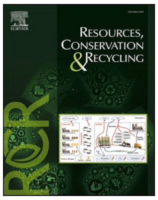
Resources, Conservation & Recycling 193 (2023) 106948

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

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



Full length article

Environmental assessment of greenhouse herb production: A case of longitudinal improvement options in Sweden

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ARTICLE INFO

Keywords:
Greenhouse horticulture
life cycle assessment (LCA)
Sustainability
Controlled environment agriculture
LED lighting
hydroponic

ABSTRACT

The greenhouse sector has seen many advances to improve its resource demands, though little is known of the environmental impacts. This study aims to assess the environmental performance of a horticultural greenhouse in Sweden producing herbs. Life cycle assessment is employed to analyze different scenarios. These include previous measures, such as switching to organic fertilizers, a pellet burner, and reducing the packaging weight. Future scenarios are assessed, including increasing biofueled logistics, switching to LEDs, densifying production, and including recyclable packaging. The results suggest that GHG emissions were reduced by 32% per kg edible portion through past scenarios in current scenario. Additionally, densifying production and switching to LED lighting can lead to an additional 14% and 10% reduction in GHG emissions compared to the current system respectively, while also reducing other environmental impact categories. These results provide insights into the implications of environmental and resource improvement measures taken at greenhouses.

1. Introduction

Food and agriculture account for over 20–25% of all anthropogenic greenhouse gas (GHG emissions (Bennetzen et al., 2016; Ivanova et al., 2016; Vermeulen et al., 2012). This is compounded by estimations of increased food demand from an expanding global population, putting pressure on natural resources and land (FAO, 2021; Fedoroff, 2015; Foley et al., 2011; Vermeulen et al., 2012). To meet the challenges to secure a more sustainable food supply, new approaches, and information are required at all levels of the global food system.

In recent years, the production of food has become increasingly technology and innovation-driven (Klerkx and Rose, 2020). In particular, greenhouse horticulture has seen significant advances in reducing water, nutrient, and resource demands while continually increasing its production output (De Pascale et al., 2018; Dias et al., 2017; Katzin et al., 2021). In Sweden, similar to much of northern Europe, a limited growing season and colder temperatures have given rise to a large number of greenhouses for the production of different products. In 2019, there were roughly 1.25 million m^2 of horticultural production in Sweden, with the largest market for cucumbers and tomatoes. Herbs and other leafy greens are also important crops from greenhouse horticulture, accounting for roughly 12% of horticultural product income (SCB, 2020).

The greenhouse sector has many challenges, including reducing energy demands and increasing yield without affecting crop quality (De Pascale et al., 2018; Dias et al., 2017; Katzin et al., 2021; Page et al., 2012, 2014). While greenhouses, compared to open field production, allow for more local production with less use of pesticides and reduced use of water and soil, there is also a high energy demand. This also represents the second largest cost after labor (Orsini et al., 2020; Taki et al., 2018). According to Ahamed et al. (2019), the energy for heating and cooling greenhouses can represent between 65 and 85% of the total energy demand, with the rest primarily employed for lighting and transportation. Considering the importance of this subject, challenges and strategies to reduce energy demand in greenhouses and other controlled environment agriculture (CEA), have been outlined in several studies. These are primarily related to synergies with external systems to reduce heat while also employing residual carbon dioxide for carbon enrichment (Marchi et al., 2018; Short et al., 2014). A critical role is also given to the use of the most efficient technologies and design possibilities, focusing for instance on the most suitable cover materials and on efficient heat pumps and artificial lighting systems (Sahdev et al., 2019;

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https://doi.org/10.1016/j.resconrec.2023.106948
Received 7 September 2022; Received in revised form 25 February 2023; Accepted 27 February 2023

Cuce et al., 2016).

In northern latitudes, supplementary lighting is often used to maximize the yield throughout the year, overcoming the limitations of low solar radiation, but also has a large energy demand (Appolloni et al., 2021; Righini et al., 2020). Among the most common types of supplementary lighting used in horticultural production are high-pressure sodium (HPS) lamps (Singh et al., 2015). However, light emitting diodes (LED) are also becoming increasingly prevalent and may provide new solutions for greenhouses, given their rapid technological evolution, potential safer management practices, long operating lifetime, the possibility to select light output conditions, and higher efficiency in converting energy into usable light (Bantis et al., 2018; Paucek et al., 2020). Accordingly, LED lights today have been found to be a more cost-effective solution, leading to an energy saving of 10–25% when compared to HPS lamps, see e.g. Katzin et al. (2021).

The horticulture sector has also been identified to have high environmental impacts from post-harvest handling and logistics (Avgoustaki and Xydis, 2020; Gruda et al., 2019). For this reason, particular attention is paid to the use of non-plastic or recycled materials for production and packaging materials (Nambuthiri et al., 2015), as well to the reduction of fossil fuel used in logistics for both inputs and deliveries of the final product (Ohyama et al., 2008).

Despite the outlined challenges and opportunities outlined above, little is known of the implications these may have on the sustainability of different greenhouse systems. With the advance of new production systems that often claim larger benefits compared to the established open field and greenhouse-based products, it is important that transparent information is available on the sustainability of current production practices from greenhouse production (Agritecture, 2022a; Martin and Bustamante, 2021; Orsini et al., 2020; van Delden et al., 2021). Furthermore, there is an increasing interest in knowing the environmental footprints and implications of the consumption of foods. As such, producers and consumers are expanding their efforts to provide life cycle-based information. This has been guided by corporate and government initiatives aimed at promoting transparent sustainability information based on life-cycle approaches (Del Borghi et al., 2019; Freidberg, 2014; Lehmann et al., 2015).

Worldwide, although there is an abundance of literature on greenhouse horticultural tomato and lettuce production (Andrews and Pearce, 2011; Dias et al., 2017; Short et al., 2014; Torrellas et al., 2012; Ureña-Sánchez et al., 2012; Goldstein et al., 2016; Blom et al., 2022), there are no studies assessing the impacts of herb production from greenhouses. Moreover, greenhouse environmental performance has been found to be influenced by site-specific climatic and technological contexts (Almeida et al., 2014; Page et al., 2014, Dias et al., 2017). To our knowledge, no studies have assessed the environmental performance of greenhouse products in Sweden. Furthermore, some studies, which aim to compare vertical farms to greenhouse systems or provide potential developments to develop synergies to employ residual heat; see e.g. (Cáceres et al., 2022; Danevad and Carlos-Pinedo, 2021; Graamans et al., 2018; Weidner et al., 2021) often base their analysis on theoretical assessments. In these studies, assumed production outputs and energy systems available in continental Europe are used to model Swedish conditions (Weidner et al., 2021; Graamans et al., 2018), e.g. employing European electricity mix and natural gas. However, few actual greenhouses in Sweden employ such energy sources, requiring more case studies to understand their life cycle impacts and designs.

Given the identified gap in knowledge, this study aims to assess the environmental performance of a greenhouse in Sweden producing herbs. This is done by studying the environmental implications of a set of improved options employing life cycle assessment to study the longitudinal development of a hydroponic greenhouse from 2014, its current setup (i.e., in 2021), and review future developments to improve the sustainability of the system.

2. Methodology

2.1. Case study greenhouse

This study is based on the production system from Svegro,[1] which is a producer of herbs and lettuce in Sweden near Stockholm. The greenhouse was chosen to be included in the study as it is included as a research partner in projects with the authors of this study, and to provide a life cycle assessment of the implications of sustainability measures conducted in the past. The company is focused only on the production of various herbs using a nutrient film technique (NFT), with a greenhouse production area of roughly 5.5 hectares. A depiction of the facility is provided in Fig. 1. Currently, the farm is producing roughly 20 million pots of herbs per year, although the capacity can be increased through densifying the production; which is also analyzed in a scenario described in subsequent text (Section 2.3).

2.2. Life cycle assessment and life cycle inventory

Life cycle assessment was employed to study the implications of different developments. The functional unit employed for the environmental assessment is 1 kg of edible plants (herbs) available to consumers, although the plants are sold as potted plants. This functional unit is also commonly used in other assessments of greenhouse products. It is assumed that each potted plant has an edible portion of roughly 32 g. In the assessment, annual, and monthly emissions from different processes are also highlighted.

The study is limited to the production and final availability of edible plants to consumers. As such, the study was conducted using a cradle-to-gate perspective, including the greenhouse infrastructure, cultivation and packaging inputs, energy, transportation of materials, distribution of the plants to regional supermarkets, and waste handling from the greenhouse. Wastes and waste handling after retail were not modeled as they were considered outside the scope of the assessment, however, their potential contribution is included in the analysis section. A depiction of the system boundaries is available in Fig. 2.

The LCA was conducted employing OpenLCA v1.10.3 software. The life cycle impact assessment (LCIA) method employed in this study was the International Reference Life Cycle Data System (ILCD) method. This was chosen as it is a robust method for exploring the implications of products and services in the European market (JRC, 2010). The impact categories included in the main text include Global warming potential (measured in kg CO_2-eq) and denoted GHG, Water resource depletion (measured in m^3 water), Acidification Potential (measured in molc $H+$ eq), Freshwater Eutrophication (measured in kg P-eq), and Mineral, fossil, and renewable resource depletion (measured in kg Sb-eq). These particular impact categories were chosen for the main text as they highlight important regional, global, and resource implications for food systems, and pertinent environmental concerns in Sweden, see e.g. (JRC, 2010; SEPA, 2020; Martin and Brandao, 2017). Furthermore, as the study, and associated scenarios, compares changes and options which also alter the energy demand and sources, fertilizers, material inputs, and waste handling methods, these associated impact categories were found important for the results. Despite the lack of studies on greenhouse products, these impact categories are commonly used in studies on agricultural systems, allowing for comparisons, as seen in previous studies in the field, see e.g. (Martin et al., 2022; De Pascale et al., 2018; Dias et al., 2017). Additionally, while our study only highlights five impact categories, the ILCD method contains 16 impact categories, and all other results for other impact categories are provided in the Supplementary Material for further information.

All life cycle inventory (LCI) data was obtained from the LCI database, Ecoinvent v. 3.7 (Ecoinvent, 2018). As the aim of the study was to

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[1] www.svegro.se

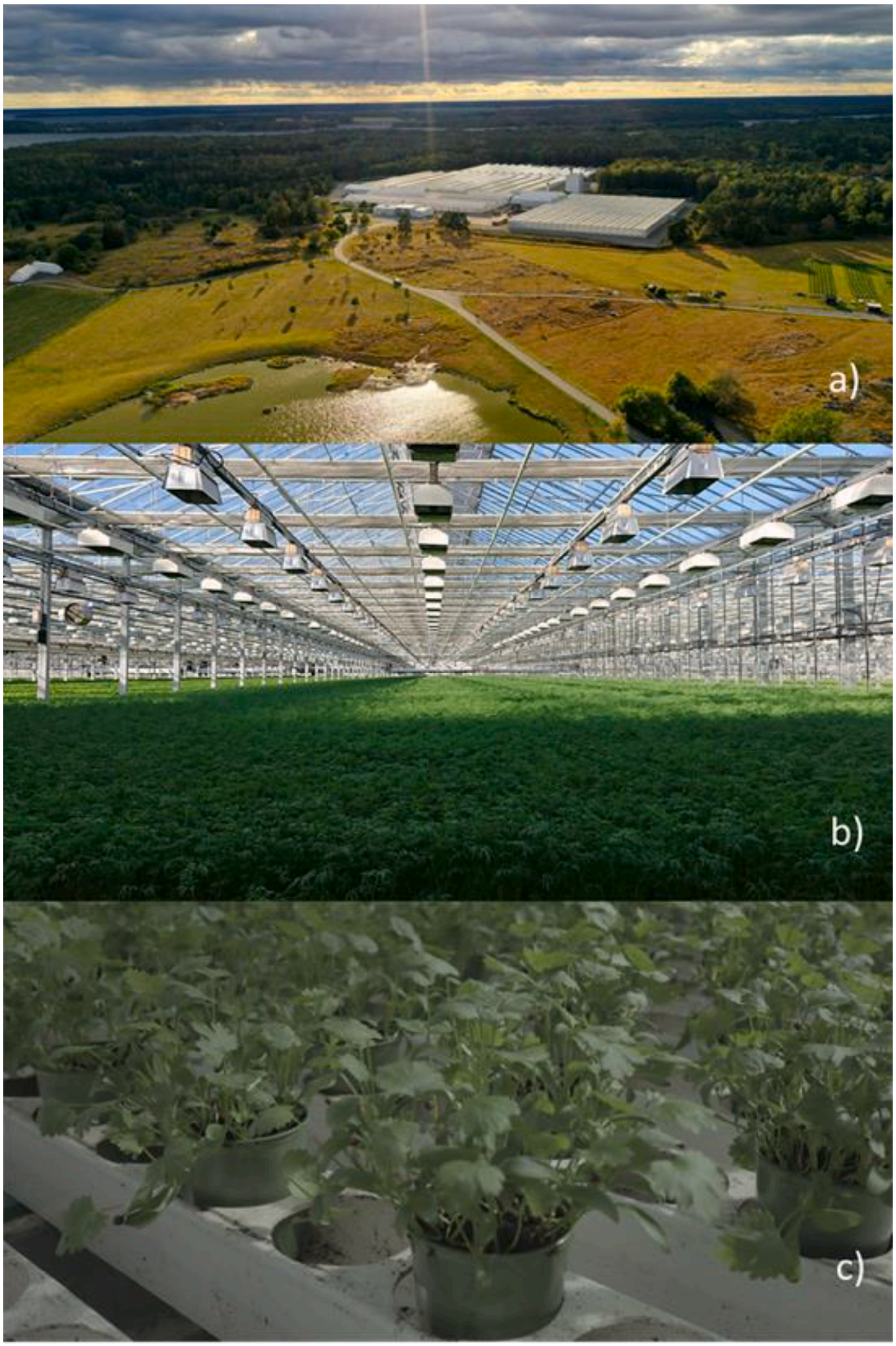

Fig. 1. Depiction of a) Svegro's greenhouse located at Färingsö, Stockholm, b) a depiction of Svegro's greenhouse from the inside, and c) depiction of potted plants growing in the nutrient film technique (NFT) gutters.

analyze the implications of different developments longitudinally, only the implications of changes to the system were analyzed, and no changes to material and energy sources temporally were included as they were considered outside the scope of this study. For example, no changes to the energy mix for different years were taken into account, and no changes in sourcing or technologies mixes were included. This limitation is also elaborated further the Discussion section below. Details and assumptions are also provided in the subsequent sections for all scenarios assessed, with further details provided in the Supplementary Material, including, e.g., a listing of all LCI datasets employed in the study, see Table S1.

2.3. Scenarios

The scenarios outlined below provide further details on the longitudinal development. See Fig. 3 for a review of the scenarios temporally. For these scenarios, all figures are based on the data obtained for the Baseline scenario (2019), where data was collected during the period September 2018-August 2019. This includes all infrastructure, material inputs, production outputs, wastes, transportation, packaging, and energy consumption. Thereafter, the Current (2021), past scenarios (before 2021), and future scenarios (after 2021) were developed to assess the implications of developments during past years and potential future developments. Past scenarios were based on different years when major developments were implemented at Svegro. Temporally, all

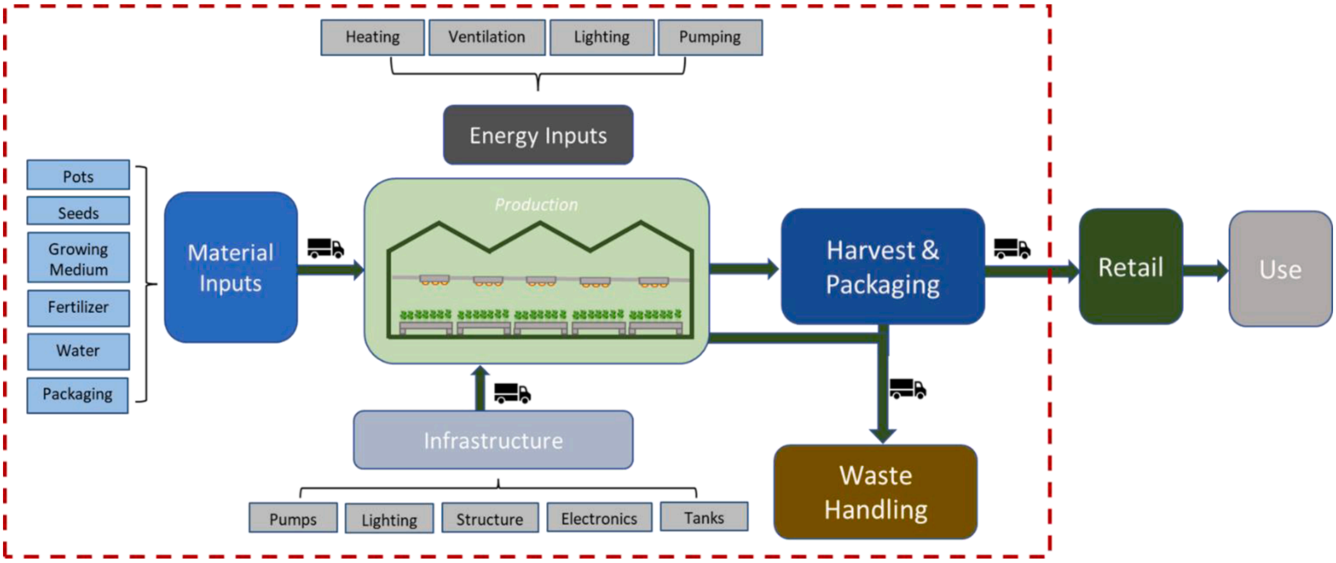

Fig. 2. System boundaries of the environmental life cycle assessment. Impacts from the use and retail are not included in the study.

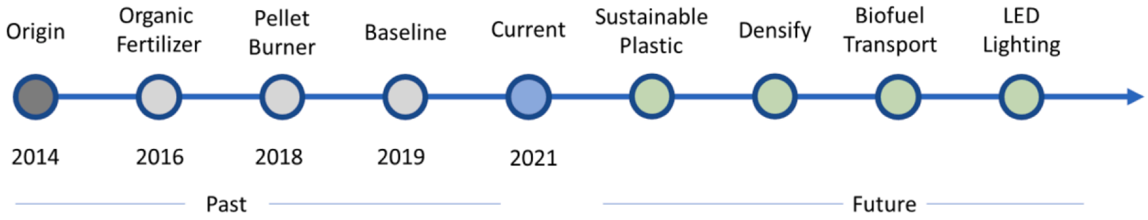

Fig. 3. Improvement and development measures assessed using different scenarios.

developments are compounded (i.e. included) in subsequent scenarios. However, future scenarios are studied individually. Future scenarios are assumed to be possible to change within the next few years, as several of these developments are in progress at the time of this writing, e.g. densification and changes to transportation fuels.

For all scenarios, it is assumed that the permanent greenhouse infrastructure is constant as the current greenhouse structure has not changed since 2014 (i.e. the Origin scenario). However, changes requiring additional equipment and other intermediate systems are included. These changes and further details for all scenarios are provided in the descriptions of the scenarios below with additional information on assumptions and modeling outlined in the Supplementary Material. Furthermore, a table with a description of changes made in each scenario is also available in the Supplementary Material, see Table S2.

2.3.1. Past scenarios

- Origin (2014)

The Origin (2014) scenario was developed to provide a context for the system in place in 2014. This included the same permanent greenhouse infrastructure as other scenarios, but before the subsequently described improvement measures were implemented. As such, the origin scenario employed conventional fertilizers and did not have pellet burner in place, instead a bio-oil burner was employed for heating the greenhouse.

- Organic Fertilizers (2016)

In 2016, Svegro converted fully to organic production. In this process, conventional mineral fertilizers were replaced with organic fertilizers. The transformation required changes in the greenhouse's infrastructure to use the organic fertilizer in the NFT system employed. This included additional pumps and tanks for nitrification processes for the organic fertilizers.

- Pellet Burner (2018)

In 2018, two wood-pellet burners and auxiliary equipment to supply heat to the greenhouse were installed. This was done to replace bio-oil burners for the heating required in the greenhouse. This was also motivated by the potential to improve the sustainable sourcing of energy and lower their carbon footprint.

2.3.2. Baseline and current scenarios

- Baseline (2019)

The baseline scenario represents the system in place in 2019. This includes all developments from past scenarios. In the baseline scenario, compared to past scenarios, the share of biofuels in the domestic logistics was increased to 62% compared to 10%, to improve the environmental impacts from logistic services.

- Current (2021)

Directly after the data collection used for the Baseline scenario, the company implemented new packaging for their sold products. In the Current scenario, which represents production in 2021, all pots and transport trays were exchanged from black polystyrene (PS) to recycled green polypropylene (PP) material and the amount of outer packaging was reduced. This included two primary motivations,[2] 1) reducing the weight of plastic for the packaging and 2) substituting black polystyrene pots and trays for green polypropylene pots and trays. The former was done to reduce the amount of plastic used, while the latter was done in order to promote recycling of the pots, as black pots cannot be recycled. See Table 1 for a review of all inputs and outputs in the Current scenario.

2.3.3. Future scenarios

- Future-Sustainable Plastic

In the future, it is envisioned that there will be more circular, i.e., recycled content and recyclable plastics used. As such, in the future, plans have been set in place to modify the sleeves around the herbs and lettuce to recyclable plastic made from renewable sources. For this scenario, an increase in recycled plastics is included. One such change outlined is the shift from fossil polypropylene to recycled polyethylene. For this change, the shift to recycled polyethylene also incurs a slight increase in the weight of the plastics. In this scenario, changes to waste handling and recycling of the plastic have been included. Furthermore, the plastic LCI datasets are also altered.

- Future-Biofuel Transport

In the Future-Biofuel Transport scenario, all transportation was assumed to be conducted employing biofuels. For this scenario, it is assumed that all (100%) transportation by truck is fueled with a mix of biodiesel (FAME) and Hydrotreated vegetable oil (HVO). These fuels have rapidly expanded in use as transportation fuels in recent years and are included in current diesel fuel in low blends (Martin et al., 2020).

- Future-LED

In the future, there is a possibility to change from the current high-pressure sodium (HPS) lighting system to light-emitting diodes (LED) to reduce energy consumption. In this scenario, the lighting requirements were maintained for optimal growing conditions. However, as the HPS lighting also emits heat, and as LEDs do not produce as much heat, switching to LEDs would incur an increased heating demand. As such, an increase in the current pellet-based heating is required. This was modeled based on input from Katzin et al. (2021) for the heating and electricity demand and Zhang et al. (2017) for information on changes to the infrastructure and material requirements. No further optimizations were studied in this scenario between the HPS and LED lighting systems, e.g. changes in production output, etc.

- Future-Densify

At the time of writing this article, the space between the gutters in the NFT system was being reduced in order to increase the overall annual production capacity. From initial tests, it was found that this would be possible to develop throughout the entire greenhouse system. As such, this scenario includes increasing from the current production output of roughly 20 million sold plants to roughly 30 million sold plants annually. This would incur an increase in water, nutrients, and associated packaging. Furthermore, transportation would increase. However, it is assumed that no increase in energy, both electricity and heat demand, are required. A depiction of the densification scenario is provided in Figure S1 in the Supplementary Material.

3. Results

The following sections outline the results of the assessment. These are presented by first reviewing the impacts of the baseline scenario to provide context. Thereafter, the influence of implemented and potential changes in the different scenarios are outlined and analyzed.

3.1. Current system

Fig. 4 illustrates the environmental impacts of the Current scenario. As the results suggest, in nearly all environmental impact categories, energy contributes to the largest share of the environmental impacts. This is primarily a result of the electricity use and pellets, each accounting for roughly 75% and 20–30% respectively in each category except for water resource depletion, where the majority of impacts stem from electricity.

Transportation, for both inputs and of the products to market, is also of importance, accounting for nearly 20% of all GHG emissions. The contribution of transportation processes to other impact categories was not as high, although it accounted for over 20% of acidification impacts. For the impact categories of freshwater eutrophication, GHG emissions, and acidification, packaging also has a major contribution, accounting for roughly 20% of impacts in all of these impact categories. This was primarily a result of cardboard packaging.

Further details on the impacts per kg of edible product produced are also provided in Table 2, showing that the Current scenario results in emissions of roughly 4.7 kg CO_2-eq/kg edible product. The water resource depletion from all life cycle stages is roughly 70 m^3/kg edible product; with the vast majority stemming from energy production. In comparison, the actual production only requires roughly 64 liters of water/ kg of edible product (roughly 7 liters per pot).

3.1.1. Temporal impacts for the current scenario

As Fig. 5 depicts, the GHG emissions for the greenhouse fluctuate monthly. This is largely dependent upon energy inputs required for lighting and heating during the cold months of the year. Additionally, production outputs, and associated inputs, also fluctuate during the year. The contribution of energy demand is also analyzed in subsequent sections (Section 4.1) to study the implications of a change from the current HPS lighting system toward LED technology. As shown, the average GHG emissions of the main product, i.e., 1 kg of edible plant, accordingly, fluctuate during the year with an average of roughly 4.7 kg CO_2-eq/kg edible product. At the highest peak (December-January), GHG emissions are roughly 5.9 kg CO_2-eq/kg edible product while being much lower in the summer months, with impact minimized in July at about 3.2 kg CO_2-eq/kg edible product.

3.2. Environmental implications of improvement measures

In Fig. 6, there is a clear trend of reductions in GHG emissions with the studied past and future improvement measures. As shown from the Original scenario from 2014, the implemented measures have led to large GHG emission reductions. A closer inspection of the results points to the introduction of the pellet burner having the largest reductions in GHG emissions compared to the Original scenario in 2014 for past improvement measures. The Future-Densify scenario also shows large GHG emissions reductions compared to the Current scenario.

Table 3 provides a comparison of the environmental impacts for each scenario per functional unit. It is apparent from this table that the implemented steps to improve the sustainability of the system show promising environmental impact reductions. However, unlike the results of Fig. 6 above, outlining only GHG emission reductions, it is apparent that there may be trade-offs between the scenarios. What stands out in the table is that increasing transportation by biofuels leads to an increase in freshwater eutrophication and water resource depletion. Furthermore, as energy efficiency is increased (i.e. reduced

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[2] While other materials were considered, including e.g., paper, Svegro chose plastic as they found that the shelf life of the product in plastic packaging was superior to other choices and reduced food wastes.

Table 1
Material and energy inputs and outputs for the annual production in the Current scenario.

Type	Category	Specific Category	Inputs	Amount (annually)	Unit
Inputs	*Material Inputs*	Growing Medium		1 192 390	kg
		Organic Fertilizers		61 340	kg
		Seeds		2 460	kg
		Water		41 640	m^3
		CO_2 (enrichment)		163 700	kg
		Packaging	Polystyrene (PS)	1 670	kg
			Recycled Polypropylene (PP)	122 890	kg
			Polypropylene	91 180	kg
			LLDEPE	2 190	kg
			PET	370	kg
			Cardboard	525 190	kg
	Transportation-Inputs		Truck	2 048 140	tonne-km
			Car	170	km
	Energy Inputs		Electricity	18 370 200	kWh
			Pellets	8 673 000	kWh
Outputs	Production Outputs		Plants sold	20 328 320	units
			Product (Herbs-Edible Portion)	650 500	kg
	Cultivation and Packaging Wastes		Plastic Waste	1 090	kg
			Organic Waste	650 510	kg
	Transportation-Outputs/Market		Market (Truck)	1 541 980	tonne-km
			Waste Handling (Truck)	110	tonne-km
Infrastructure	Structures and Equipment		Greenhouse Structure	44 200	m^2
			Other Storage	10 800	m^2
			Furnace	1	unit
			HPS Light Fixtures	6 600	units
			Tanks	10	units
			Other Equipment (Bagging/Conveyors)	2	units

electricity demand), nearly all scenarios have improved environmental performance. The current scenario was identified to have large improvements for freshwater eutrophication impacts, while future developments may also reduce these further, e.g. in the Future-Densify and Future-LED scenarios. Finally, a large reduction in water resource depletion is seen in the Future-LEDs and Future-Densify scenarios, which is primarily a result of reduced electricity demand per functional unit.

4. Analysis

4.1. LED energy demand

Fig. 7 depicts the monthly energy consumption from the different lighting solutions. As shown, while LED lighting reduces electricity consumption, the pellet burner-based heating requirements are increased. For the LED scenario, the resulting total energy savings was roughly 22% during the year, with a 49% reduction in electricity consumption, despite an increase of roughly 25% in pellet burner-based heating.

4.2. Inclusion of end-of-life impacts

While the study was limited to a cradle-to-gate assessment, and as several scenarios address the packaging, the implications of including the end-of-life treatment of the product and packaging were analyzed to highlight its potential influence on the overall life cycle impacts. For this additional analysis, it was assumed that plastics and growing media in the final product are both incinerated and recycled to different degrees. All growing medium was assumed to be composted and incinerated (50% in each case) to account for different disposal options, although no modeling of consumer behavior was included. All polystyrene was assumed to be incinerated. Other plastics were also recycled or incinerated (50% in each case). To distinguish between these two possibilities, Fig. 8 illustrates the GHG emissions per edible kg of product. Further details on assumptions are provided in the Supplementary material.

As illustrated in Fig. 8, including the end-of-life increases the overall environmental impacts. However, there is considerable uncertainty on the fate and method for treatment or disposal of the products and packaging and thus for this study it was not included in the scope of the main assessment.

4.3. Sensitivity to electricity system

The energy demand was highlighted as an important contributor to all environmental impacts, primarily electricity. As the Swedish electricity mix is low impact compared to other European countries, due to a large share of renewables, including hydro (39%), nuclear (39%), wind (12%), and solar power (0.4%), the study can be highly sensitive to the choice of electricity employed (SEA, 2021). The chosen mix (Swedish electricity mix) was compared with a dataset for a Nordic electricity mix, which may contain a larger share of fossil fuels. Svegro also purchases electricity with renewable certificates from wind and hydropower. As such, the sensitivity to including these separately, and as a mix (50/50) are included; see Table 4.

As the results suggest, if employing the Nordic mix of electricity, there was an increase of roughly 0.26 kg CO_2-eq per kg edible, or an annual increase of 167 tonnes CO_2-eq for the total annual production, see the Supplementary Material for further information on annual impacts. Hydropower-based electricity reduced GHG emissions by roughly 0.63 kg CO_2-eq per kg edible, while employing wind power-based electricity reduced this by 0.82 kg CO_2-eq per kg edible. From the table, it is evident that hydropower was found to reduce eutrophication and acidification impacts in addition to largely reducing resource depletion. Wind power largely reduced water resource depletion compared to other electricity sources, primarily due to less reliance on water resources and reservoirs needed for hydro and nuclear energy. Employing the purchased electricity, i.e., based on the mix certified, the emissions would be roughly 3.95 kg CO_2-eq/kg edible product, which again is lower than the employed Swedish electricity mix. This shows that employing the purchased electricity compared to Swedish electricity could result in roughly 16% less GHG emissions.

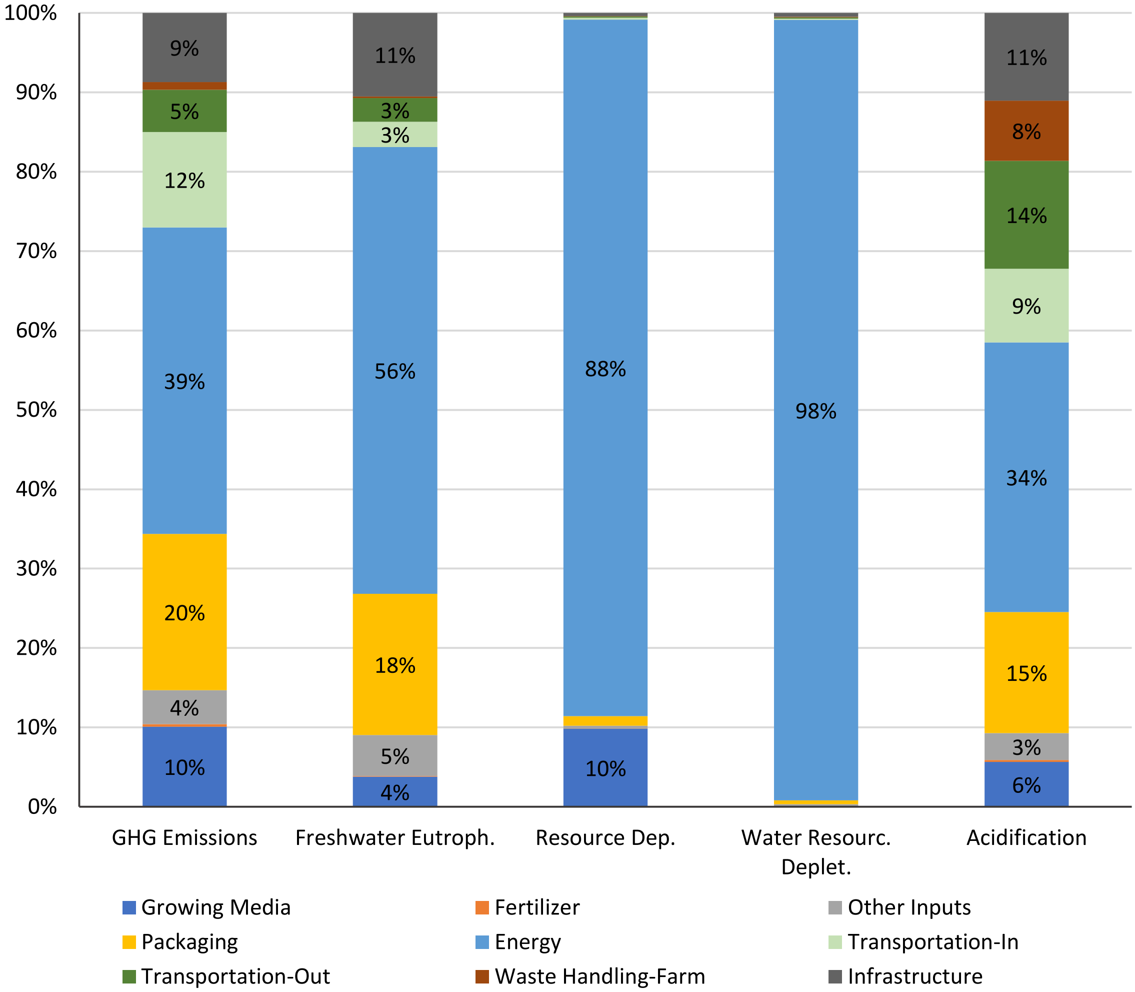

Fig. 4. Contribution of different processes to the environmental impacts of 1 kg of edible plant for the Current scenario. (Freshwater Eutroph–Freshwater Eutrophication, Resource Dep. –Mineral, Fossil and Renewable Resource Depletion, Water Resourc. Deplet. –Water Resource Depletion). Data labels are provided for those processes contributing over 3% of the share.

Table 2
Contribution analysis of different processes and inputs to the cradle-to-gate life cycle impacts of 1 kg of edible product for the Current scenario. (Freshwater Eutroph–Freshwater Eutrophication, Resource Dep. – Mineral, Fossil and Renewable Resource Depletion, Water Resourc. Deplet. –Water Resource Depletion).

	GHG Emissions (kg CO_2-eq)	Freshwater Eutroph. (kg P eq)	Resourc. Deplet. (kg Sb eq)	Water Resourc. Deplet. (m^3 water eq)	Acidification (mol *H+* eq)
Growing Media	0.47	6.34E-05	5.89E-06	0.06	1.62E-03
Fertilizer	0.01	1.53E-06	3.80E-09	0.00	7.33E-05
Other Inputs	0.20	8.60E-05	2.26E-07	0.16	9.68E-04
Packaging	0.93	2.98E-04	7.17E-07	0.34	4.39E-03
Energy	1.81	9.42E-04	5.27E-05	68.89	9.76E-03
Transportation-In	0.57	5.28E-05	1.53E-07	0.11	2.67E-03
Transportation-Out	0.25	5.03E-05	9.88E-08	0.13	3.90E-03
Waste Handling-Farm	0.02	1.75E-06	9.89E-09	0.02	1.10E-03
Infrastructure	0.41	1.76E-04	2.35E-07	0.34	3.17E-03
Total	***4.67***	***1.67E-03***	***6.00E-05***	***70.05***	***2.76E-02***

5. Discussion

This study suggests that past and future measures at the studied greenhouse to improve resource efficiency largely improve the environmental performance of the system. The following sections provide further discussions on the results in relation to other studies, highlight the limitations in the modeling, and provide potential improvement areas and suggestions for future research.

5.1. Longitudinal improvements

As the results suggest, measures taken to improve the resource efficiency for the greenhouse have resulted in large environmental impact reductions. Temporally, these are compounded which helps to improve the environmental performance of the system and products.

From past years, large environmental impact reductions were seen, in all impact categories, from reducing the amount and type of plastics and from the installation of a pellet burner. Switching to organic

Table 3
Comparison of the environmental impacts for each scenario per functional unit. Results are compared with the Original values in 2014 to show the change. (Eutroph–Eutrophication, Resource Dep. – Mineral, Fossil and Renewable Resource Depletion, Water Resourc. Deplet. –Water Resource Depletion).

Scenario	GHG Emissions kg CO_2 eq.	Freshwater Eutroph. kg P eq.	Resource Dep. kg Sb eq.	Water resource depletion m^3 water eq.	Acidification molc $H+$ eq.
Original (2014)	100%	100%	100%	100%	100%
Organic Fertilizer (2016)	97%	98%	97%	100%	98%
Pellet Burner (2018)	85%	88%	98%	100%	47%
Baseline (2019)	80%	90%	97%	100%	45%
Curent (2021)	68%	89%	98%	100%	51%
Future-Sustainable Plastic	66%	92%	97%	100%	45%
Future-Densi.	58%	70%	68%	67%	37%
Future-Biofuel Transp.	66%	93%	97%	100%	57%
Future-LED Lighting	61%	74%	61%	57%	41%

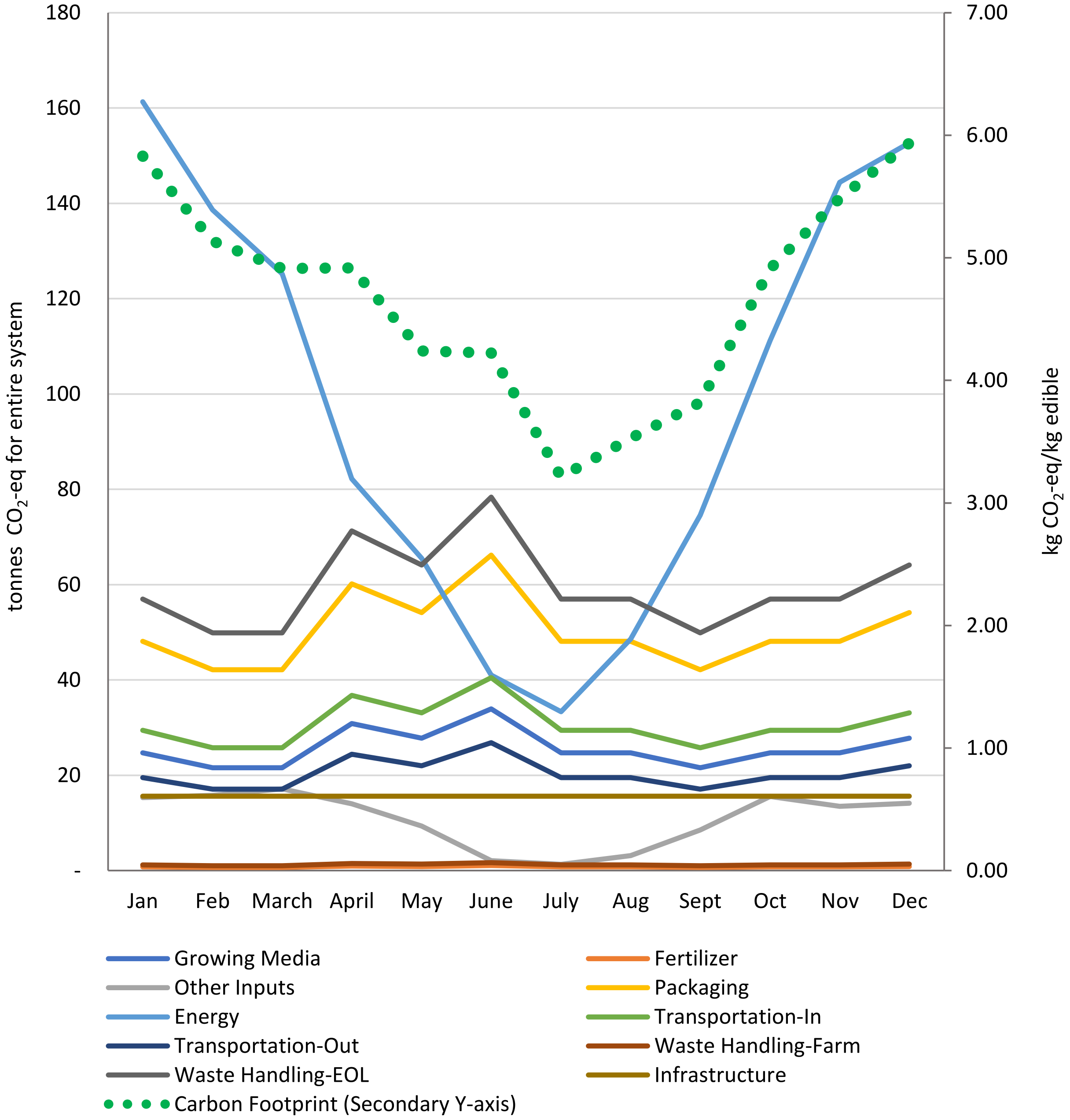

Fig. 5. Analysis of monthly GHG emissions (measured in tonnes CO_2-eq) in the Current scenario during one year for the different processes (left y-axis). The chart also illustrates the monthly carbon footprint of the main product, (measured in kg CO_2 eq. per edible kg product on the secondary y-axis), depicted as a dotted green line.

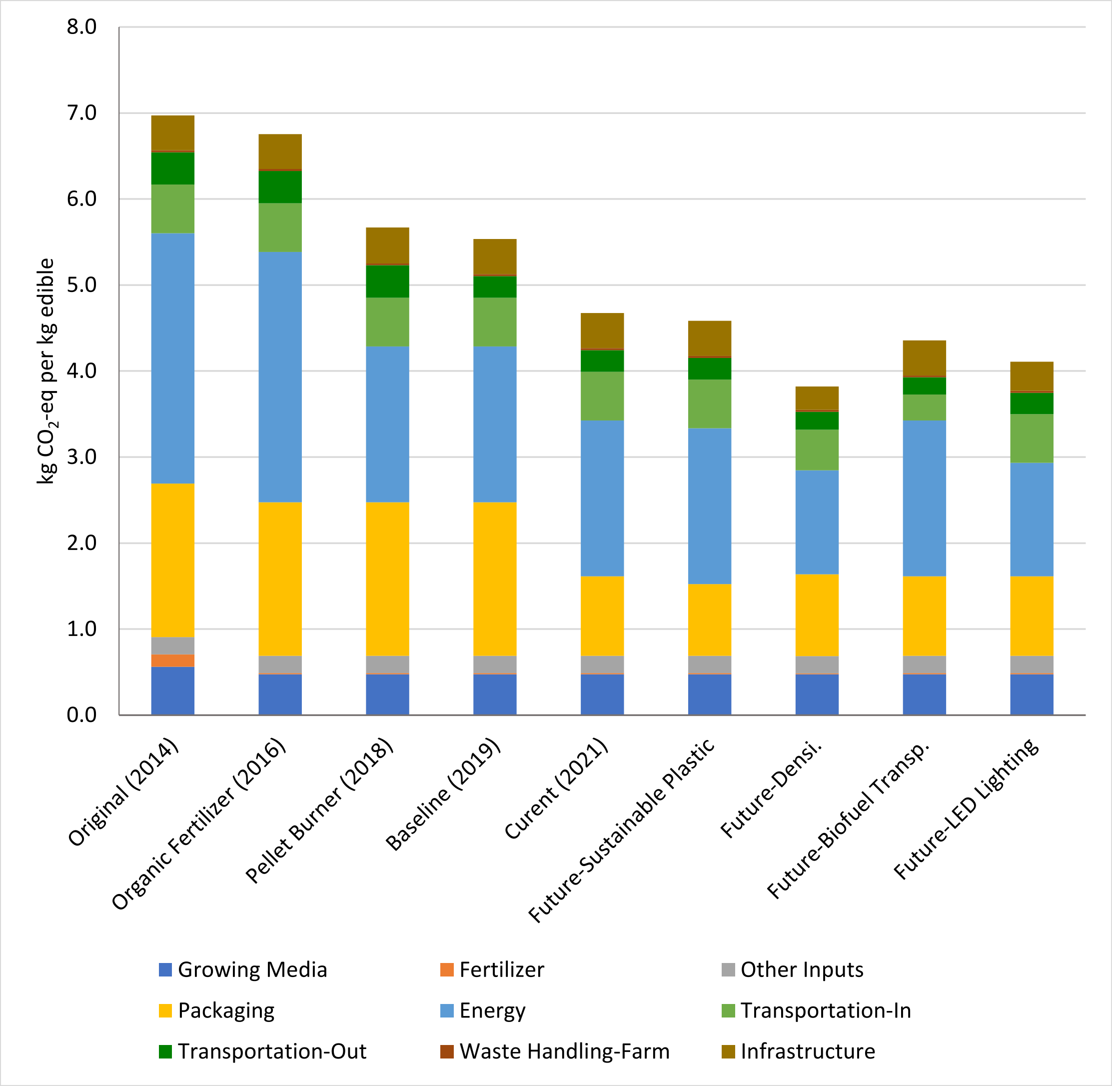

Fig. 6. Comparison of the annual GHG emissions of the different scenarios, also illustrating the contribution of different processes and inputs.

fertilizers only slightly reduced environmental impacts. Similar findings for improved environmental performance through optimization have been identified in Spångberg et al. (2011) and for heating greenhouses in Short et al. (2014). However, few previous studies have studied the effects of changes over time for greenhouses, instead focusing primarily on a static picture of annual production of a greenhouse. As such the results from this study can provide important insights into the benefits of developing sustainability measures and testing options to improve resource efficiency. The results show that the energy demand and sourcing, packaging, and transportation were important hotpots in the life cycle assessment. Similar findings have been shown in Dias et al. (2017). As such, all three future scenarios were geared toward addressing these concerns. Further details are also outlined in sections below.

5.2. *Implications for products*

The results point to a large potential to reduce the environmental impacts associated with the edible plants. From the original system in 2014, the environmental impacts were reduced from roughly 7 to 4.7 kg CO_2-eq/kg edible product through measures leading up to the current scenario. Future scenarios were also shown to reduce this further to 4.1 kg CO_2-eq/kg edible product, i.e., in the Future-LED Lighting scenario. The sensitivity analysis also suggests that if other data choices for e.g., the electricity mix, were used instead, the GHG emissions could be even lower. These values are slightly lower than those found in studies by CarbonCloud (2022) who reported 6.0 kg CO_2-eq/kg edible product for potted herbs and VHB (2022) who outlined an impact of roughly 450 gram CO_2-eq per pot of cilantro, which is roughly 14 kg CO_2-eq/kg edible product. Few studies have assessed greenhouse herb production and there are few other metrics to compare with. However, Orsini et al. (2020) also outline water use efficiency for basil produced in greenhouses to be roughly 20 g edible product/liter. The results of this study are slightly lower at roughly 15 g edible product/liter water.

As outlined, the impacts from the plants also vary considerably during the year. In the summer months, due to a reduced energy demand, the environmental impacts are lower than 3.2 kg CO_2-eq/kg edible product, potentially having comparable results to land-based systems (Orsini et al., 2020). Such information regarding the fluctuation is important, as often greenhouse production is compared with open-field farming which may also take place only during the optimal cultivation months, while the products from a greenhouse featuring artificial lighting are likely to be available year-round. Such results and metrics are important for benchmarking, highlighting improvement areas, and promoting collaboration and development in the field. Nonetheless, comparisons to other specific products may be challenging as there are currently no scientific articles reporting the environmental impact of herbs from greenhouses available in the literature. While the

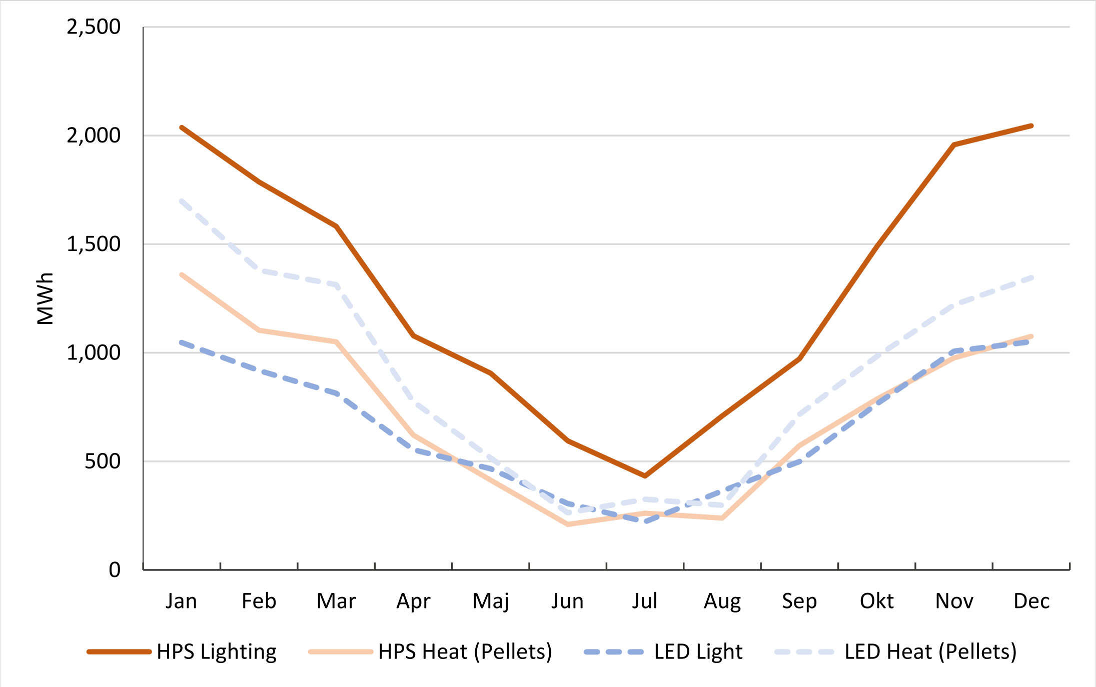

Fig. 7. Monthly energy consumption for HPS and LED lighting. Results are shown in monthly energy consumption in MWh for both electricity (lighting) and heat (pellet-based heat) energy. .

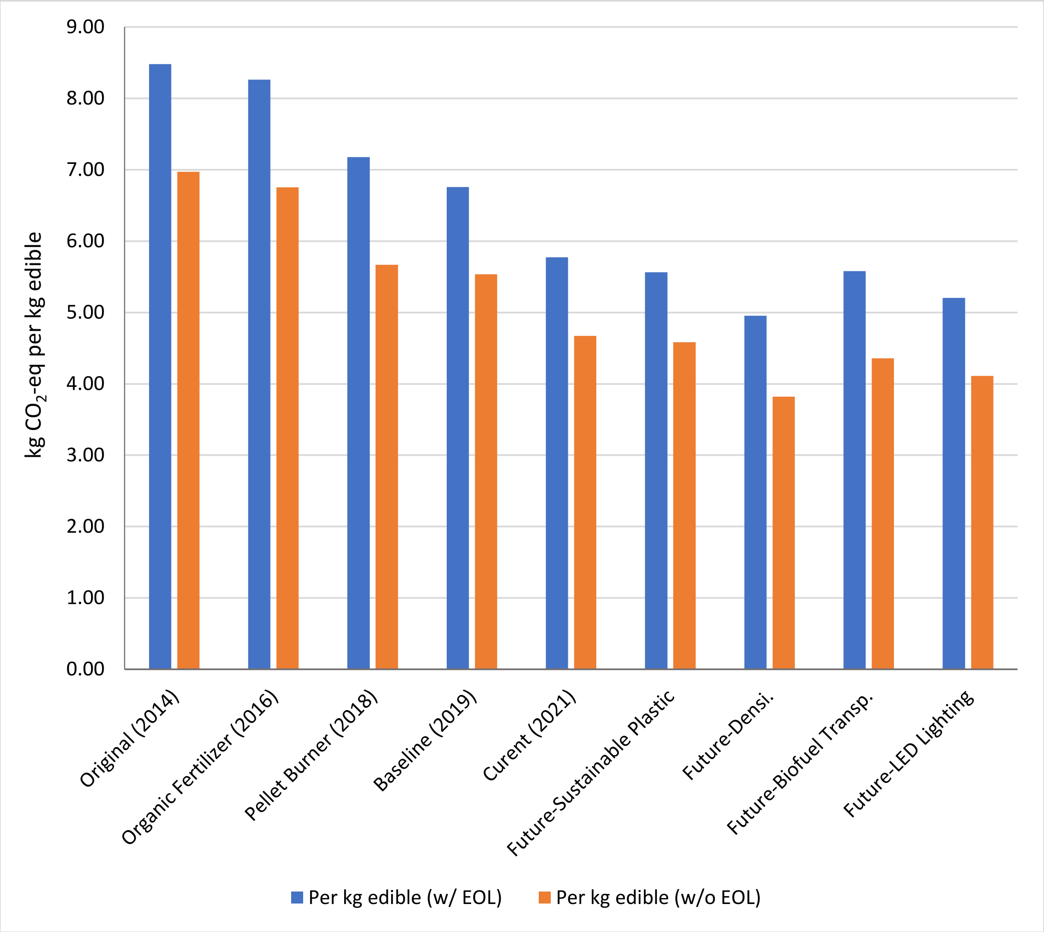

Fig. 8. Sensitivity of the GHG emissions per functional unit (i.e. kg CO_2-eq per kg edible product) to the inclusion of end-of-life (EOL) emissions. (w/ EOL denotes impacts with EOL, while w/o EOL denotes those without EOL impacts).

Table 4
Sensitivity to the choice of electricity system employed on the different environmental impacts (shown environmental impacts per functional unit for each respective impact category). The colors show those scenarios with the largest (red) and smallest (green) impacts in the respective impact categories. (Eutroph–Eutrophication, Resource Dep. – Mineral, Fossil and Renewable Resource Depletion, Water Resourc. Deplet. –Water Resource Depletion).

Electricity Source	GHG Emissions kg CO_2 eq.	Freshwater Eutroph. kg P eq.	Resource Dep. kg Sb eq.	Water Resourc. Deplet. m^3 water eq.	Acidification molc H+ eq.
Current scenario (Swedish Mix)	4.67	1.67E-03	6.00E-05	70.0	2.76E-02
Wind	3.85	1.62E-03	4.11E-05	2.32	2.77E-02
Hydro	4.04	1.03E-03	8.20E-06	123	2.23E-02
NordEl	4.93	1.46E-03	4.11E-05	41.7	2.78E-02
Certificate (Wind& Hydro)	3.95	1.32E-03	8.33E-06	62.8	2.50E-02

greenhouse produces a variety of different crops, with varying production cycles, the actual impacts for certain herbs may be higher or lower than those shown per kg of edible output. Furthermore, these may vary throughout the year with seasonal demand and conditions for their growth. Although this was not analyzed in this study, further research should be focused on accounting for the outputs of different plants.

5.3. Packaging design and end-of-life

In the overall results for the Current scenario, packaging was also shown to have a large contribution to freshwater eutrophication, GHG emissions, and acidification, accounting for roughly 20% in all aforementioned impact categories. This was primarily a result of cardboard packaging and not plastic. Similar results have also been found in Dias et al. (2017) and Cellura et al. (2012). However, as highlighted in the change from the *Baseline* to the *Current* scenario, the reduction of packaging resulted in large environmental performance improvements. This was primarily due to a reduction in the overall weight of the plastics used by shifting from polystyrene to polypropylene, in addition to employing recycled material. Although the impact of a single pot does not change much, given the production output of the assessed greenhouse, the overall reductions in plastic use were substantial. Similar results are also highlighted when shifting from polypropylene pots to allow for new solutions for the packaging from potted edible plants, see e.g. Martin and Molin (2019). Nonetheless, few studies have reviewed the redesign of packaging for greenhouse products, although similar assertions on the implications of reducing the weight and designing for recycling can be found in Wikström and Williams (2010) and Licciardello and Piergiovanni (2020) and calls for such development have been increasingly seen in the industry (Agritecture, 2022b). For food products, the design of packaging can also influence the sustainability perception of the product (Boesen et al., 2019).

In this study, the contribution of the end-of-life had a small but important increase in the impacts per kg of edible plant. Although the end-of-life treatment of the product was only analyzed to show the implications it may have on the overall impact on the product, the results point to the importance of also developing approaches to improve packaging recyclability and consumer awareness (Wikström and Williams, 2010; Williams et al., 2008). For modeling the end-of-life treatment, this study chose a conservative approach, assuming that only 50% of the pots would be recycled by consumers. This was done as the actual share of recycled plastics, beyond PET, is relatively low in Sweden (Naturvårdsverket, 2021). Importantly, it should also be noted that the branch organization for recycling of packaging suggests not recycling the pots from potted plants (FTI, 2022). The reason for this may be that not all producers use recyclable materials, e.g., employing black polyethylene pots. However, this should be reviewed once again as companies such as the studied greenhouse producer could design their packaging to allow for recycling, and information provided by the FTI may send divergent signals to consumers. Indeed, regional waste handling companies also address waste streams from potted plants to be complex and often awkward waste stream to handle (NSR, 2021), again calling for more thorough assessments. However, specific figures for packaging such as that used by producers of potted plants are scarce. Future studies could focus on understanding the recycling rates of such packaging and the behavior of consumers and consider this for packaging design.

5.4. Energy demand and sensitivity

The environmental impacts of the different scenarios are largely due to the energy demand, as highlighted in the results. Furthermore, it can be concluded that the results are highly sensitive to the source of electricity. Similar assertions have been found in a number of previous studies of hydroponic greenhouses (Dias et al., 2017; Graamans et al., 2018) and vertical farms (Martin and Molin, 2019; Weidner et al., 2021). From the sensitivity analysis, the importance of associated dataset choices is also highlighted. The environmental impacts of the employed datasets available in Ecoinvent are much larger than those available from e.g., Environmental Product Declarations (EPDs) available from regional electricity suppliers. According to EPDs available from Vattenfall (2019, 2021) the climate impacts from electricity generated from wind are roughly 15.5 g CO_2-eq/kWh (Vattenfall, 2019) and 6.9 g CO_2-eq/kWh from hydropower (Vattenfall, 2021). Corresponding datasets from Ecoinvent for wind power range from 4 to 49 g CO_2-eq/kWh from hydropower and 14–24 g CO_2-eq/kWh from wind.

Furthermore, for studies of past and future scenarios, a limitation in this study is the electricity LCI data used for the different scenarios. For more accurate implications of past and current scenarios, the national or regional mix for the actual years reviewed could be used for more accuracy, see e.g., Papageorgiou et al. (2020). However, for past scenarios, and during the past decade, the electricity mix has remained relatively stable (SEA, 2021) and was assumed to have little effect on the results. Nonetheless, for future scenarios, electricity mixes are uncertain and could affect the results (SEA, 2016; Söderholm et al., 2011; Kan et al., 2020). As the future scenarios include measures that are currently being implemented at the time of writing this article and assumed to be implemented in the next few years, the implications of changes to the energy system were not included, although they may have an influence on the results.

The results highlight that a shift from HPS to LED lighting could largely reduce energy demand. However, there are limitations in this scenario, as it assumes similar production outputs and reviews only the change in energy and heat demand in addition to the change in infrastructure. Furthermore, this study used a photon efficacy of 3.5 μmol/J, despite the fact that studies such as Paucek et al. (2020) suggest most commercial LED fixtures have an efficacy of 2–3 μmol/J. However, according to the calculation of Kusuma et al. (2020), considering potential performances of the current technologies, this can be as high as 4.1 μmol/J for LEDs with a mixture of red and blue fixtures. In particular, it should be noted that, unlike HPS lamps, LED lamps allow the control of light intensity and light spectrum according to the plant needs throughout the growth cycle, thus leading to an increase in yield and quality (Singh et al., 2015; Kalaitzoglou et al., 2019).

Consequently, while all scenarios are assumed to employ the same electricity mix, these may have also changed over the years due to changes in the Swedish electricity mix and the purchased certificates at the case study greenhouse, which may require further scientific evaluation to understand the role it may have on the impacts over time. This study did not review the implications of changes in the greenhouse infrastructure, although research suggests that changes in designs can lead to improvements to heating demand (Ahamed et al., 2019) and could be the subject for future research in the greenhouse horticulture field in Sweden. While some studies have addressed how the economic performance of energy demand could benefit controlled environment agriculture (Avgoustaki and Xydis, 2021), future research could expand upon the environmental implications of actual electricity demand, sourcing, and timing. In the scenario outlining densification, it is assumed that no additional energy demand is required based on findings from initial tests. However, extended assessments should be conducted to ensure that the added densification does not require increased climate control demands or adversely affect the production capacity. Further studies should assess and review the implications for the growing conditions, climate and in particular humidity control, and crop production efficiency (Katzin et al., 2021; Nicole et al., 2019).

5.5. *Developing supply chains and reducing transportation impacts*

The results also highlight that a large share of the emissions from the operations stem from supply chain material inputs and logistics to deliver final products to retail. As such, for large greenhouses such as the subject of this study, optimization of transportation logistics and the associated environmental impacts are of importance. Similar assertions have been highlighted in previous studies to create more sustainable supply chains (Aronsson and Huge Brodin, 2006; Handfield et al., 2005; Sim et al., 2006).

As shown in the results for the Future scenario employing an increase in biofuels for logistics, large reductions in GHG emissions are possible. However, such developments may take time to achieve, as logistics providers are undergoing changes in vehicle fleets and energy carriers (Börjesson et al., 2014; Wehner et al., 2022). While temporal changes in vehicles fleets were not modeled in this study, in reality, this may have implications for different scenarios. Once again, however, this was considered outside the scope of this study. Furthermore, contractual agreements with logistic services may be needed (Evangelista, 2014; Wehner et al., 2022). While the greenhouse has contractual agreements with domestic logistics for deliveries of the products to market, stipulating minimal shares of renewable fuels, there is less control on logistics for international logistic services, e.g., material inputs. Through procurement contracts with international suppliers, these could be further improved, and a larger share of renewable fuels could be employed, which may greatly reduce GHG emissions (Cerutti et al., 2016; Gustafsson et al., 2021). Further developments in transportation, e.g., electric trucks for regional logistics, could further reduce these emissions.

There is also potential for logistic services by sourcing material inputs domestically. An example is the large volumes of the substrate sourced from elsewhere in Europe. One such input is peat, where sourcing peat from domestic sources could reduce environmental impacts. However, the sustainability of peat extraction in the Nordic countries continues to be a controversial subject (Airaksinen and Albrecht, 2019; Chapman et al., 2003; Zetterberg et al., 2004). Removing or reducing the share of peat from the growing media mix could also be of interest in the future to reduce the share of fossil products in the final product. Similar approaches have been done in many urban-vertical farms (Martin and Molin, 2019) which have been shown to reduce the environmental impacts of the growing media by employing residual products from other industries, although the sourcing of e.g., coir can also incur added transportation impacts.

6. Conclusions

Improvement measures taken at the case study greenhouse were found to have an essential role in reducing the environmental impacts and improving the resource efficiency of the hydroponic greenhouse operations from the past. The current system has reduced GHG emissions compared to the Origin scenario in 2014 by over 32%. Above all, switching to bioenergy-based heating resulted in large environmental impact reductions, reducing the GHG emissions from energy consumption by roughly 38%. Reducing the amount and type of plastics was also found to largely improve the environmental performance, nearly halving packaging GHG emissions. However, the scenario for switching from conventional fertilizers to organic fertilizers had no significant environmental impact reductions. Future scenarios were also outlined to improve the current system, where large environmental impact reductions in all environmental impact categories are possible. Switching the current lighting system to use LED lighting was shown to reduce GHG emissions from the current scenario by over 10% and densifying the greenhouse to increase the production capacity could reduce GHG emissions by 14%. Other future scenarios for expanding the use of renewable and recyclable plastics and transitioning toward a larger share of renewable energy in the transportation logistics could reduce GHG emissions by 4% and 3% respectively. However, it should also be noted that there can be environmental tradeoffs with certain scenarios. For example, while the increased use of biofuels reduces GHG emissions, it may also increase the potential for acidification, eutrophication, and water resource depletion. Furthermore, the assessment also found that the environmental performance is also greatly affected by the choices made for modeling, most importantly, the source of electricity and the life cycle inventory data employed.

The results provide insights to growers of greenhouse produce using NFT systems of the benefits of addressing improvements to current greenhouses and products. The knowledge produced from this study provides an understanding of the environmental implications of greenhouse horticulture for herbs in Sweden and adds to the developing literature on the sustainability of controlled environment agriculture by studying the environmental performance of a case study greenhouse in a Nordic context. Finally, it is suggested that future research should focus on the viability, feasibility, and potential of future scenarios to improve resource and energy efficiency, in addition to modeling the temporal changes in supply mixes.

Funding

The research has been funded through a grant from the Swedish Innovation Agency (Vinnova), grant 2019–03178 in the project ‘Urban

farming for resilient and sustainable food production in urban areas.'

CRediT authorship contribution statement

Michael Martin: Funding acquisition, Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Elin Bengtsson:** Conceptualization, Investigation, Data curation, Methodology, Writing – original draft. **Laura Carotti:** Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Kristin Orrestig:** Conceptualization, Formal analysis, Investigation, Data curation, Methodology, Writing – original draft. **Francesco Orsini:** Formal analysis, Methodology, Investigation, Writing – original draft.

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

No data was used for the research described in the article.

Acknowledgments

We would like to thank the staff at Svegro for continued support in data collection, feedback, and suggestions throughout the development of this assessment. We would also like to thank the reviewers of this article for their input and comments, leading to the improvement of the article.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2023.106948.

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