FW	Land use, m^2/kg yield FW	Water use, litres /kg yield FW	Energy use, MJ/kg yield FW	Land use, m^2/kg yield FW	Water use, litres /kg yield FW
Greenhouse production, lettuce												
This study	**Finland, heated**	**500**	**2.0–3.3**	**69–81**	**9–14**	**10–16**	**120–133**	**0.02**	**7**	**140–145**	**4.6–5.9**	
Avgoustaki and Xydis (2020)	Not specified	410	0.35	–	–	–	432	0.02	20			
Bartzas et al. (2015)	Spain, not heated	23	0.23	28	15	57				3		
Bartzas et al. (2015)	Italy, not heated	27	0.21	34	13	53				3		
Blom et al. (2022)	The Netherlands	291–530	0.62–1.3	21–72	6–16	18–65						
Casey et al. (2022)	Hydroponic greenhouse production in several countries/ circumstances	1540	0.48–17.8	-	-	-	-	0.0065	1.6	4.1–239	-	-
Graamans et al. (2018)	–	–	–	–	–	–	110–163		1–20			
Hospido et al. (2009)	UK, heated	48–68	2.55	97	< 0.5	3					0.05	40
Hospido et al. (2009)	UK, not heated	–	2.82	> 99	–	–					0.02	22
Li et al. (2020)[a]	Singapore	45	0.21	–	91	9				4		
Romero-Gámez et al. (2014)	Spain, not heated	–	1.46	65	Not included	35%						
Räsänen et al. (2014)	Finland, heated	500	2.70	92	Not included	6%			7			
Silvenius et al. (2019)	Finland, heated	–	4.30	–	–	–			16			
Stoessel et al. (2012)	Switzerland, heated	–	3.5	74	Not included	27%						
Yrjänäinen et al. (2013)	Finland, heated	–	2.82	> 99	–	–					0.02	22
Vertical farming, lettuce												
This study	**Finland**	**660**	**1.0–2.5**	**16–66**	**16–39**	**18–45**	**10–95**	**0.02**	**24**	**28–113**	**0.5–2.9**	
Avgoustaki and Xydis (2020)	Not specified	100	0.16	–	–	–	900	0.01	1			

Table 5 (continued)

Source	Country and greenhouse type	Yield, t/ha/ year	Climate change, kg CO_2-eq./kg yield FW	Share of climate change impact, %			Resource use, direct			Resource use, life cycle		
				Energy use	Infra/ green-house structure	Other	Energy use, MJ/kg yield FW	Land use, m^2/ kg yield FW	Water use, litres /kg yield FW	Energy use, MJ/kg yield FW	Land use, m^2/ kg yield FW	Water use, litres /kg yield FW
Blom et al. (2022)	The Netherlands	1010	1.63–7.75	72–90	1–2	10–25						
Graamans et al. (2018)	Sweden, the Netherlands, United Arab Emirates	–	–	–	–	–	70		1			
Hallikainen (2019)	Sweden, the Netherlands, United Arab Emirates, Japan	4400	0.05–32	–	–	–		0.002	20			
Kikuchi et al. (2018)	Japan	2000	0.40	> 99	–	< 1%						1
Li et al. (2020)[a]	Singapore	–	0.22–1.44	> 99	–	–					0.01–0.04	13–16
Martin et al. (2023a)	Sweden	3110	0.75–0.98	46	7	47	-	-	-	-	-	2300
Shiina et al. (2011)	Japan	1700	6.40	98	–	2%						
Wildeman (2020)	USA	–	8.47	99	0.4	1						

[a]Lettuce and other leafy vegetables

Silvenius et al. (2019) assessed the water-use impact of greenhouse lettuce production using the AWARE method (Boulay et al. 2018) but reported a lower value than was obtained in this study (36 l–eq. vs 1 m^3 eq/kg lettuce). The difference in results is due to differences in the system boundary. In the study of Silvenius et al. (2019), the water-use impact included only direct water consumption for onsite irrigation, as well as the production of plastic packaging materials, but as Usva et al. (2023) conclude, indirect water consumption in food products may have a significant impact. It is notable that in lettuce production, the direct use of water, i.e. irrigation, has only a small effect on the final result. The proportion of irrigation out of the total water scarcity impact was 1.0–1.4% in greenhouse lettuce, and 1.4–3.0% in vertical lettuce. In Finland, the water situation is good and the characterization factor of the water scarcity effect used in the AWARE method is small (Boulay et al. 2018).

It should be noted that this study's results represent the current situation of vertical farming systems in Finland. Vertical farming systems are still in an early developmental stage, and production efficiency can probably be remarkably improved in the future. There is potential for decreasing electricity consumption in optimising different growth environment parameters, lighting in particular, and future improvements can make VF operated with renewable energy in relation to land feasible (Kobayashi et al. 2022). Integration of VF to city power and heating sectors can enable lower costs associated with energy usage and maximise the share of renewable energy sources (Arabzadeh et al. 2023). Part of these future development scenarios (waste heat utilisation, changing luminaires) are applicable also to greenhouse production systems and reinforcing this, results from Martin et al. (2023b) and the current study show that changing from HPS to LED luminaires both decreased the climate change impact and improved resource-use efficiency. Especially vertical farming would benefit from further ex-ante LCA study (Cucurachi et al. 2018) studying emerging technologies and could provide understanding on the impacts of the future options mentioned above, and therefore could support the development of vertical farming.

5 Conclusions

This study provides new information about environmental impacts of vertical farming in Northern conditions. Producing lettuce in VF using renewable electricity and utilising waste heat was the optimal scenario from the perspective of climate change, cumulative energy demand, resource use of fossil energy sources, resource use of minerals and metals, land use, and water scarcity. Using renewable energy sources and improving energy-use efficiency were both important measures for ensuring a lower impact for both VF and the greenhouse production of lettuce. In terms of resource-use impacts, increasing energy-use efficiency was more important than using renewable energy sources. However, if VF uses other than renewable electricity, and no special attention is paid to energy-use efficiency, the climate change impact and resource-use efficiency are not inevitably better than in more traditional greenhouse production. Increasing the yield level seems to have a potential to further decrease GHG emissions and improve production system energy efficiency. Effective use of the production area in both VF and greenhouses therefore contributes to resource-use efficiency, mainly by improving overall energy efficiency. As vertical farming systems are still in an early developmental stage, it is likely that production efficiency can be remarkably improved in the future. Paying attention to the energy sources and its use, it enables a decrease in environmental impacts of lettuce production.

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Data availability The datasets generated during and/or analysed during the current study are not publicly available due to confidentiality agreement with the grower but are available from the corresponding author on reasonable request and with permission of the grower.

Declarations

Competing interests The authors declare no competing interests.

References

Anderson J (2010) LED-valaistus kasvihuoneisiin (LED lighting for greenhouses). Master's Thesis, Aalto University, School of Science and Technology. http://lib.tkk.fi/Dipl/2010/urn100209.pdf. Accessed 15 March 2023

Antón A, Torrellas M, Montero JI, Ruijs MNA, Vermeulen P, Stanghellini C (2012) Environmental impact assessment of Dutch tomato crop production in a Venlo glasshouse. Acta Hortic. https://doi.org/10.17660/ActaHortic.2012.927.97

Arabzadeh V, Miettinen P, Kotilainen T, Herranen P, Karakoc A, Kummu M, Rautkari L (2023) Urban vertical farming with a large wind power share and optimised electricity costs. Appl Energy. https://doi.org/10.1016/j.apenergy.2022.120416

Asseng S, Guarin JR, Raman M, Monje O, Kiss G, Despommier DD, Meggers FM, Gauthier PPG (2020) Wheat yield potential in controlled-environment vertical farms. Proc Natl Acad Sci. https://doi.org/10.1073/pnas.2002655117

Avgoustaki DD, Xydis G (2020) How energy innovation in indoor vertical farming can improve food security, sustainability, and food safety? Adv Food Secur Sustain. https://doi.org/10.1016/bs.af2s.2020.08.002

Bartzas G, Zaharaki D, Komnitsas K (2015) Life cycle assessment of open field and greenhouse cultivation of lettuce and barley. Inf Process Agric. https://doi.org/10.1016/j.inpa.2015.10.001

Blom T, Jenkins A, Pulselli RM, van den Dobbelsteen AAJF (2022) The embodied carbon emissions of lettuce production in vertical farming, greenhouse horticulture, and open-field farming in the Netherlands. J Clean Prod. https://doi.org/10.1016/j.jclepro.2022.134443

Boulard T, Raeppel C, Brun R, Lecompte F, Hayer F, Carmassi G, Gaillard G (2011) Environmental impact of greenhouse tomato production in France. Agron Sustain Dev. https://doi.org/10.1007/s13593-011-0031-3

Boulay A-M, Bare J, Benini L, Berger M, Lathuilliére M, Manzardo A, Margni M, Motoshita M, Nuñez M, Pastor AV, Ridoutt B, Oki T, Worbe S, Pfister S (2018) The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). Int J Life Cycle Assess. https://doi.org/10.1007/s11367-017-1333-8

Casey L, Freeman B, Francis K, Brychkova G, McKeown P, Spillane C, Bezrukov A, Zaworotko M, Styles D (2022) Comparative environmental footprints of lettuce supplied by hydroponic controlled-environment agriculture and field-based supply chains. J Clean Prod. https://doi.org/10.1016/j.jclepro.2022.133214

Cucurachi S, van der Giesen C, Guinée J (2018) Ex-ante LCA of emerging technologies. Procedia CIRP. https://doi.org/10.1016/j.procir.2017.11.005

European Commission (2021) Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32021H2279. Accessed 15 March 2023

Finnish Energy (2023) Electricity statistics 2016–2020. https://energia.fi/en/statistics/electricity_statistics. Accessed 17 Feb 2023

Graamans L, Baeza E, van den Dobbelsteen A, Tsafaras I, Stanghellini C (2018) Plant factories versus greenhouses: comparison of resource use efficiency. Agric Syst. https://doi.org/10.1016/j.agsy.2017.11.003

Hallikainen E (2019) Life cycle assessment on vertical farming. Master of Science in Technology, Aalto University, School of Engineering, 49 pp. https://aaltodoc.aalto.fi/bitstream/handle/123456789/36351/master_Hallikainen_Eero_2019.pdf?isAllowed=y&sequence=2. Accessed 14 February 2023

Hischier R, Weidema B, Althaus H-J, Bauer C, Doka G, Dones R, Frischknecht R, Hellweg S, Humbert S, Jungbluth N, Köllner T, Loerincik Y, Magni M, Nemecek T (2010) Implementation of life cycle impact assessment methods. pp 176. Ecoinvent report No. 3, v2.2 Swiss Centre for Life Cycle Inventories, Dübendorf. https://ecoinvent.org/wp-content/uploads/2020/08/201007_hischier_weidema_implementation_of_lcia_methods.pdf. Accessed 15 February 2023

Hoekstra AY, Chapagain AK, Aldaya MM, Mekonnen MM (2011) The water footprint assessment manual: setting the global standard. Routledge. https://waterfootprint.org/media/downloads/TheWaterFootprintAssessmentManual_2.pdf. Accessed 15 February 2023

Hospido A, Milà i Canals L, McLaren S, Truninger M, Edward-Jones G, Clift R (2009) The role of seasonality in lettuce consumption: a case study of environmental and social aspects. Int J Life Cycle Assess. https://doi.org/10.1007/s11367-009-0091-7

IPCC (2019) 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. In Calvo Buendia E, Tanabe K, Kranjc A, Baasansuren J, Fukuda M, Ngarize S, Osako A, Pyrozhenko Y, Shermanau P, Federici S (eds). Published: IPCC, Switzerland. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html. Accessed 12 March 2023

Katzin D, Marcelis LFM, van Mourik S (2021) Energy savings in greenhouses by transition from high-pressure sodium to LED lighting. Appl Energy. https://doi.org/10.1016/j.apenergy.2020.116019

Kikuchi Y, Kanematsu Y, Yoshikawa N, Okubo T, Takagaki M (2018) Environmental and resource use analysis of plant factories with energy technology options: a case study in Japan. J Clean Prod. https://doi.org/10.1016/j.jclepro.2018.03.110

Kobayashi Y, Kotilainen T, Carmona-García G, Leip A, Tuomisto HL (2022) Vertical farming: a trade-off between land area need for crops and for renewable energy production. J Clean Prod. https://doi.org/10.1016/j.jclepro.2022.134507

Li L, Li X, Chong C, Wang C-H, Wang X (2020) A decision support framework for the design and operation of sustainable urban farming systems. J Clean Prod. https://doi.org/10.1016/j.jclepro.2020.121928

Martin M, Elnour M, Cabrero Siñol A (2023a) Environmental life cycle assessment of a large-scale commercial vertical farm. Sustainable Production and Consumption 40:182–193. https://doi.org/10.1016/j.spc.2023.06.020

Martin M, Bengtsson E, Carotti L, Orrestig K, Orsini F (2023b) Environmental assessment of greenhouse herb production: a case of longitudinal improvement options in Sweden. Resour Conserv Recycl. https://doi.org/10.1016/j.resconrec.2023.106948

Natural Resources Institute Finland Statistics (2021) Horticultural statistics. https://www.luke.fi/en/projects/puutarhatilastot. Accessed 8 Feb 2023

Neha M, Vitika V (2022) Greenhouse horticulture market by crop type (fruits and vegetables, nursery crops, flowers and ornamentals, others), by type (plastic greenhouse, glass greenhouse): global opportunity analysis and industry forecast, 2021–2030. Allied Market Research, report code A16608. https://www.alliedmarketresearch.com/greenhouse-horticulture-market-A16608. Accessed 10 March 2023

Pohjala M (2014) Mikä on energia- ja kasvuturpeen elinkaaren ilmastovaikutus? Master's Thesis study, Department of Forest Sciences, University of Helsinki, Forest Ecology and Management, 76 pp. https://helda.helsinki.fi/handle/10138/136417. Accessed 10 March 2023

Romero-Gámez M, Audsley E, Suárez-Rey EM (2014) Life cycle assessment of cultivating lettuce and escarole in Spain. J Clean Prod. https://doi.org/10.1016/j.jclepro.2013.10.053

Romero-Gámez M, Suárez-Rey EM (2020) Environmental footprint of cultivating strawberry in Spain. Int J Life Cycle Assess. https://doi.org/10.1007/s11367-020-01740-w

Räsänen K, Saarinen M, Kurppa S, Silvenius F, Riipi I, Nousiainen J, Erälinna L, Mattinen L, Jaakkola S, Lento S, Mäkinen-Hankamäki S (2014) Lähiruuan ekologisten vaikutusten selvitys. Jokioinen MTT Raportti 145:97. http://urn.fi/URN:ISBN:978-952-487-538-7. Accessed 14 January 2023

SharathKumar M, Heuvelink E, Marcelis LFM (2020) Vertical farming: moving from genetic to environmental modification. Trends Plant Sci. https://doi.org/10.1016/j.tplants.2020.05.012

Shiina T, Hosokawa D, Roy P, Nakamura N, Thammawong M, Orikasa T (2011) Life cycle inventory analysis of leafy vegetables grown in two types of plant factories. Acta Hortic. https://doi.org/10.17660/ActaHortic.2011.919.14

Silvenius F, Usva K, Katajajuuri J-M, Jaakkonen A-K (2019) Kasvihuonetuotteiden ilmastovaikutuslaskenta ja vesijalanjälki. Luonnonvarakeskus. Luonnonvara- ja biotalouden tutkimus 82/2019: 25 pp. https://jukuri.luke.fi/handle/10024/545046. Accessed 13 Jan 2023

Silvenius F, Katajajuuri JM (2021) Reduction of the climate impact of Finnish greenhouse vegetables achieved by energy acquisitions between 2004 and 2017. J Hortic Sci Res. https://doi.org/10.36959/745/408

Statista (2022) Projected vertical farming market worldwide in 2020 and 2026. https://www.statista.com/statistics/487666/projection-vertical-farming-market-worldwide. Accessed 8 Feb 2023

Stoessel F, Juraske R, Pfister S, Hellweg S (2012) Life cycle inventory and carbon and water FoodPrint of fruits and vegetables: application to a Swiss Retailer. Environ Sci Technol. https://doi.org/10.1021/es2030577

Usva K, Hietala S, Nousiainen J, Vorne V, Vieraankivi M-L, Jallinoja M, Leinonen I (2023) Environmental life cycle assessment of Finnish broiler chicken production: focus on climate change and water scarcity impacts. Submitted manuscript to Journal of Cleaner Production

van Delden SH, SharathKumar M, Butturini M, Graamans LJA, Heuvelink E, Kacira M, Kaiser E, Klamer RS, Klierkx L, Koostra G, Loeber A, Schouten RE, Stanghellini C, van Ieperen W, Verdonk JC, Vialet-Chabrand S, Woltering EJ, van den Zedde R, Zhang Y, Marcelis LFM (2021) Current status and future challenges in implementing and upscaling vertical farming systems. Nat Food. https://doi.org/10.1038/s43016-021-00402-w

Vatistas C, Avgoustaki DD, Bartzanas T (2022) A systematic literature review on controlled-environment agriculture: how vertical farms and greenhouses can influence the sustainability and footprint of urban microclimate with local food production. Atmosphere. https://doi.org/10.3390/atmos13081258. Accessed 14 January 2023

von Zabeltitz C (2010) Integrated greenhouse systems for mild climates: climate conditions, design, construction, maintenance, climate control. Springer Science & Business Media, Springer-Verlag Berlin Heidelberg, p 192. https://doi.org/10.1007/978-3-642-14582-7_1

VTT Technical Research Centre of Finland (2017) LIPASTO unit emissions database. Average emissions and energy use of working machines per fuel in Finland in 2016. http://lipasto.vtt.fi/en/index.htm. Accessed 14 January 2023

Wernet G, Bauer C, Steubing B et al (2016) The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess. https://doi.org/10.1007/s11367-016-1087-8

Wildeman R (2020) Vertical farming: a future perspective or a mere conceptual idea? A comprehensive life cycle analysis on the environmental impact of a vertical farm compared to rural agriculture in the US. http://essay.utwente.nl/83529. Accessed 8 Feb 2023

Yrjänäinen H (2011) Carbon footprint of electricity in Finland. Master of Science Thesis, Tampere University of Technology, Master's degree programme in Electrical Engineering. Accessed 14 January 2023

Yrjänäinen H, Silvenius F, Kaukoranta T, Näkkilä J, Särkkä L, Tuhkanen E-M (2013) Kasvihuonetuotteiden ilmastovaikutuslaskenta: loppuraportti. MTT 83:43. https://jukuri.luke.fi/handle/10024/438290. Accessed 14 January 2023

Zhang H, Burr J, Zhao F (2017) A comparative life cycle assessment (LCA) of lighting technologies for greenhouse crop production. J Clean Prod. https://doi.org/10.1016/j.jclepro.2016.01.014

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