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The embodied carbon emissions of lettuce production in vertical farming, greenhouse horticulture, and open-field farming in the Netherlands

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ABSTRACT

Over the past decades, various farming methods have evolved in response to the global challenges of increasing food demands, decreasing availability of arable land, and climate change. One of these new farming methods is vertical farming. To understand the contribution of vertical farms to future sustainable food production, beyond its efficient land-use and high yields, this paper evaluates the current carbon footprint of lettuce produced in an operational vertical farm in comparison to conventional open-field farming and both soil-based and hydroponic greenhouse cultivation in the Netherlands. The assessment includes the greenhouse gas emissions of the life cycle of the farm and the crop, from cradle-to-grave. An alternative scenario is explored to include the lost carbon sequestration potential by land-use change, identical packaging for all farming methods, and renewable energy usage. The carbon footprint of the vertical farm was 5.6–16.7 times greater than that of the conventional farming methods in the baseline scenario and 2.3 to 3.3 times in the alternative scenario. The electricity demands of the vertical farm represented 85% of the carbon footprint in the baseline scenario and 66% in the alternative scenario, suggesting that a significant reduction in electricity use is required to compete with conventional farming methods from a carbon footprint perspective. If this could be achieved, vertical farming could become a valid component of future sustainable and food secure systems by its efficient use of land, high yields, minimal use of water, nutrients, pesticides and herbicides, and the ability to be located within or adjacent to cities.

1. Introduction

1.1. Food security and the climate change

Climate change and food security are inextricably linked and are both factors that endanger the future health and wellbeing of people across the globe. Agriculture is one of the major contributors to climate change, emitting ∼11% of total anthropogenic greenhouse gas (GHG) emissions (Smith et al., 2008) and between 26% (Poore and Nemecek, 2018) and 37% (Mbow et al., 2019) of GHG emissions when considering the full value chain. Food production will be greatly impacted in the future by the globally decreasing availability of agricultural land (Benke and Tomkins, 2017) and declining yields due to adverse weather and increased food spoilage as direct consequence of climate change (Edwards et al., 2011). This creates great challenges as global food production will need to increase by up to 70% between 2017 and 2050 due to a growing global population and changing diets (Hunter et al., 2017). To produce the extra food required by 2050 without further destruction of natural landscapes to provide new arable land, the environmental impact of food production systems needs to be reduced and new methods of cultivating crops are desperately needed.

A farming technique that has been developed to reduce the environmental impacts of agriculture whilst maximising productivity is vertical farming. Closed-box vertical farms (CBVFs) are indoor growth systems that use artificial light and air treatment systems exclusively alongside multi-layer hydroponic systems; creating uniform growing conditions independent of the outdoor climate (Delden et al., 2021). This allows CBVFs to achieve year-round production with maximum density and productivity (Graamans et al., 2018). Kalantari et al. (2017) performed a literature survey on the benefits of vertical farming; literature frequently suggested that CBVFs reduce the use of water, pesticides and herbicides, whilst increasing productivity per unit area. Benke and Tomkins (2017) state that CBVFs potentially require less fertilisers and Germer et al. (2011) note that the limited use of pesticides,

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herbicides, and fertilisers minimises the risk of discarding these chemicals into the environment. Germer et al. (2011) also draw attention to the capability of CBVFs to reduce food waste due to controlled growth environments and shorten food miles by placing such facilities within or adjacent to cities. The creation of short supply chains can also reduce the need for storage and packaging (Kalantari et al., 2017). Considering these benefits, it could be concluded that the environmental impact of CBVFs is lower than that of conventional agricultural practices for crop cultivation; in this paper referred to as open-field farming and greenhouse horticulture. The advantages of CBVFs, however, result in higher electricity demands for artificial lighting and air conditioning (Delden et al., 2021). This electricity demand exceeds the energy consumption of greenhouse systems (Graamans et al., 2018) to such an extent that, in terms of carbon footprint, it could outweigh the aforementioned benefits altogether (Kikuchi and Kanematsu, 2020).

1.2. The carbon footprint of vertical farming

To explore the potential role of CBVFs as a component of future sustainable food production, a greater depth of knowledge is required to determine the environmental impact of the practice relative to conventional farming systems. Three carbon footprints of CBVFs were found in existing literature (Table 1). The most comprehensive analysis, performed by Kikuchi et al. (2018), did not only include the carbon emissions released during crop cultivation – the core emissions – but also the emissions produced by both pre-production and post-production processes of the crop, i.e. upstream, downstream, and end-of-life emissions of the crop life cycle. The life cycle of the farm was also taken into account. Considering that 75% (Kikuchi et al., 2018), 85% (Benis et al., 2017) and 90% (Li et al., 2020) of the carbon footprints represent artificial light, the electricity consumption per kg fresh weight (FW) varies greatly (Table A.1, #1–3) and results in a large dispersion between the carbon footprints. These data also suggest that the emissions to produce a kWh of electricity differs significantly between countries. To put this into perspective the electricity use of these three CBVFs were compared to that of other CBVFs studied in existing literature, which mostly represent simulated farms. The electricity use for artificial light variated greatly between 3.1 and 31.5 kWh per kg FW produced (Table A.1, #4–8), suggesting a wide range of carbon footprints. The carbon footprint of the lettuce producing CBVF located in Kashiwa, Japan, was compared to that of conventional cultivation within plastic tunnel greenhouses without artificial light. Kikuchi et al. (2018) also studied hydroponic greenhouse production with both artificial and natural light relative to conventional horticulture, focussing on tomato production. Both studies focus on different crops, making it difficult to compare the carbon footprints. The GHG emissions of the CBVF in Kashiwa were reduced by 60% by using more efficient and sustainable technologies, such as implementing photovoltaic (PV) production on the CBVF roof and using a hydrogen powered combined heat and power system. These technologies were not applied to the conventional farming methods resulting in an unfair comparison. Table A.1 also presents details on the energy use for artificial lighting in relation to crop yields of these CBVFs. The carbon footprint studies (Table A.1, #1–3) did not document all data, such as photoperiods and yields, which made it difficult to validate the findings presented or compare them to the other CBVFs in a robust manner.

The quantity of energy used (Avetisyan et al., 2013), the source of energy (Delden et al., 2021), the local climate conditions affecting resource use efficiency (Graamans et al., 2018), and local farm typologies (Benis and Ferrão, 2018) make the sustainability of food systems context specific, meaning that the emissions vary per region. To the authors' knowledge, no quantitative comparison of carbon emissions associated with both the life cycle of the farm and the crop, from cradle to grave, exist for CBVFs relative to open-field farming and both soil-based and hydroponic greenhouse horticulture within the Dutch context. The goal of the study presented is to evaluate the carbon footprint of CBVF in comparison to conventional farming systems to determine the potential role of CBVF as a sustainable cultivation method in the Netherlands. This paper performs a quantitative carbon footprint assessment of lettuce cultivation in open-field farming (OF), soil-based greenhouse horticulture (GH(s)), hydroponic greenhouse horticulture (GH(h)) and vertical farming (VF) in the Netherlands, including the upstream, core, downstream, and end-of-life emissions of both the farm life cycle and crop life cycle, from cradle to grave. In the discussion section, the paper proposes three alternative scenarios to include the lost carbon sequestration potential by land-use change, identical packaging and renewable energy usage across all case studies to provide a fair basis of comparison across the four food systems analysed. Finally, the energy use and proportion of energy used for artificial light of the studied VF is presented to provide an opportunity to contextualise the results, relative to other CBVFs from literature.

2. Materials and methods

2.1. Description of the case studies

This study presents the carbon footprint assessment of butterhead lettuce grown in four different farming systems in the Netherlands: OF, GH(s), GH(h), and VF. A typical farm is defined for open-field farming and both forms of greenhouse horticulture, based on existing databases. An operational commercial VF located in the Netherlands was used as a case study as it is not yet possible to define a typical VF due to the breadth of approaches. Butterhead lettuce was used as the sole crop of comparison in this study as it is one of the most important leafy vegetables worldwide due to their fast growth and short production cycles, which also makes them an interesting proposition for vertical farmers (Voutsinos et al., 2021).

Table 1
Comparison of carbon footprints of CBVF from literature and the activities included within those footprints.

Carbon footprint $kgCO_{2\text{-eq}}\ kg^{-1}$	Life cycle farm	Life cycle crop				Reference
		Upstream	Core	Downstream	End-of-life	
1.32	–	–	Water, Electricity	Transport	–	Benis et al. (2017)
1.44	–	Fertilisers, Seeds	Water, Electricity, CO_2	–	–	Li et al. (2020)
~25[a]	Construction and decommissioning of buildings and devices	Fertilisers, Pesticides, Seedlings, Culture media, Packaging	Water, Electricity, Fuels, CO_2	Transport	Waste treatment	Kikuchi et al. (2018)

[a] Value taken from Fig. 4B (Kikuchi et al., 2018).

2.1.1. Open-field farming

OF is defined as the cultivation of crops in soil, open to the air, with the application of nutrients, pesticides, and herbicides (Barbosa et al., 2015). European crops grown in open-field farming systems are rainfed (Portmann et al., 2010) and use additional irrigation (Breukers et al., 2014). OF requires machinery, such as tractors, buildings for storage, and vast areas of land to achieve the economy of scale required to generate profit. Within the Dutch context, the average vegetable producing OF is 15 ha gross in size (CBS, 2021) and produces 84,300 butterhead lettuce crops per ha per growth cycle (Schreuder et al., 2009). On average, open-field lettuce farms have three growth cycles per year (Snoek, 1985) and a crop FW of 350 g. This FW corresponds with Snoek (1985), suggesting that lettuce crops are harvested when the FW of 100 crops is approximately 35 kg, Resulting in the production of 253,000 heads of lettuce per ha, i.e. 8.9 kg m^{-2} y^{-1}.

2.1.2. Soil-based greenhouse horticulture

Greenhouse horticulture includes a wide range of different approaches from soil-based, uncontrolled environments in polytunnels through to hydroponic, semi-closed, controlled environments in glasshouses. In this study, GH(s) refers to soil-based cultivation of lettuce crops in the semi-closed growth environment of a Venlo greenhouse with active application of nutrients, pesticides, and herbicides, alongside drip-fed irrigation. The growing conditions are achieved and maintained through a combination of mechanical and passive strategies, where sunlight is used as the primary source for heating and exclusively for lighting (Graamans et al., 2018). On average, the heating temperature is 8 °C above ambient and the maximum relative humidity is 92% (Raaphorst and Benninga, 2019). Natural ventilation is used for passive cooling, ventilation, and dehumidification. GH(s) require an active supply of carbon dioxide (CO_2) to compensate the losses of CO_2 into the atmosphere by natural ventilation and maintain CO_2 levels of 800 ppm (Graamans et al., 2018). In the Netherlands, the average greenhouse covers an area of 4 ha and produces 830,000 lettuce heads per ha of 350 g each (Raaphorst and Benninga, 2019), i.e. 29.05 kg m^{-2} y^{-1}.

2.1.3. Hydroponic greenhouse horticulture

GH(h) refers to hydroponic lettuce cultivation using nutrient film technique (NFT), in which roots partially hang in a sloped channel through which a thin layer of nutrient solution is pumped (Lennard and Leonard, 2006). The crops are produced within the same indoor environment as described for GH(s), but includes the use of artificial light with LED systems of 87 μmol m^{-2} s^{-1} for 2000 h y^{-1} in addition to natural light. The heat dissipated by these LED systems results in a slightly higher average indoor temperature of 10 °C above ambient. The crops are harvested at 220 g FW, producing 241.8 lettuce heads per m^2, i.e. 53.2 kg m^{-2} y^{-1} (Raaphorst and Benninga, 2019).

2.1.4. Vertical farm

The operational VF used in this study occupies two rooms in an existing office building: a growing room and a processing room (Fig. 1). The growth chamber of the VF is not airtight and consists of an opaque façade with a single covered window and an access door. The VF produces basil, butterhead lettuce, and multi-leaf lettuce crops in a hydroponic system. Within the hydroponic system, each crop is grown in an individual plastic pot filled with nutrients and water. The containers are placed in moveable, multiple-layer trollies equipped with built-in LED lights. One split air conditioning unit and a dehumidifier maintain the climate conditions in the VF. The growing chamber is not enriched with CO_2 because it is not a sealed compartment. Any enriched CO_2 added to the growth chamber would simply leak into the processing room and the rest of the building. The VF produces 2068 kg of basil and 4550 kg of lettuce annually with a total cultivation area of 122 m^2 and a total footprint of 90 m^2, inclusive of the processing room. Lettuce is produced within 10 7-layer trollies and basil within 10 6-layer trolleys. The VF achieves 14.6 growth cycles a year by re-arranging growth densities throughout each growth cycle and by harvesting the crops at a relatively low FW of 110 g. The lettuce production per floor area is 101 kg m^{-2} y^{-1} as 50% of the floor area is assigned to lettuce and 54% of the cultivation area.

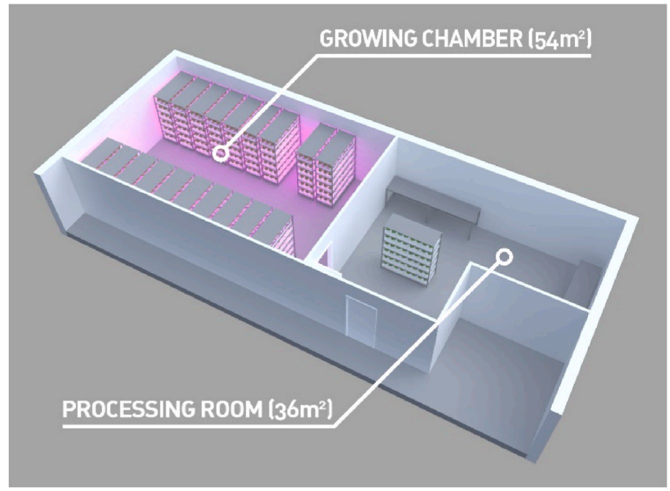

Fig. 1. Three-dimensional model of the operational VF case study.

Fig. 2 presents the yields of the four case studies per m^2 gross floor area per year; including the floor areas used for processes other than cultivation, e.g. seeding and storage, within all case studies. The VF has a significantly higher yield per m^2, despite the minimal FW per crop, due to its vertical arrangement, the optimised indoor growth conditions, and year-round production.

2.2. Methodology

2.2.1. Functional unit

The functional unit (FU) used in this carbon footprint assessment is 1 kg FW butterhead lettuce. The emission of GHGs is represented as kg of carbon dioxide equivalent ($CO_{2\text{-eq}}$) per kg FW butterhead lettuce (kg$CO_{2\text{-eq}}$ kg^{-1}).

2.2.2. Category indicator

The unit $CO_{2\text{-eq}}$ is the category indicator of the impact category for Global Warming Potential (GWP100) of an LCA, i.e. the carbon footprint. The $CO_{2\text{-eq}}$ includes the GHG emissions released into the atmosphere by human activities: mainly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Pulselli et al., 2019).

2.2.3. System boundaries

This study includes the upstream, core, downstream, and end-of-life emissions of both the farm life cycle and crop life cycle, from cradle to

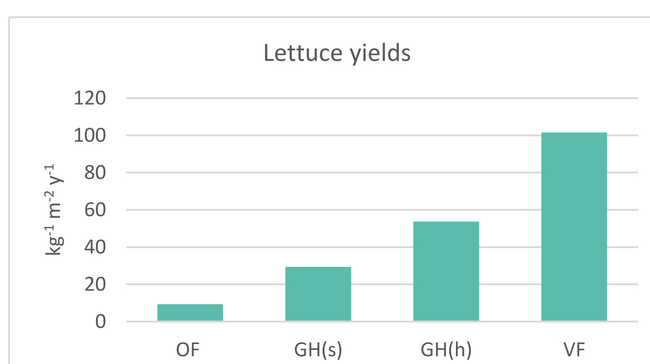

Fig. 2. Annual lettuce yields per m^2 gross floor area.

grave. Fig. 3 represents the different activities assessed in this study, which includes the lifecycle of the farm on the left and the life cycle of the crop on the right, with the addition of inputs to and outputs from each life cycle stage, on the far left and far right respectively.

The upstream emissions of the farm life cycle include the extraction, processing, manufacturing and transportation of the materials of built structures, and the replacement of these materials after their useful lifespan. The end-of-life emissions of the materials of the farm include the transportation of the materials to a treatment site but not the process of material recycling, as this is considered part of the upstream emissions of a new production chain. Due to the lack of robust and scientific data in some key areas, a few emissions are not included in this study. These include the emissions associated with the materials used in machinery, climate installations and auxiliary equipment, the energy used to construct and disassemble the farm, and land-use change, i.e. the emissions from energy used to transform land from one type of usage into another, in this case agricultural land. Later in the study, the lost potential for carbon sequestration is included to account for some of the impacts subsequent to converting land for agricultural purposes. This considers the CO_2 that could be sequestered if the land occupied by agriculture, was a forest instead.

The upstream emissions of the crop life cycle include the extraction, processing, and manufacturing of fertilisers, pesticides, herbicides, growing media, packaging materials and pressurised CO_2 for carbon enrichment, the energy and resources used to produce seeds and seedlings, and the emissions related to the transportation of these inputs to the growth facility. The core emissions are emissions released to extract, process, and produce the energy and resources needed to sow and plant seeds, irrigate crops, and maintain growing conditions, such as temperature and humidity, where necessary. The core emissions also

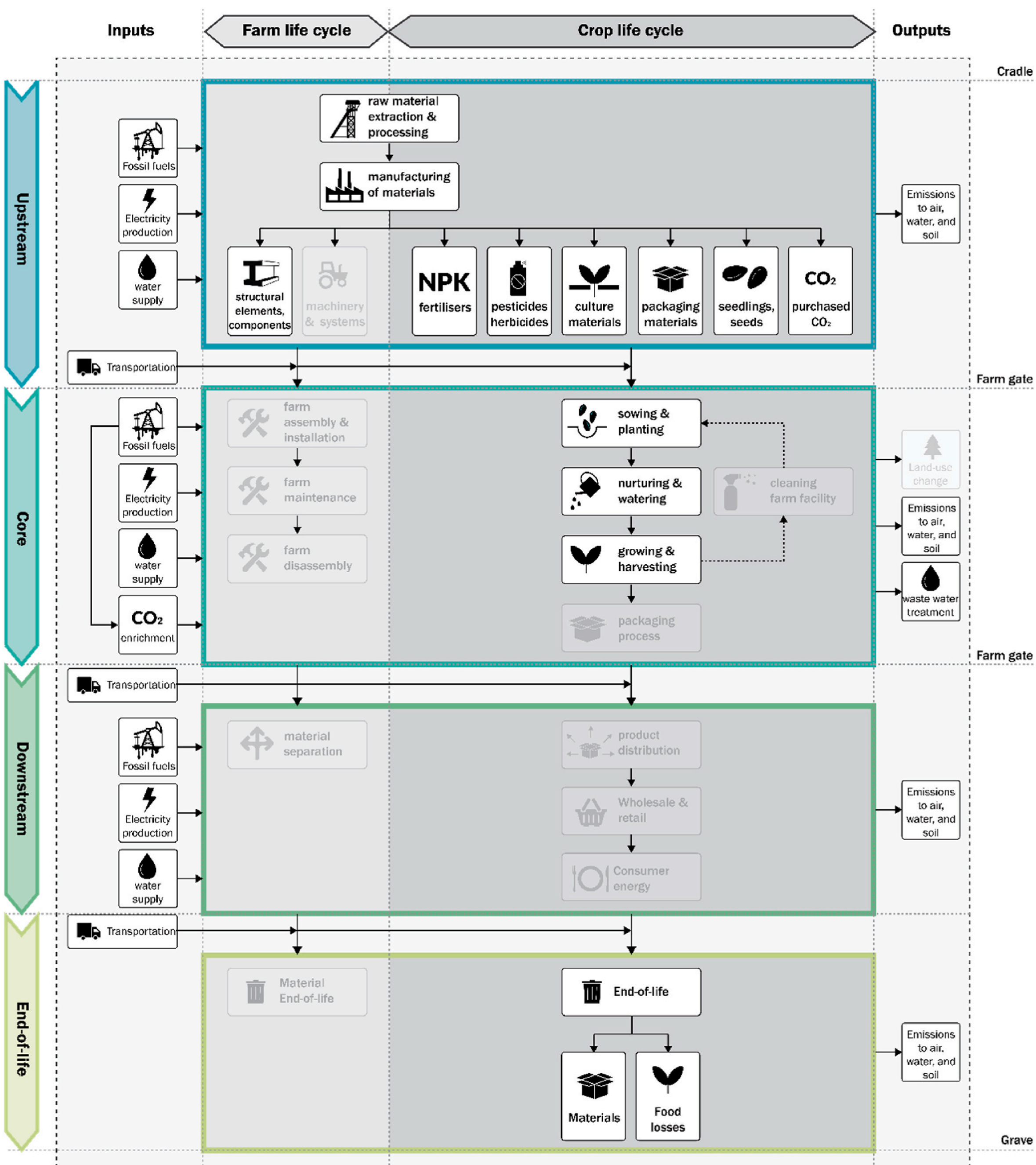

Fig. 3. The system boundaries and the included activities of the life cycle of the crop and the farm. Activities excluded by this study are faded in grey.

include the lubricants used for agricultural machinery. The downstream emissions consist of the emissions from the transportation of the crops to the wholesale or retail location. The emissions released during incineration of growth and packaging materials, composting of food lost during cultivation, distribution and consumption, and transportation of waste to a treatment facility are part of the end-of-life emissions. Due to the lack of scientific data, the crop life cycle does not include the energy used to package the crops, clean the farming facility and refrigerate the crop by the consumer, and the energy and resources needed in the food supply chain after the food reaches the retail or wholesale location, such as on-site refrigeration.

2.2.4. Activity data and emissions factors

The carbon footprint of each case study is calculated by accounting for all the GHG emissions from activities within the system boundaries (Fig. 3). These GHG emissions were calculated as follows:

$$CO_{2\text{-eq}} = \text{activity data x EF} \quad \text{(Eq. 1)}$$

where $CO_{2\text{-eq}}$ is the carbon footprint of the activity in kg $CO_{2\text{-eq}}$, and EF is the emission factor of the activity in kg $CO_{2\text{-eq}}$ per unit of the activity data. These EFs are assessed by the IPCC GWP100a characterisation method in SimaPro 9.0.0, which is based on the Ecoinvent 3.6 database. Appendix B provides an overview of the references of the EF used within the study. Country-specific EFs for the Netherlands were used for natural gas and electricity consumption to reflect the correct energy mix.

2.3. Inventory of activity data

The collected activity data, their references, and the assumptions made for each case study are discussed in Sections 2.3.1-2.3.4 and Appendix C. The following assumptions were applied to all case studies, except for instances where specific data were available. The transportation of the crop inputs to greenhouse facilities varies between 55 and 200 km (Montero et al., 2011a, 2011b); a distance of 100 km was assumed for all case studies (1). As no data were available on the distance travelled between the farm and retail location of lettuce crops produced and consumed in the Netherlands, green beans with an average transportation distance of 160 km (Pegge et al., 2006) were taken as a reference (2). For both the transportation of the crops and the crop inputs, diesel lorry transportation between 3.5 and 7.5 t was selected (3). Food losses in Dutch supermarkets are approximately 1.7% of the food they stock, of which potatoes, vegetables, and fruits form 34.5% (WUR, 2020) (4). Once sold, 9.5% of the food is, on average, lost by Dutch households (Dooren, 2019) (5). A distance of 50 km was assumed for the transportation of all end-of-life materials to a treatment facility (6). A dry weight (DW) of 5% was applied to all butterhead lettuce crops produced (Monsees et al., 2019) (7).

2.3.1. Open-field farming

The activity data of the upstream and core processes of the crop life cycle were obtained from the KWIN database for open-field farming (Table C.1). The KWIN database provides an insight into the average crop-specific inputs per ha of open-field butterhead lettuce production in the Netherlands (Schreuder et al., 2009). The application of nitrogen (N) fertilisers to soil-based crop production systems results in both direct and indirect emission of N_2O–N. Nitrogen fertiliser application directly results in denitrification of the soils of about 0.01 kg N_2O–N per kg synthetic N applied to the crop. Indirectly, it results in both N_2O emissions from volatilization (0.001 kg N_2O–N kg^{-1} N) and leaching (0.002 kg N_2O–N kg^{-1} N) (Klein et al., 2006; Table C.1). To define the materiality of the buildings of the OF, a theoretical model was created as no sources of information were found that categorically identify the nature, type, and number of agricultural buildings that were required by an open-field farm of a specific size. A farm of 15 ha is assumed that grows only butterhead lettuce crops, consisting of two steel-framed and steel-clad sheds for storing fertilisers, pesticides, herbicides, machinery, and harvested crops, with a total floor area of 1400 m^2 (Appendix D). The operational lifespan of these buildings is 50 y (Nemecek and Kägi, 2007).

2.3.2. Soil-based greenhouse horticulture

The activity data for the life cycle of the crop for GH(s) were obtained from the KWIN database for greenhouse production (Raaphorst and Benninga, 2019) (Table C.2). The average GH(s) represented by this database does not use artificial light. It does use natural gas for heating (5.6 $m^3\ m^{-2}\ y^{-1}$) as well as soil steaming to remove pests and pathogens between growth cycles (5 $m^3\ m^{-2}\ y^{-1}$) (Raaphorst and Benninga, 2019). The exhaust gases produced when burning natural gas on-site are used for carbon enrichment of greenhouses (Li et al., 2018), resulting in 1.78 $kgCO_2$ per m^3 natural gas combusted (Smit, 2010). The average demands for CO_2 enrichment of vegetable production in Dutch greenhouses without artificial light is 10 $kgCO_2\ m^{-2}\ y^{-1}$ (Velden and Smit, 2019). In GH(s) on-site natural gas combustion produces 100% of these demands. Italian values were used from Ecoinvent 3.6 for fertiliser, pesticide, and herbicide use as no data were available for Dutch GH(s) lettuce farms. The fifth deliverable of the EUPHOROS project (Montero et al., 2011a, 2011b) provided the data on the structure of a typical greenhouse as it describes the materiality of a 4 ha, Dutch, Venlo greenhouse structure to a great degree of detail, including the quantities of each material used. Although most greenhouse growers use their facility longer, their useful lifespan was set to 15 y for all structural elements, in accordance with the European code CEN 2001 (Montero et al., 2011a). The activity data per FU were achieved by assuming year-round production in a greenhouse that grows only butterhead lettuce.

2.3.3. Hydroponic greenhouse horticulture

The KWIN database for greenhouse horticulture provided the data related to the life cycle of the crop (Table C.3). The use of fertilisers, pesticides and herbicides was expressed in average money spend for GH (s) and GH(h). Per kg produce, GH(h) growers use 43% of the fertiliser and 41% of the pesticide budget spend by GH(s) growers (Raaphorst and Benninga, 2019). To estimate the quantities used these ratios were applied to the consumption of these chemicals by GH(s) (Section 2.3.2). Within a hydroponic growth environment the water surface open to air is limited, minimising evaporation (Benke and Tomkins, 2017). The water usage was estimated by including the minimal evapotranspiration (ET) rate to avoid tip burn of 1.4 L per 5 g DW lettuce (Ciolkosz et al., 1998) and nutrient flushing of 1.1 times the minimal ET requirements (Barbosa et al., 2015). In total 18.7 $kgCO_2\ m^{-2}\ y^{-1}$ is supplied to GH(h) to enrich the growing atmosphere (Raaphorst and Benninga, 2019) of which 45% is produced with on-site natural gas combustion, using the calculation method cited in Section 2.3.2. The remaining 55% is purchased as liquefied CO_2, which is a widely used carbon enrichment source for greenhouses (Li et al., 2018). PVC CropKing's Classic channels of 3.7 m with 24 plant spaces (CropKing, 2022) and Rockwool substrates were selected for the NFT system. GH(h) uses the same 4 ha Venlo greenhouse as GH(s) but has a greater yield than the GH(s) per m^2, resulting in significantly lower quantities of materials used per kg FW.

2.3.4. Vertical farm

An operational commercial VF in the Netherlands, which produces multi-leaf lettuce, butterhead lettuce, and basil provided the activity data for the CBVF (Table C.4). The VF is currently not operational on its full capacity and the measured inputs and outputs, based on several thousands of crops grown and sold, were extrapolated to achieve data for full operation. The water, nutrients, and seed inputs were specified for basil and lettuce separately, together with growth and packaging materials. As stated by the manufacturer, both 6 and 7 layer trolleys use 600 W of LED and a photoperiod of 20 h, resulting in an electricity use of 9.7 kWh per kg lettuce. The remaining electricity demands were provided for the farm as whole and required assumptions to determine the allocation between lettuce and basil. The electricity demands for cooling and fan usage were allocated according to the electricity consumption of the LEDs (50% lettuce), as heat dissipated by artificial light leads to most of the cooling demands (Graamans et al., 2018). Propagation light was assigned according to the amount of seeds, for each lettuce seeds, 15 basil seeds were propagated. To allocate dehumidification of mainly leaf transpired vapour, FW was used (65% lettuce). These allocations resulted in a total electricity demand of 14.7 kWh kg^{-1}. The crops produced never travel more than 15 km to the point of sale, as the VF is located very close to retailers. The transportation also includes for the weight of water within the sales pot of 5.45 L kg^{-1} lettuce. The materiality of the farm only considers components and materials up to, but not including, the walls, ceilings and floors of the rooms utilised by the farm due to its integration within an existing room in an existing building.

3. Results

Fig. 4 presents the total carbon footprint of lettuce cultivation within the four farming typologies: OF, GH(s), GH(h), and VF. The carbon footprint of the VF is 8.177 $kgCO_{2\text{-eq}}$ kg^{-1}, 16.7 times greater than that of the OF (0.490 $kgCO_{2\text{-eq}}$ kg^{-1}), 6.8 times greater than GH(s) (1.211 $kgCO_{2\text{-eq}}$ kg^{-1}), and 5.6 times greater than GH(h) (1.451 $kgCO_{2\text{-eq}}$ kg^{-1}). The performance of VF is specific to the case study used and is not representative of every vertical farming operation. Other vertical farms, which employ different technologies and operational methods, may have differing results.

The carbon emissions of the different life cycle stages of the farm (Fig. 5A and B) and the crop (Fig. 5C–F) were compared between the case studies. GH(s) has the highest emissions relating to the farm itself, both for upstream and end-of-life emissions (Fig. 5A and B). Regarding the crop life cycle, the VF has the highest upstream (Fig. 5C), core (Fig. 5D), and end-of-life emissions (Fig. 5F), which results in the highest crop life cycle emissions overall. The core emissions accounted for 85% of the total footprint of the VF, 56% of GH(h), 65% of GH(s), and 30% of OF. These emissions mostly related to electricity and fuel use, which represent the largest share of the total carbon footprint in GH(s), GH(h) and VF. Carbon enrichment to enhance plant growth accounted for 38% of the upstream emissions of GH(h) and did not result in emissions for GH(s) (Fig. 5C), as they were already accounted for in the core emissions due to on-site natural gas combustion (Fig. 5D). Most upstream emissions relate to the energy and resources used to produce the seedlings used within OF, GH(s) and GH(h), respectively 65%, 62% and 46%. The VF propagates seedlings on-site and includes the energy and resources used in the upstream and core emissions of the crop life cycle. Transportation of the crop to the retail location resulted in relatively high downstream emissions for the conventional methods (Fig. 5E), representing between 5.9% and 17.3% of their total carbon footprints.

4. Discussion

The baseline scenario examined and compared empirical data between the four farming systems. Three alternative scenarios are proposed to improve the comparability of the data and include prospective improvements to the carbon footprints of all farming systems through the use of renewable energy. These scenarios include the lost potential of carbon sequestration by of land-use change (1), an alternative packaging scenario where all farms use polypropylene bags (2), and a scenario where all energy needs are met through renewable energy and bio-based fuels (3). The electricity use of the studied VF is later compared to that of existing literature to obtain a better understanding of its performance.

4.1. Farm life cycle

The farm life cycle of the GH(s) structure, with a lifespan of 15 y, emits 2.7 times more $CO_{2\text{-eq}}$ than the VF, and 23 times more than the OF (Fig. 5A). GH(h) uses NFT channels to produce lettuce within the exact same greenhouse as GH(s). The annual yields of GH(h) are 1.8 times greater than GH(s), resulting in 25% less upstream emissions. The OF, with a total building footprint of 1400 m^2, uses significantly larger quantities of materials than the VF. The lower emissions are explained by the total OF area of 15 ha gross (CBS, 2021) and the 50 y lifespan of the agricultural buildings (Nemecek and Kägi, 2007), compared to the 8–10 y lifespan of the VF components. If the studied VF was not integrated within an existing building it would require additional materials to construct the enclosure around the farm, leading to greater emissions. It should be emphasised that the materiality of the OF was based on assumptions made in a theoretical model (Appendix D) and the materials used in auxiliary equipment, climate installations, and machinery were not included both due a lack of robust data (Section 2.2.2).

4.1.1. The indirect impacts of land-use change

The indirect impacts of land-use change are explored by considering the potential capacity of agricultural land to sequester CO_2 if it was a forest instead. Fig. 6 presents the potential for carbon uptake if the land used for agriculture was a young European forest, which is equivalent to

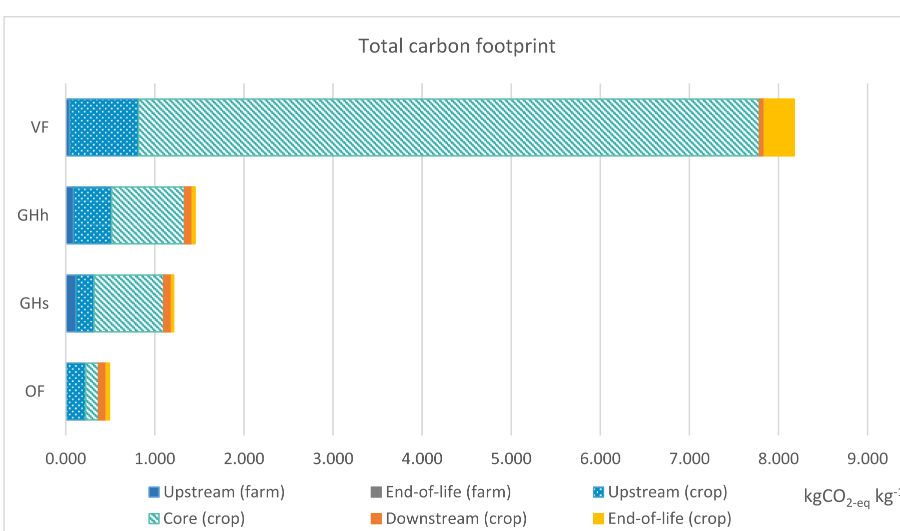

Fig. 4. The total carbon footprint of lettuce production within OF, GH(s), GH(h) and VF (please note that the farm end-of life value is not visible at this scale but is still included).

Fig. 5. Comparison of the carbon footprint per life cycle stage of the four case studies: the life cycle of the farm including upstream emissions (A) and end-of-life emissions (B), and the life cycle of the crop including upstream emissions (C), core emissions (D), downstream emissions (E) and end-of-life emissions (F).

0.78 $kgCO_2\ m^{-2}$ (COM, 2021). The potential for carbon sequestration that is lost by using land for the farming practice is significantly smaller for the VF due to its increased productivity and vertical arrangement. The equivalent loss of carbon uptake presented in Fig. 6 is not representative for VF as vertical farming is unlikely to occupy space that would otherwise be forest due to their location within urban environments. The lost potential for carbon sequestration by the studied VF, specifically, is considered to be zero as it is a form of zero-acreage farming; characterised by the non-use of land (Thomaier et al., 2014) by using existing space within or upon buildings, as opposed to farming systems that take up space at ground level (Specht et al., 2015). For every ton of FW lettuce grown in the VF, the land freed up elsewhere would allow 15 to 88 $kgCO_2$ to be sequestered, if that land was to become a young forest.

4.2. *Crop life cycle*

4.2.1. *Upstream*

The literature reviewed in Section 1.1. suggested that vertical farms, compared to greenhouse horticulture and open-field farms, reduce the use of water, fertilisers, pesticides, and herbicides. The VF studied consumes no pesticides and herbicides but consumes the highest concentration of nutrients. These nutrients are applied as tablets to the growth pots, which limits dosing options. At the end of the growth cycle, 20% of these nutrients are discarded, which could easily be addressed and reduced. It is also a possibility that a recirculating system, as opposed to a closed system, would lead to additional nutrient efficiencies (Son et al., 2020). The nutrient consumption of the VF does not solely explain the high upstream emissions; another aspect is the use of growth and packaging materials, which represent 42% and 48% of these

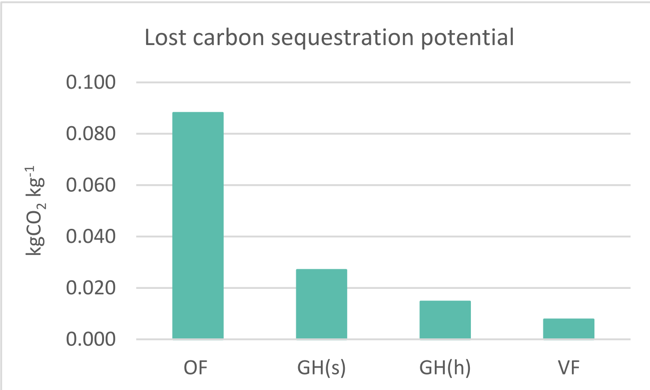

Fig. 6. Carbon sequestration if the gross floor area used to produce one kg of lettuce was a young forest.

emissions respectively (Fig. 5C). The VF studied uses a growth pot (clear plastic), and sales pot (bamboo paper with PE coating) to allow the plant to survive once purchased. This is seen as a unique selling point by the farmers. An alternative scenario was created where all lettuce crops from all case studies are wrapped in polypropylene bags, as is already the case for conventionally grown lettuce. This scenario decreases the upstream emissions of the VF by 46% (Fig. 7). It was not possible to create uniformity of the growth materials across the different case studies as these are an essential characteristic of each farming practice, i.e. the use of soil by OF and GH(s), Rockwool by GH(h) and VF, and growth pots in VF.

4.2.2. Core

In the baseline scenario, electricity use from the national grid represented 85% of the total footprint of the VF. LED light of 91 W m^{-2} and a photoperiod of 20 h uses 65% of this electricity. To put the electricity use of the VF into perspective, the usage is compared to that of other CBVFs in Section 4.5. Evaporation of water is minimised in the hydroponic systems of GH(h) and VF by the limited surface open to air. The VF uses 9.1 L kg^{-1} water in the cultivation phase, when excluding the water discarded at the end of each growth cycle, compared to 1.5 L kg^{-1} by GH (h). This indicates a high transpiration rate in the VF. Majid et al. (2021) confirmed this finding by stating that the transpiration rate of deep-water culture - in some ways comparable to the growth pots of the VF - is significantly higher than that of a NFT system. Changing to a hydroponic NFT system could potentially reduce the water use of the studied VF. These savings will not be reflected in the carbon footprint as the current contribution of water in both GH(h) and VF is below 1%.

4.2.3. Downstream

The lettuce grown within the VF travels no further than 15 km to its selling location, compared to the 160 km for the conventional supply chains (Section 2.3). The reduction in carbon footprint is limited to 37% as the baseline scenario considers the transportation of the crop in addition to the sales pot and the water within it (5.45 L kg^{-1}). The alternative packaging scenario reduces these emissions to 0.008 $kgCO_{2\text{-}eq}$ kg^{-1}, 90% lower than that of the conventional supply chain (Fig. 8). The overall reduction of the VF footprint is limited to 1%.

4.2.4. End-of-life

Vertical farms have the potential to reduce food losses during cultivation, transportation, and consumption due to optimised growth conditions, reduced food miles (Grewal and Grewal, 2012), and improved shelf life (Benke and Tomkins, 2017). Given the lack of data on food losses in the supply chain and consumption phase, it was not possible to confirm the reduced food losses with the studied VF. The cumulative food losses represent a small fraction of the total end-of-life emission of the VF, as the packaging and growth materials are responsible for 86% of these emissions (Fig. 5F). The alternative scenario in which all farms use polypropylene packaging decreases the end-of-life emissions of the VF by 56% (Fig. 9).

4.3. Renewable energy scenario

The transition to renewable energy would significantly reduce the contribution of energy use to the carbon footprint of the farming practices. In this scenario, the electrification of heating with a ground source heat pump, steam production with an electric boiler, bio-diesel use for agricultural machinery, and electricity production with PV panels were considered (Appendix E). This transition reduces the core emissions of the OF, GH(s), GH(h) and VF by 23%, 75%, 85% and 83% respectively (Fig. 10). The remaining core emissions of the GH(s), GH(h) and VF are mostly explained by the EF used for electricity production with grid-connected PV panels in the Netherlands (Ecoinvent 3.6). This EF includes the emissions from the extraction of the required materials for the panel, the electric components and mounting systems, the transportation of these materials to the production site, the panel production, waste treatment, and the panel installation. To translate these emissions into $kgCO_{2\text{-}eq}$ kWh^{-1}, country-specific yields based on local irradiation levels and current PV efficiencies are included (Jungbluth et al., 2007). Electricity production with PV panels results in carbon emissions of 0.167 $kgCO_{2\text{-}eq}$ kg^{-1} for GH(s), 0.125 $kgCO_{2\text{-}eq}$ kg^{-1} for GH(h) and 1.173 $kgCO_{2\text{-}eq}$ kg^{-1} for VF. To produce all electricity required by 1 m^2 cultivation area in the VF, 5.1 m^2 of south facing, 40° inclined, PV cell area is needed, corresponding to about 6.8 m^2 of land (Appendix E). A significant area when compared to the 0.69 m^2 floor area used per m^2 lettuce production. If the VF farm was a standalone structure with PV panels covering the entire south, east and west facades, and the roof, each m^2 cultivation area would still require 3.8 m^2 PV cell area at ground level. The land-use of these PV panels would most likely result in a lost

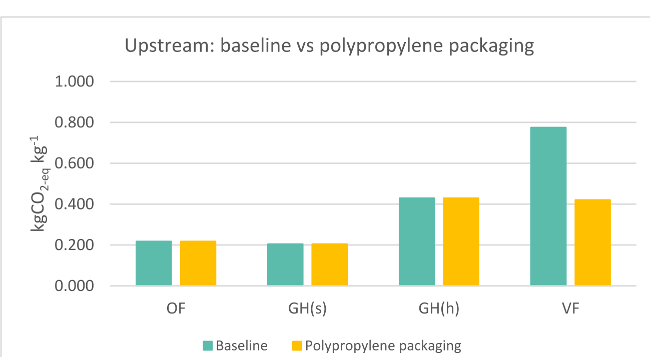

Fig. 7. Upstream emissions in the baseline scenario versus those when all farming methods use polypropylene packaging.

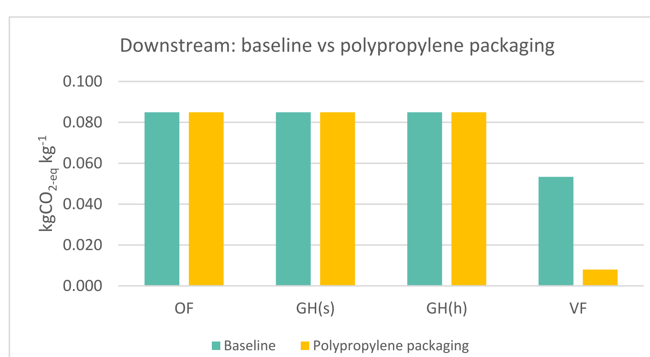

Fig. 8. Downstream emissions in the baseline scenario versus those when all farming methods use polypropylene packaging.

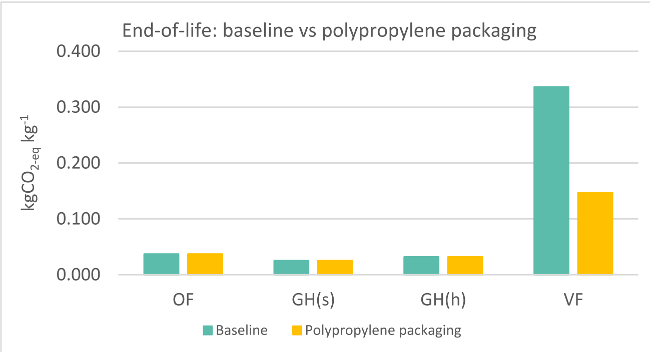

Fig. 9. End-of-life emissions of the baseline scenario versus those when all farming methods use polypropylene packaging.

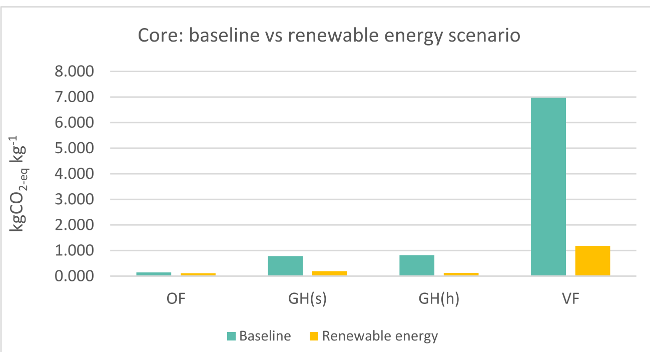

Fig. 10. Total core emissions in the baseline scenario versus those in the renewable energy scenario.

potential for carbon sequestration but this falls beyond the intended scope of this research.

External sources of CO_2 have to be sought as no CO_2 will be produced on-site when using all-electric heating. These sources would need to be of biogenic origin, such as biogas, biomass or carbon capture and storage (Li et al., 2018). In this research, biogas was selected as the primary source of greenhouse carbon enrichment. Biogas consists of 55% methane (CH_4) and 43% CO_2. The remaining 2% includes impurities that are not useful. When upgrading biogas to the quality of natural gas, CH_4 is separated from CO_2. After separation, the CO_2 mixture is purified to remove impurities before using it as carbon enrichment of crops (Dijk et al., 2014). To represent emissions from CO_2 production, 44% of the EF for biogas was allocated to carbon enrichment. This reflects the proportion of gaseous content that is CO_2 as well as a proportional share of the impurities that need to be removed. The renewable energy scenario increases the emissions from carbon enrichment of the GH(s) from zero to 0.139 $kgCO_{2\text{-eq}}\ kg^{-1}$ and reduces those of GH(h) from 0.429 to 0.407 $kgCO_{2\text{-eq}}\ kg^{-1}$. It should be noted that the energy transition will reduce the availability of CO_2 drastically due to the limited availability of biogas and biomass worldwide (Beuchelt and Nassl, 2019).

4.4. Total footprint with alternative scenarios

Fig. 11 presents the carbon footprint when considering the use of identical packaging, the transition to renewable energy, and the loss of potential carbon sequestration altogether. The use of PV panels reduced the core emissions of the VF with 83%; still electricity use represents 66% of the alternative carbon footprint. In total, the carbon footprints of GH(s), GH(h) and VF are reduced by 35%, 48%, and 78% respectively when compared to the baseline scenarios (Fig. 12). Due to its high land-use, the carbon footprint of the OF increases with 11% when including the lost carbon sequestration potential. When combining the three alternative scenarios the vast differences in carbon footprints of the conventional farming methods and the VF seen in the baseline scenario are reduced from a factor of 16.7 to a factor of 3.3 difference between OF and VF.

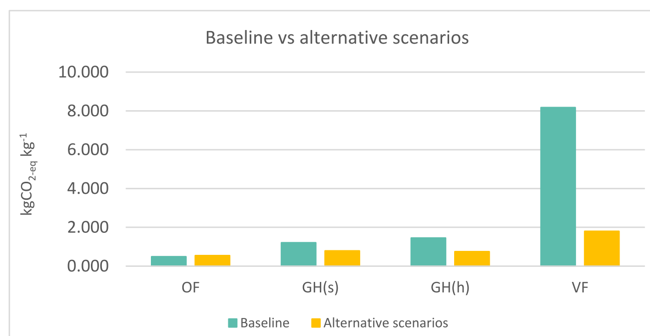

Fig. 12. The total carbon footprint of lettuce production in the baseline scenario versus the alternative carbon footprint when considering the use of identical packaging, the transition to renewable energy, and the loss of potential of carbon sequestration.

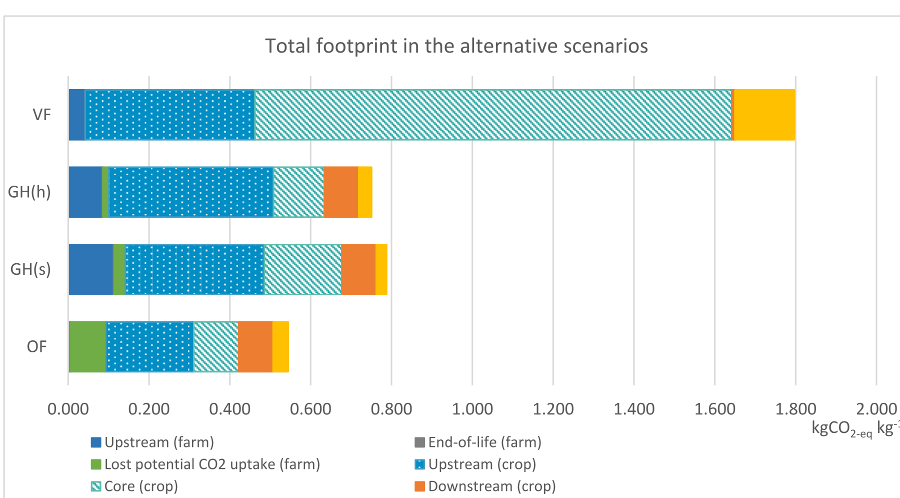

Fig. 11. The total carbon footprint of lettuce production when considering the use of identical packaging, the transition to renewable energy, and the lost potential of carbon sequestration (please note that the farm end-of life value is not visible at this scale but is still included).

4.5. Comparison to other literature

The electricity use was the largest contributor to the carbon footprint of the VF in both the baseline and alternative scenario. Table A.1, #1–8 represents the diverging electricity use per kg FW of CBVFs from literature and includes details on yields and light characteristics. The VF studied is added to this comparison in Fig. 13 (and Table A.1, #9) and uses relatively little electricity with a lower proportion allocated to artificial light.

The amount of FW produced per kWh electricity depends on many factors, such as the photosynthetic photon flux density (PPFD) and the photoperiod. The relation between PPFD (μmol m^{-2} s^{-1}) and power of the light (W m^{-2}) is the molar efficacy, which currently ranges between 2.1 and 3.5 μmol J^{-1} for LED (Weidner et al., 2021). The CBVF simulated by Benis et al. (2017) uses the least amount of kWh kg^{-1} FW, however, the data are too optimistic as the molar efficacy is 9.1 μmol J^{-1} (47 W m^{-2}; 427 μmol m^{-2} s^{-1}). The studied CBVF uses 91 W m^{-2} LED with a PPFD of 140 μmol m^{-2} s^{-1}, resulting in a very low molar efficacy of 1.54 μmol J^{-1}. The best performance in terms of quality and yield for lettuce production requires approximately 240 μmol m^{-2} s^{-1} and a 16 h photoperiod (Matysiak et al., 2022); a daily light integral (DLI) of 13.8 mol m^{-2} d^{-1} compared to 10.1 mol m^{-2} d^{-1} in the VF studied. To obtain more insight into the performance of the studied VF the yearly amount of photosynthetic active photons reaching the crops to produce a kg FW were presented in Fig. 14, i.e. moles of light per kg FW.

Matsyiak et al. (2022) noted significantly more cases of tipburn above the optimal DLI of 13.8 mol m^{-2} d^{-1}. Similar findings were noted by Sago (2016) stating that an increase of PPFD from 150 to 300 μmol m^{-2} s^{-1} resulted in significantly more cases of tipburn. Both studies of Graamans et al. (2018) and Li et al. (2020) used a PPFD far above this level. PPFDs between 200 and 300 μmol m^{-2} s^{-1} were applied by Zhang et al. (2018), Avgoustaki and Xydis (2021; 2021) and Weidner et al. (2021). Fig. 14 did not include the studies of Zhang et al. (2018) and Li et al. (2020) as no data on their yields were provided. Kikuchi et al. (2018) did not present data on yield, photoperiod, DLI and PPFD, making it hard to compare the measured data of this CBVF with that of the studied VF. Aside from lettuce production the mol kg^{-1} of basil production in the studied VF was included in Fig. 14. The mol kg^{-1} of basil was significantly higher than that of lettuce, as the FW of the basil produced was significantly lower while using similar lighting properties. Comparing basil production in Avgoustaki and Xydis (2020; 2021) and lettuce in Weidner et al. (2021) gives similar findings, as the DLI of basil is higher. The studied VF consumes relatively little electricity for artificial light to produce a kg of lettuce, whilst the molar efficacy and the PPFD are low. This suggests that the lettuce crops in the studied VF very efficiently convert moles of light into FW. To put this in perspective relative to findings from other studies, the mol kg^{-1} FW of lettuce produced in the simulated VF of Weidner et al. (2021) was applied to the studied VF. A DLI of 15.06 mol m^{-2} d^{-1}, a photoperiod of 20 h and a molar efficacy of 2.1 μmol J^{-1} results in 99.6 W m^{-2} LED with an electricity usage of 10.6 kWh kg^{-1}. Using this value increases the baseline carbon footprint by 4% and the alternative footprint with 3%.

5. Conclusion

This paper performed a quantitative carbon footprint assessment of lettuce cultivation within a typical open-field farm, soil-based greenhouse, hydroponic greenhouse, and an operational VF in the Netherlands to evaluate the current carbon footprint of vertical farming systems. The assessment included the emissions related to both the life cycle of the farm and the crop, from cradle-to-grave. The baseline empirical data showed that the carbon footprint of the VF (8.177 $kgCO_{2\text{-}eq}$ kg^{-1}) was 16.7 times greater than OF (0.490 $kgCO_{2\text{-}eq}$ kg^{-1}), 6.8 times greater than GH(s) (1.211 $kgCO_{2\text{-}eq}$ kg^{-1}) and 5.6 times greater than GH (h) (1.451 $kgCO_{2\text{-}eq}$ kg^{-1}) per kg FW. Three alternative scenarios were considered to improve the comparability of the baseline data as well as present potential carbon savings in all case studies by using renewable energy. These scenarios included: the lost carbon sequestration potential as a result of land-use change (1), identical packaging for all farming systems (2), and the transition to renewable energy (3). When these scenarios were considered collectively, the carbon footprint of the VF (1.797 $kgCO_{2\text{-}eq}$ kg^{-1}) reduced to only 3.3 times greater than OF (0.544 $kgCO_{2\text{-}eq}$ kg^{-1}), 2.3 times greater than GH(s) (0.788 $kgCO_{2\text{-}eq}$ kg^{-1}) and 2.4 times greater than GH(h) (0.751 $kgCO_{2\text{-}eq}$ kg^{-1}). Even with the use of PV panels, the largest contributor to the VF carbon footprint was electricity, representing 66% of the overall alternative carbon footprint. Artificial light accounted for 65% of this electricity. To put this electricity use into perspective, the kWh kg^{-1} and LED characteristics of the VF were compared to that of other CBVFs from literature. This literature review showed that most of the existing vertical farming data are based on simulated farms and often not all data on the light characteristics and yields are presented, which makes it difficult to make a fair comparison. This lack of data applied in particular to the studies that presented the carbon footprint of vertical farming. The studied VF used a low amount of electricity for artificial light and still had high yields. Using mol kg^{-1} FW values from literature to improve its representation of an average vertical farm resulted in a slight increase in the baseline and alternative carbon footprint by 4% and 3% respectively. This illustrates that vertical farms, as they exist today, are not able to provide a sustainable solution to the global issues of decreasing availability of arable land and increasing food demands, even though they offer great benefits when compared to conventional farming methods. To become a sustainable solution, vertical farms need to decrease their energy use drastically to significantly reduce their carbon footprint and compete with conventional farming techniques from an environmental perspective. The upstream and end-of-life emissions of the growth materials represented the second largest carbon emissions in the alternative scenario. Suggesting that, simultaneously reducing the use of these growth materials and the

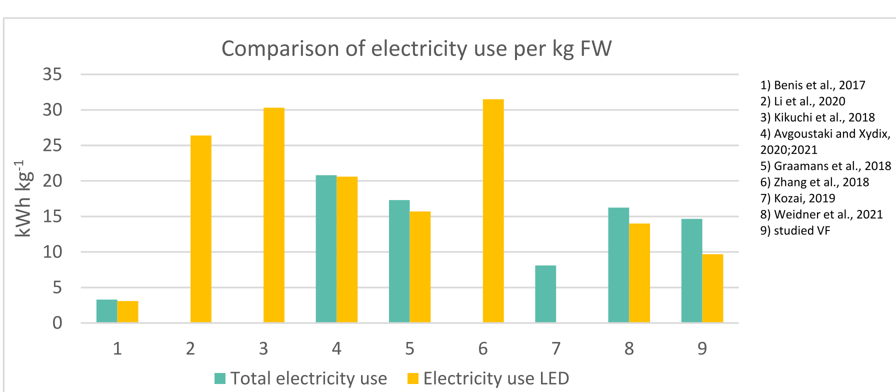

Fig. 13. Comparison of electricity use per kg FW produced by the studied VF and other CBVFs from literature.

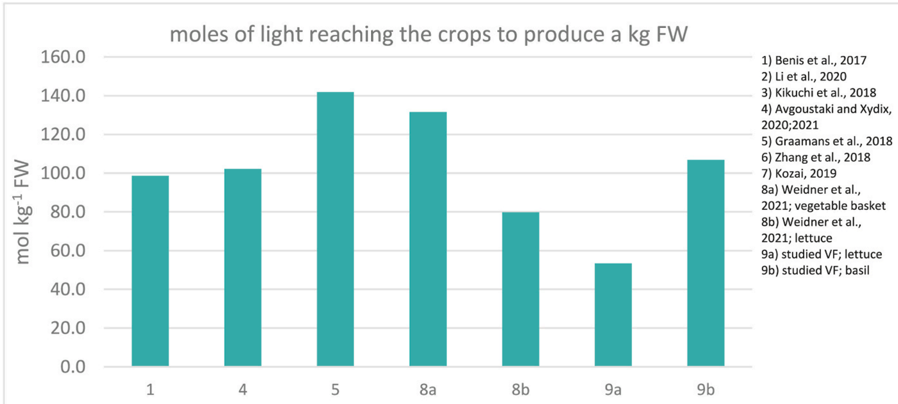

Fig. 14. Moles of light reaching the crops to produce a kg of FW in mol y^{-1}.

electricity demands will greatly improve the carbon footprint of the practice. Further research is required to determine how these reductions might be achieved and whether it is a possibility that vertical farming might one day compete with greenhouse horticulture from a carbon footprint perspective. If this can be achieved, vertical farming could form part of a sustainable, low carbon, and secure future food system as a result of its efficient use of land, high yields, minimal use of water and nutrients, the redundancy of pesticides and herbicides, and the ability to be located within or adjacent to cities where demands for food are highest.

CRediT authorship contribution statement

T. Blom: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, preparation. **A. Jenkins:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – review & editing, Supervision. **R.M. Pulselli:** Methodology, Formal analysis, Writing – review & editing. **A.A.J.F. van den Dobbelsteen:** Conceptualization, Writing – review & editing, Supervision.

Declaration of competing interest

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

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Appendix A. Energy use and lighting characteristics of CBVFs in literature

Table A.1
Data on electricity use and artificial light characteristics of CBVF in literature and the studied VF (part I).

#	Location	Crop	Yields	LED	PFFD	DLI	photoperiod
			kg m^{-2} y^{-1}	W m^{-2}	μmol m^{-2} s^{-1}	mol m^{-2} d^{-1}	h d^{-1}
1	Lisbon, Portugal	Tomato	74	47	427	20.0	13
2	Singapore	Leafy vegetable	–	–	735	29.1	11
3	Kashiwa, Japan	Lettuce and herbs	–	364	–	–	–
4	Aarhus, Denmark	Basil	50	176	243	14.0	16
5	The Netherlands	Lettuce	74.1	199	500	28.8	16
6	Beijing, China	Lettuce	–	–	250	14.4	16
7	Japan	Lettuce	–	–	–	–	–
8a	Stockholm, Sweden	Vegetable basket	38	104	272	13.7	14–16
8b	Stockholm, Sweden	Lettuce	52.6		200	11.5	16
9a	Netherlands	Lettuce	68.9	91	140	10.1	20
9b	Netherlands	Basil	36.9	106	150	10.8	20

#	Total electricity use	Electricity use LED	Method		Reference
	kWh kg^{-1}	kWh kg^{-1}	simulated	measured	
1	3.3	3.1	X		Benis et al. (2017)
2	–	26.4	X		Li et al. (2020)
3	–	30.3		X	Kikuchi et al. (2018)
4	20.8	20.6	X		Avgoustaki and Xydis, 2020; 2021
5	17.3	15.7	X		Graamans et al. (2018)
6	–	31.5		X	Zhang et al. (2018)
7	7.1–9.1	–			Kozai (2019)
8a	15–17.5	14	X		Weidner et al. (2021)
8b	–	–	X		Weidner et al. (2021)
9a	14.8	9.7		X	CBVF studied
9b	30.7	21		X	CBVF studied

Appendix B. List of emission factors used within this research

Table B.1
References used per EF

Activity	Unit	Reference	Notes & IPPC GWP100a EF reference
Seeds and seedlings			
Seeds	$kgCO_{2\text{-}eq}/kg$	Ecoinvent v3.6	Wheat seed taken as reference, for sowing {GLO}| market for | Alloc Rec, U
Seedlings	$kgCO_{2\text{-}eq}/n$	Ecoinvent v3.6	Strawberry seedlings taken as reference, for planting {GLO}| market for | Cut-off, U
Water and nurturing			
Water (irrigation)	$kgCO_{2\text{-}eq}/m^3$	Ecoinvent v3.6	Tap water {Europe without Switzerland}| market for | Alloc Rec, U
Nitrogen Fertilisers*	$kgCO_{2\text{-}eq}/kg$	Ecoinvent v3.6	Nitrogen fertiliser, as N {GLO}| market for | Alloc Rec, U
Phosphate Fertilisers	$kgCO_{2\text{-}eq}/kg$	Ecoinvent v3.6	Phosphate fertiliser, as P2O5 {GLO}| market for | Alloc Rec, U
Potassium Fertilisers	$kgCO_{2\text{-}eq}/kg$	Ecoinvent v3.6	Potassium fertiliser, as K2O {GLO}| market for | Alloc Rec, U
Lime – Calcium oxide	$kgCO_{2\text{-}eq}/kg$	Ecoinvent v3.6	Lime, packed {GLO}| market for | Alloc Rec, U
Sulfur trioxide (SO_3)	$kgCO_{2\text{-}eq}/kg$	Ecoinvent v3.6	Sulfur trioxide {RER}| production | Alloc Rec, U
Magnesium	$KgCO_{2\text{-}eq}/kg$	Ecoinvent v3.6	Magnesium oxide {GLO}| market for | Alloc Rec, U
Pesticide	$kgCO_{2\text{-}eq}/kg$	Ecoinvent v3.6	Pesticide unspecified, at regional storehouse/RER U
Herbicides	$kgCO_{2\text{-}eq}/kg$	Ecoinvent v3.6	Herbicides, at regional storehouse/RER U
Potting/garden soil	$kgCO_{2\text{-}eq}/kg$	Ecoinvent v3.6	Peat potting soils 20L = 7.5 kg (Pokon) Peat {GLO}| market for | Cut-off, U
CO_2 enrichment	$kgCO_{2\text{-}eq}/kg$	Ecoinvent v3.6	Pressurised liquid carbon dioxide, liquid {RER}| market for | Alloc Rec, U
N_2O from soils	$kgCO_{2\text{-}eq}/kg$	Forster et al., 2021	kg N_2O–N * (44/28) = kg N_2O (Klein et al., 2006) 1 kg N_2O emission refers to 273 $kgCO_{2\text{-}eq}$
Operating energy			
Electricity	$kgCO_{2\text{-}eq}/kWh_e$	CO2 emissiefactoren (2021)	Dutch electricity mix
Electricity production with PV	$kgCO_{2\text{-}eq}/kWh_e$	Ecoinvent v3.6	Electricity, production mix PV, at plant/NL U
Natural gas	$kgCO_{2\text{-}eq}/m^3$	CO2 emissiefactoren (2021)	Groningen gas
Diesel	$kgCO_{2\text{-}eq}/kg$	Ecoinvent v3.6	z_diesel con emissioni
Bio-diesel	$kgCO_{2\text{-}eq}/kg$	CO2 emissiefactoren (2021)	Vegetable oil methyl ester {GLO}| market for | Alloc Rec, U
Biogas	$kgCO_{2\text{-}eq}/m^3$	Ecoinvent v.3.6	Biogas {RoW}| market for biogas | Cut-off, U//density 1.15 kg/m^3
Lubricants	$kgCO_{2\text{-}eq}/kg$	Ecoinvent v3.6	Lubricating oil {GLO}| market for | Alloc Rec, U
Disposable materials			
Bamboo with PE coating	$kgCO_{2\text{-}eq}/kg$	(−)	Calculated by material composition, PE: 15% of total mass (Ligthart et al., 2018).
Polyethylene (PE)	$kgCO_{2\text{-}eq}/kg$	Ecoinvent v3.6	Polyethylene, low density, granulate {GLO}| market for | Alloc Rec, U
Bamboo paper	$kgCO_{2\text{-}eq}/kg$	Ecoinvent v3.6	Kraft paper taken as reference, unbleached {GLO}| market for | Alloc Rec, U
Bioplastic (PLA)	$kgCO_{2\text{-}eq}/kg$	Ecoinvent v3.6	Polyester-complexed starch biopolymer {GLO}| market for | Alloc Rec, U
Polypropylene (PP)	$kgCO_{2\text{-}eq}/kg$	Ecoinvent v3.6	Polypropilene, granulate {GLO}| market for | Alloc Rec, U
Rockwool	$kgCO_{2\text{-}eq}/kg$	Ecoinvent v3.6	Rock wool {GLO}| market for | Alloc Rec, U
Materiality: structure, equipment and machinery			
Steel	$kgCO_{2\text{-}eq}/kg$	Ecoinvent v3.6	Steel, unalloyed {GLO}| market for | Alloc Rec, U
Aluminium	$kgCO_{2\text{-}eq}/kg$	Ecoinvent v3.6	Aluminium, cast alloy {GLO}| market for | Alloc Rec, U
Reinforced concrete	$kgCO_{2\text{-}eq}/m^3$	Ecoinvent v3.6	Concrete, normal {GLO}| market for | Alloc Rec, U
Glass	$kgCO_{2\text{-}eq}/kg$	Ecoinvent v3.6	Flat glass, uncoated {GLO}| market for | Alloc Rec, U
PVC	$kgCO_{2\text{-}eq}/kg$	Ecoinvent v3.6	Polyvinylchloride, emulsion polymerised {GLO}| market for | Alloc Rec, U
Polyester	$kgCO_{2\text{-}eq}/kg$	Ecoinvent v3.6	
Polyethylene (PE)	$kgCO_{2\text{-}eq}/kg$	Ecoinvent v3.6	Polyethylene, low density, granulate {GLO}| market for | Alloc Rec, U
Polycarbonate (PC)	$kgCO_{2\text{-}eq}/kg$	Ecoinvent v3.6	Polycarbonate {GLO}| market for | Cut-off, U
Transportation			
Lorry	$kgCO_{2\text{-}eq}$/ton km	Ecoinvent v3.6	Transport, freight, lorry 3.5–7.5 metric ton, EURO5 {GLO}| market for | Alloc Rec, U
End-of-life			
waste-to-energy	$kgCO_{2\text{-}eq}/kg$	Pulselli et al. (2019)	incineration
organic waste-to-compost	$kgCO_{2\text{-}eq}/kg$	Pulselli et al. (2019)	
Carbon sequestration			
Forestry	$kgCO_2/m^2\ yr^{-1}$	COM (2021)	Young European forest

[*] The specific emission factors for the two different fertilisers used in the VF were calculated based on their nutrient composition. Within this research, only the macronutrients were included to calculate these specific emission factors. In this case, the macronutrients N, P, K, Ca, Mg, and S (Wada, 2019), which represent the largest share of the minerals.

Appendix C. Activity data

Table C.1
Activity data for butterhead lettuce production in an open-field farm per kg FW.

Activity	Activity data FU	Unit	Note
FARM LIFE CYCLE			
Upstream			
Steel	1.08E-03	kg	structure, corrugated steel roof and façade panels, lifespan 50 y (Appendix D)
Polycarbonate (PC)	7.22E-05	kg	Windows, lifespan 50 y (Appendix D)
Reinforced concrete	4.23E-05	m^3	Floor, lifespan 50 y (Appendix D)
Insulation Rockwool	1.13E-04	kg	Façade insulation, lifespan 50 y (Appendix D)
Transportation	1.00E-02	kg km	Section 2.3
End-of-life			
Transportation	5.00E+01	km kg	Section 2.3
CROP LIFE CYCLE			
Upstream			
Seedlings	3.36E+00	n	Schreuder et al. (2009)
Fertiliser			
Nitrogen (N)	3.90E-03	kg	Schreuder et al. (2009)

(continued on next page)

Table C.1 (*continued*)

Activity	Activity data FU	Unit	Note
Potassium (K_2O)	6.81E-03	kg	Schreuder et al. (2009)
Pesticides & herbicides			
Pesticides	4.32E-04	kg	Schreuder et al. (2009)
Herbicides	0	kg	Schreuder et al. (2009)
Packaging materials			
Polypropylene bags	1.14E-02	kg	4 g per crop (Afvalfonds Verpakkingen, 2017)
Transportation inputs	1.00E+02	km kg	Section 2.3
Core			
Watering	1.51E+01	L	5.3 m^3 per 1000 lettuce heads, excluding rainfall (Breukers et al., 2014)
N_2O from soils (direct and indirect)	3.90E0-05	kg	Calculated for synthetic fertiliser application according to Klein et al. (2006) (TIER 1). *
Fuel use	3.11E-02	kg	Diesel used for machinery (Schreuder et al., 2009)
Lubricants	1.93E-04	kg	Lettuce production OF Italy taken as reference (Ecoinvent 3.6)
Downstream			
Transportation	1.60E+02	km kg	Section 2.3
End-of-life			
Cultivation phase			
Cultivation losses	1.50E-01	kg	15% losses, 85% production yields (Schreuder et al., 2009)
Supply chain			
Food losses	5.87E-03	kg	Section 2.3
Consumer			
Food losses	9.50E-02	kg	Section 2.3
Packaging	1.14E-02	kg	Polypropylene bags
Transportation	5.00E+01	km kg	Section 2.3

* Both direct and indirect N_2O emissions from managed soils were calculated according to Klein et al. (2006), using tier 1 as no specific data was available. This case study only includes synthetic fertilisers. For direct N_2O emissions the following formulae were applied.

$$N_2O_{direct}\text{-}N = N_2O\text{-}N_{N\text{-}inputs} \tag{Eq. C.1}$$

in which $N_2O\text{-}N_{N\text{-}inputs}$ represents the annual direct N_2O–N emissions from N inputs to managed soils in kg N_2O–N y^{-1}.

$$N_2O\text{-}N_{N\text{-}inputs} = F_{sn} * EF_1 \tag{Eq. C.2}$$

in which F_{sn} is the annual amount of synthetic N fertiliser applied to soils in kg N y^{-1} and EF_1 the emission actor for N_2O from N inputs of 0.01 kg $N_2O\text{-}N_N$ (kg N input)$^{-1}$.

The indirect N_2O–N emissions from managed soils were calculated by summing the N_2O emissions from atmospheric deposition of N volatised ($N_2O_{(ATD)}$-N) and the N_2O emissions from leaching and runoff ($N_2O_{(L)}$-N), using formulae C.3. and C.4:

$$N_2O_{(ATD)}\text{-}N = (F_{sn} * Frac_{GASF}) * EF_4 \tag{Eq. C.3}$$

In which $Frac_{GASF}$ is the fraction of synthetic fertiliser N that volatilises as NH_3 and NO_x in kg N volatilised of 0.10 kg $NH_3 + NO_x$-N (kg N)$^{-1}$ and EF_4 the activity's emission factor of 0.010 kg $N_2O\text{-}N_N$ (kg $NH_3 + NO_x$-N volatilised)$^{-1}$.

$$N_2O_{(L)}\text{-}N = (F_{sn} * Frac_{leach\text{-}(H)}) * EF_5 \tag{Eq. C.4}$$

In which $Frac_{leach\text{-}(H)}$ is the fraction of N added to managed soils that is lost through leaching and runoff of 0.30 kg N (kg N)$^{-1}$ applied and EF_5 the activity's emission factor of 0.075 (kg $N_2O\text{-}N_N$ (kg N)$^{-1}$.

N_2O–N emissions were converted into N_2O-emissiosn using:

$$N_2O = N_2O\text{–}N * (44/28) \tag{Eq. C.5}$$

Table C.2
Activity data for butterhead lettuce production in a soil-based greenhouse horticulture per kg FW.

Activity	Activity data FU	Unit	Note
FARM LIFE CYCLE			
Upstream			
Steel	2.53E-02	kg	Roof bars, girders, stability braces, rails, posts, tie beams, foundations, reinforcements, high wire system, ventilation opening mechanism, 15 y lifespan (Montero et al., 2011a, 2011b)
Aluminium	6.48E-03	kg	Gutters, ridges, bars, ventilator opening mechanism, energy screens (Montero et al., 2011a, 2011b)
Reinforced concrete	1.05E-05	m^3	Foundations and path/15 y lifespan (Montero et al., 2011a, 2011b)
Glass	2.74E-02	kg	Covering and walls/15 y lifespan (Montero et al., 2011a, 2011b)
Polyester	3.35E-04	kg	Floor material and screens/15 y lifespan (Montero et al., 2011a, 2011b)
Transportation	1.00E+02	km kg	Section 2.3
End-of-life			
Transportation	5.00E+01	km kg	Section 2.3
CROP LIFE CYCLE			

(continued on next page)

Table C.2 (*continued*)

Activity	Activity data FU	Unit	Note
Upstream			
Seedlings	3.00E+00	n	(Raaphorst and Benninga, 2019)
Fertiliser			
Nitrogen (N)	3.14E-03	kg	Lettuce production in Italian GH taken as reference (Ecoinvent 3.6)
Phosphate (P_2O_5)	2.00E-03	kg	Lettuce production in Italian GH taken as reference (Ecoinvent 3.6)
Potassium (K_2O)	4.29E-03	kg	Lettuce production in Italian GH taken as reference (Ecoinvent 3.6)
Magnesium	1.44E-04	kg	Lettuce production in Italian GH taken as reference (Ecoinvent 3.6)
Pesticides & herbicides			
Pesticides	1.44E-04	kg	Lettuce production in Italian GH taken as reference (Ecoinvent 3.6)
Herbicides	–	kg	Lettuce production in Italian GH taken as reference (Ecoinvent 3.6)
Growth materials			
Potting soil	3.80E-01	L	Peat potting soil, 20 L = 7.52 kg (Pokon), (Raaphorst and Benninga, 2019)
Packaging materials			
Polypropylene bags	1.14E-02	kg	4 g per crop (Afvalfonds Verpakkingen, 2017)
Transportation inputs	1.00E+02	km kg	Section 2.3
Core			
Watering	1.90E+01	L	(Raaphorst and Benninga, 2019)
N_2O from soils (direct and indirect)	6.45E-05	kg	Calculated for synthetic fertiliser application according to Klein et al., 2006 (TIER 1), see footnote Table C.1.
Fuel use	3.67E-01	m^3	Natural gas for heating and steaming (Raaphorst and Benninga, 2019)
Electricity use	1.38E-01	kWh	(Raaphorst and Benninga, 2019)
Total carbon enrichment	3.46E-01	kg	10 kg m^{-2} (Velden and Smit, 2019)
Downstream			
Transport	1.60E+02	km kg	Section 2.3
End-of-life			
Cultivation phase			
Cultivation losses	5.00E-02	kg	5% cultivation losses (Raaphorst and Benninga, 2019)
Supply chain			
Food losses	6.00E-03	kg	Section 2.3
Consumer			
Food losses	9.50E-02	kg	Section 2.3
Packaging	1.14E-02	kg	Polypropylene bags
Transportation	5.00E+01	km kg	Section 2.3

Table C.3
Activity data for butterhead lettuce production in a hydroponic greenhouse per kg FW.

Activity	Activity data FU	Unit	Note
FARM LIFE CYCLE			
Upstream			
Steel	1.38E-02	kg	Section 2.3.2
Aluminium	3.52E-03	kg	Section 2.3.2
Reinforced concrete	5.70E-06	m^3	Section 2.3.2
Glass	1.49E-02	kg	Section 2.3.2
Polyester	1.82E-04	kg	Section 2.3.2
PVC	9.08E-03	kg	CropKing Classic NFT channel of 3.7m with 24 plant spaces per channel, 2 mm PVC thickness (CropKing, 2022), PVC density 1420 kg/m^3, lifespan 8 y
Transportation	1.00E+02	km kg	Section 2.3
End-of-life			
Transportation	5.00E+01	km kg	Section 2.3
CROP LIFE CYCLE			
Upstream			
Seedlings	4.72E+00	n	(Raaphorst and Benninga, 2019)
Fertiliser			43% of the fertilisers used in GHs (Raaphorst and Benninga, 2019)
Nitrogen (N)	1.33E-03	kg	
Phosphate (P_2O_5)	8.60E-04	kg	
Potassium (K_2O)	1.84E-03	kg	
Magnesium	6.19E-05	kg	
Pesticides & herbicides			41% of the pesticides used in GHs (Raaphorst and Benninga, 2019)
Pesticides	5.92E-05	kg	
Herbicides	–	kg	
Growth materials			
Substrate	1.14E-02	kg	(Raaphorst and Benninga, 2019); Rockwool 0.0675 kg/dm^3 (Bougoul et al., 2005)
Packaging materials			
Polypropylene bags	1.14E-02	kg	polystryne bag, same weight per kg FW as OF and GHs

(*continued on next page*)

Table C.3 (*continued*)

Activity	Activity data FU	Unit	Note
Transportation inputs	1.00E+02	km kg	Section 2.3
Core			
Watering	1.540E+00	L	1.4 L per 5 g DW lettuce (Ciolkosz et al., 1998) multiplied by 110% to include nutrient flushing (Barbosa et al., 2015)
Fuel use	8.84E-02	m^3	Natural gas for heating (Raaphorst and Benninga, 2019)
Electricity use	1.37E+00	kWh	(Raaphorst and Benninga, 2019)
Total carbon enrichment	3.52E-01	kg	(Raaphorst and Benninga, 2019)
Downstream			
Transport	1.60E+02	km kg	Section 2.3
End-of-life			
Cultivation phase			
Cultivation losses	4.00E-02	kg	4% cultivation losses (Raaphorst and Benninga, 2019)
Growth materials	1.14E-02	kg	Rockwool
Supply chain			
Food losses	6.00E-03	kg	Section 2.3
Consumer			
Food losses	9.50E-02	kg	Section 2.3
Packaging	9.09E-03	kg	Polystyrene bags
Transportation	5.00E+01	km kg	Section 2.3

Table C.4
Activity data for butterhead lettuce production in a CBVF per kg FW.

Activity	Activity data FU	Unit	Note
FARM LIFE CYCLE			
Upstream			
Steel	4.23E-03	kg	Leaf carriers and propagation, lifespan 8 y
Steel	3.60E-03	kg	Tables and cable trays, lifespan 10 y
Aluminium	6.70E-03	kg	Leaf carrier and propagation, lifespan 8 y
Transportation	1.00E+02	km kg	Section 2.3
End-of-life			
Transportation	5.00E+01	km kg	Section 2.3
CROP LIFE CYCLE			
Upstream			
Seeds	1.21E-05	kg	
Fertiliser			Supplied in tablet form (2 per pot)
Nutrients NPK	1.39E-02	kg	NPK fertiliser
Nutrients N Ca0	1.86E-02	kg	Nitrogen and calcium fertiliser
Pesticides & herbicides	–		Not applied
Growth & culture materials			
Polypropylene	1.15E-01	kg	Growth container and lid used for 5 growth cycles on average
Bioplastic	3.06E-02	kg	Plug holder, assumed PLA material: polyester-complexed starch biopolymer
Rockwool	6,69E-03	kg	
Packaging materials			
Bamboo with PE coating	2.88E-01	kg	15% polyethylene film, 75% bamboo of total weight (Ligthart et al., 2018)
Transportation inputs	1.00E+02	km kg	Section 2.3
Core			
Watering	1.68E+01	L	per crop: 700 mL + 550 mL (refill) growth pot, of which 248 mL left and discharged before moving to selling pot filled with 600 mL water.
Electricity use	1.47E+01	kWh	66% LED lighting with 20 h photoperiod, 22% cooling and fans, 12% dehumidification, 0% propagation light
Carbon enrichment			Not applied
Downstream			
Transport	1.50E+01	km kg	Sold at local supermarket, including water the product weighs 6.45 kg per kg lettuce
End-of-life			
Cultivation phase			
cultivation losses	2.00E-02	kg	2% cultivation losses
Growth materials	1.15E-01	kg	Polypropylene growth containers and lid; plugs and Rockwool moved to selling pot after growth phase
Discharged nutrients	6.49E-03	kg	20% of nutrients applied
Supply chain			
Food losses	5,87E-03	kg	Section 2.3
Consumer			
Food losses	9.50E-02	kg	Section 2.3
Plant debris	1.82E-01	kg	Non consumable part of the crop
Packaging	3.26E-01	kg	Bamboo pot and lid, plugs and Rockwool
Transportation	5.00E+01	km kg	Section 2.3

Appendix D. Theoretical model materiality open-field farm

To define the materiality of agricultural buildings on an average open-field farm in The Netherlands, a theoretical model was created as no reference data were available. Nine case studies of open-field farms were studied to determine the type and number of buildings that an average farm has. These case studies were collected from the Dutch property sales website: 'Funda in Business'. This website provided information on the total plot size, and the number, dimensions and materiality of the agricultural buildings present. The average farm size of the analysed case studies was 13.9 ha per farm, close to the national average open-field farm size of 15 ha (CBS, 2021). On average, the studied farms had two agricultural buildings with an average total floor area of 1400 m^2, for the storage of fertilizers, pesticides, herbicides, machinery, and crops. The materiality of agricultural buildings is described in Fig. D.1 and Table D.1. Approximately half of the agricultural buildings studied were insulated. The structural steel was sized using structural rules of thumb (Table D.1). The lifespan of the two agricultural buildings was set at 50 years (Nemecek and Kägi, 2007).

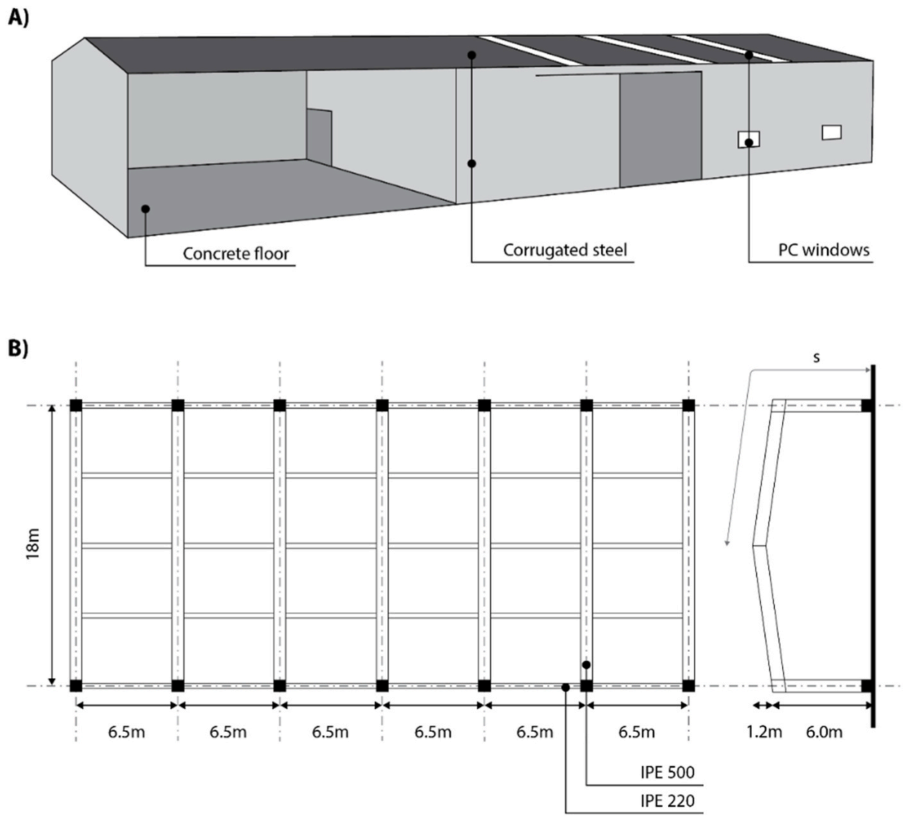

Fig. D.1. A) 3D model of one of two 700 m^2 agricultural buildings used in the theoretical model. B) Typical structural arrangement of the agricultural building using a steel columns and beams.

Table D.1
Material characteristics of the agricultural storage building as included in the theoretical model for the open-field farm. Two of these buildings are included in the model of which one of the two buildings is insulated.

Element	Materials	Dimension	Density	Number or area	Quantity materials	Note
Structure						
Portal frame	Steel	Total length frame (s) 30.2 m, IPE 500	92.5 kg/m	7 x	19.5 ton	Rule of thumb portal h = 1/30 * s (Boveldt, 1999)
Beam	Steel	Length 6.5m, IPE 240	26.7 kg/m	35 x	6 ton	Rule of thumb roof beam single field h = 1/30 * length (Boveldt, 1999)
Rails and purlins	Steel				3.8 ton	Estimated additional 15% of structure weight
Façade						
Cladding	Corrugated steel sheets	Thickness 0.4 mm	3.8 kg/m^2	745 m^2	2.8 ton	(HGM Benelux, 2021)
Insulation	PIR insulation	Thickness 400 mm	34 kg/m^3	550 m^2	7.5 ton	1 of the 2 sheds insulated (Unilin Insulation, 2021)
Cladding interior side insulation	Corrugated steel sheets	Thickness 0.4 mm	3.8 kg/m^2	550 m^2	2.1 ton	Only applied to the insulated shed
Roof						
Roof panels	Corrugated steel plates	Thickness 0.4 mm	3.8 kg/m^2	702 m^2	2.7 ton	(HGM Benelux, 2021)
Windows						
Windows & sky Lights	PC	Thickness 6 mm	2 kg/m^2	120 m^2	0.2 ton	(DaglichtDirect, 2021)

(continued on next page)

Table D.1 (*continued*)

Element	Materials	Dimension	Density	Number or area	Quantity materials	Note
Floor						
Concrete floor	Reinforced concrete	Thickness 20 mm	–	700 m^2	140 m^3	

Appendix E. Renewable energy scenario

Table E.1 presents the fossil fuels used within the baseline scenario of the case studies and the alternative renewable technologies and fuels used in the renewable energy scenario. Table E.2 represents the core emissions of each farming typology in the renewable energy scenario. To determine the carbon footprint of the renewable energy scenario, the electricity demands for GH heating and steaming had to be calculated first.

Greenhouse heating

In the renewable energy scenario heating with a closed loop ground source heat pump (GSHP) was considered as these are identified as an effective and efficient alternative for greenhouse heating (Anifantis et al., 2016; Benli, 2013). A COP of 4 for estimated for the GSHP using Baetschmann and Leibundgut (2012, p. 1054) and the following characteristics for the GSHP system: a heating temperature of 8 °C above ambient for GHs and 10 °C for GHh (Raaphorst and Benninga, 2019), an average ground temperature of 4 °C at 2–4 m depth (Ligget and Milne, 2018), and an exergy coefficient of 0.4 for the GSHP (Maivel and Kurnitski, 2015). A thermal efficiency of 90% was used for the natural gas boiler in the baseline scenario, resulting in a heat demand of 1.7 kWh kg^{-1} for GH(s) and 0.8 kWh kg^{-1} for GH(h) and a electricity demand of 0.43 kWh kg^{-1} and 0.19 kWh kg^{-1}.

Greenhouse steaming

Aside from heating, 5 m^3 m^{-2} of natural gas was used to steam the soil of GH(s) (Raaphorst and Benninga, 2019). A water output temperature of 100 °C was assumed and an average water input temperature of 15 °C. With this information, the baseline water volume for steaming was calculated using the following formula:

$$q = m * Cw * \Delta T, \quad \text{(eq. E.1)}$$

where q is the energy required to heat the volume of water in the boiler with ΔT in KJ, m is the heated volume (L), Cw is the specific heat capacity of water (J/g°C), and ΔT is the temperature difference between the supply water and the steamed water. An efficiency of 90% for the gas boiler was assumed. This resulted in a water volume of 15 L kg^{-1}. By using the same formulae and a COP of 1 for the electric boiler in the renewable energy scenario an electricity demand of 1.52 kWh kg^{-1} was calculated.

Table E.1
Fossil fuel sources within the baseline scenario and the alternative renewables in the renewable energy scenario.

Farm	Purpose	Baseline scenario	Renewable energy scenario
Open-field	Machinery	Diesel	Bio-diesel
Soil-based greenhouse	Heating	Natural gas boiler	GSHP
	Steam	Natural gas boiler	Electric boiler
	Electricity	National grid-mix	PV panels
	CO_2	On-site natural gas combustion	CO_2 from biogas
Hydroponic greenhouse	Heating	Natural gas boiler	GSHP
	Electricity	National grid-mix	PV panels
	CO_2	1) on-site natural gas combustion 2) Liquefied CO_2	CO_2 from biogas
Vertical farm	Electricity	National grid-mix	PV panels

Table E.2
Core missions in the renewable energy scenario

Activity	OF	GH(s)	GH(h)	VF
	kg $CO_{2\text{-eq}}$ kg^{-1}	kg $CO_{2\text{-eq}}$ kg^{-1}	kg $CO_{2\text{-eq}}$ kg^{-1}	kg $CO_{2\text{-eq}}$ kg^{-1}
Watering	0.006	0.008	0.001	0.007
Bio-diesel	0.083			
N_2O from soils	0.022	0.018		
Electricity use		0.167	0.125	1.188
Total emissions	**0.111**	**0.192**	**0.126**	**1.194**

PV panel production

The kWh of electricity produced per m^2 PV is calculated with the following formula:

$$E_{pv} = \eta_{pv} * \eta_{or} * q_{sun} \quad \text{(eq. E.2)}$$

Where η_{pv} is the efficiency of the PV panels of approximately 20% (Delden et al., 2021), η_{or} the orientation efficiency and q_{sun} the solar radiation in the Netherlands of 1000 kWh m^{-2}. The orientation efficiency can be determined with a radiation diagram for the Netherlands (Induurzaam, n.d.). The production for south facing PV panels under an optimal angle of 40° for placement on flat surfaces and those for 90° for façade panels at east, west and south orientation are presented in Table E.3. Each m^2 of cultivation area requires 1013 kWh y^{-1} of electricity to be produced by 5.1 m^2 south-orientated 40° PV cell area. Assuming a land area efficiency of 75% for these PV panels (Delden et al., 2021) results in 6.8 m^2 of land area. If the vertical farm was a standalone building 13500 kWh of electricity could be produced on its roof and 18826 kWh on the east, west and south facades. According to the allocation of electricity (Section 2.3.4), 51% of the total electricity is used for lettuce cultivation. Therefore, 51% of the PV panels are allocated to lettuce, resulting in a total production of 251 kWh per m^2 lettuce cultivation. The remaining electricity required for the production of lettuce still requires 3.8 m^2 of south facing PVs under a 40° angle per m^2 cultivation area.

Table E.3
yearly production of PV panels in the Netherlands

PV orientation and angle	η_{or}	E_{pv}
	%	kWh m^{-2}
South, 40°	100%	200
South, 90°	75%	150
East, 90°	60%	120
West, 90°	55%	110

Appendix F. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.134443.

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