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The role of aeroponic container farms in sustainable food systems – The environmental credentials

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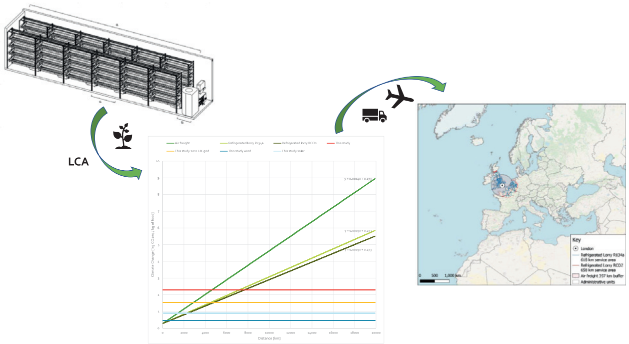
HIGHLIGHTS

- Energy source is critical to reduce most of the environmental impacts of aeroponics.
- Aeroponic container farm system generates 1.52 kg CO_2eq./kg peashoot using 2021 UK grid.
- Solar & wind power lowers GHG emissions of aeroponic container farms by up to 80 %.
- Renewable-powered aeroponic show lower GHG than salads imported from most of Europe.
- Aeroponic container farms show competitive performance against conventional methods.

GRAPHICAL ABSTRACT



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ABSTRACT

Sustainable food production and consumption are key to face the current climate and environmental crisis, hence innovation to produce food with lower impacts are taking more attention. Controlled environment agriculture, also known as vertical farming, is seen as one innovative approach to reduce impacts of producing food while also improving food security. Aeroponic is one of such innovations, which environmental impacts have not been well understood yet. Therefore, this study assesses the environmental impacts of aeroponic farm container system in the UK, including a full set of 19 indicators. The results show that energy requirements drive all the impacts, with climate change estimated at 1.52 kg CO_2eq. per 1 kg of microgreens (pea shoots) using 2021 UK grid. Renewable powered systems improve almost all the impacts, with climate change reduced by up to 80 %, making this system competitive with conventional agricultural systems. This study proves that aeroponic farm container could offer lower impact food than equivalent imported to the UK, and that also could improve food security in terms of availability, stability, and access to food. Affordability issues need to be assessed in future work.

1. Introduction

Food production and consumption are affecting both the population and the planet's health (Foley et al., 2011). Over a third of the global greenhouse gas (GHG) emissions are emitted by the food system (Tubiello et al., 2021) while malnutrition is one of the main sources of mortality in the world (WHO, 2021). The increasing threat of climate change will likely carry-on affecting agriculture and farming, hence endangering food security. Furthermore, rising sea level and frequent flooding will adversely impact communities, especially those already living in precarious conditions (Oppenheimer et al., 2019). Additionally, malnutrition due to lack of access

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and availability of affordable and culturally relevant nutritious food could lead to higher consumption of cheap low quality processed food (Silva et al., 2021; Yin et al., 2020), putting pressure on the health system with non-communicable diseases requiring expensive and regular health treatments (Willett et al., 2019).

Sustainable food production and consumption are being actively considered as adaptation and mitigation strategies for reducing and managing climate change, and for reducing pressure on the environment and society's infrastructure (e.g., health system, food system, etc.) (Clark et al., 2019). The challenges across these sectors are vast, including high migration from rural to urban areas, lack of workers for carrying farming and agriculture activities, provision of affordable and nutritious food in urban areas for growing population, and more recently the lack of fast response to shock and disruptions in international food supply chains due to COVID-19 and economic and political instability in the region, increasing the amount of people experiencing food insecurity and creating anxiety across the whole population (e.g., stock piling) (Hobbs, 2020).

Therefore, the role of local food production remains key, with an increasing interest on the use and exploration of vertical farming methods to support resilience, availability, accessibility, and stability of fresh and nutritious food in urban areas. The rise in vertical farming projects is noticeable when analysing the market trends; since 2020 the global vertical farming market has grown ~55 %, from USD 5.5billion to USD 8.5 billion in 2022, expected to reach USD ~20 billion in 2026 (STATISTA, 2020a). In relation to the market distribution, by market value, there is nearly an equal distribution within North America (USD 1375 million), Europe (USD 1353 million) and Asia-Pacific (USD 1254 million), with the rest of the world sharing the remaining USD 665.5 million (STATISTA, 2020b).

Vertical farming growing methods include hydroponics, aquaponics, and aeroponics; hydroponics is the most well-known method with a market value of USD 1.33 billion in 2020 (STATISTA, 2020c). It is followed by aquaponics and aeroponics, which share the rest of the market, estimated at USD 1.91 billion (STATISTA, 2020c). Aeroponics and hydroponics are the technologies that are expected a larger growth between 2020 and 2027, with a compound annual growth rate (CAGR) of ~21 % and ~20 %, respectively (STATISTA, 2020d).

The benefits of vertical farming or controlled environment agriculture to the resilience of our fresh produce supply are vast; the literature describes many advantages associated to these food production methods (Stiles and Wootton-Beard, 2017), from reducing land requirements to produce equivalent crops (Touliatos et al., 2016) avoiding losses of nutrients, to reducing waste and water use, and to better control pests and diseases, and reduce or avoid the dependency of imports and the impacts associated with it (Stiles and Wootton-Beard, 2017). It is therefore imperative to understand these claims and estimate the potential environmental impacts of the mainstream use of vertical farming, particularly due to the current policy environment. For example, in the UK, the environmental impact performance of food grown in vertical farming could potentially contribute to the *Net Zero Strategy: Build Back Greener* (BEIS, 2021), while at the same time will help to support decision-making, especially in terms of procurement and local policies, that align with the National Food Strategy (DEFRA, 2022; Dimbleby, 2021) and the efforts toward accounting and reporting scope 3 GHG emissions in the food and drink sector (WRAP, 2022).

In relation to environmental impact assessment, most of the studies refer to hydroponics as the main and sometimes only technique for growing food indoors (Al-Chalabi, 2015; Fischetti, 2008). Hence, it is not surprising that when investigating the environmental implications of vertical farming, most of the studies consist of assessment of hydroponic systems. For example, Al-Chalabi (2015) aimed to determine the “feasibility and plausibility” of hydroponics for food production in the UK. The author estimated and compared the carbon footprint of the food produced, in this case lettuce, by the hydroponic system with the conventional open-field option, and assessed the energy required and the feasibility of using renewable powered systems. The analysis was done by design and optimization models based on literature, while the carbon footprint was done using pilot data and from direct interviews with hydroponic system owners. Similarly, Molin and Martin (2018) and Martin and Molin (2019) assessed the performance of hydroponic systems in Sweden following life cycle assessment (LCA) methodology using a cradle-to-gate approach; the authors assessed the energy consumption and carbon footprint (Molin and Martin, 2018) in addition to other four environmental indicators i.e., Acidification, Eutrophication, Human Toxicity and Abiotic Resource Depletion of fossil fuels. This study builds the inventories using data from a hydroponic company and compares its results with conventional food production methods. In the same region, De Geyter (2018) carried out a comparison between three systems for the vegetable (lettuce) market in Norway, namely vertical farming using hydroponic nutrient film technique, greenhouses and food import from Mediterranean countries applying cradle to gate scope. The authors assessed six impacts including Global Warming Potential (GWP), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Particulate Matter (PM), Terrestrial Acidification (TA) and resource depletion water. In North America, Wildeman (2020) compared the environmental impacts of a fictional vertical farming system (hydroponic - Stacked Horizontal System) with conventional methods of producing lettuce in the US.

The studies report different outcomes when comparing with conventional food grown systems. For example, Al-Chalabi (2015) showed a variation of between 5 and 2 times larger carbon footprint than the conventional growing system for lettuce grown by a hydroponic system. The main reason of such large variation relies on the energy requirements, mainly electricity. Although solar powered systems were integrated, the amount of energy generated does not provide full independency for the UK energy mix, which although has increased the renewable generation, still relies on fossil fuels, especially by the time of this study. Molin and Martin (2018) first determined the yield of different production systems, concluding that vertical farming has the highest (3.7), followed by greenhouse (2.7) and then open field (0.2) for herbs production. When assessing energy consumption, the vertical farming requires three times more energy than greenhouses, but when only heating is compared, the vertical farming requires ~25 % less heat (Molin and Martin, 2018). Although the carbon footprint was not explicitly compared, the authors declared that the values are higher than those for conventional methods. However, in their latest publication, Martin and Molin (2019) suggested that their results are competitive with those of urban farming and other hydroponic systems. Similarly, De Geyter, 2018 concluded that for most of the impact categories the vertical farming system has lower impacts than the greenhouses and even importing lettuces from Mediterranean countries; however, impacts related to water, such as water depletion and freshwater eutrophication, the greenhouse system performs the best. Opposite results are found by Wildeman (2020) who reported that vertical farming shows the largest impacts, with values over 10 times worst. Wildeman (2020) assumed that the different scopes and the inclusion of infrastructure in their study are the main reason for such large difference.

As far as the authors are aware, there are not studies assessing the environmental impacts of the production of food using any kind of aeroponic system. Hence, this study aims to fill this gap by estimating for the first time the environmental impacts of an aeroponic container farm food production system in the UK. This research also seeks to determine the potential contribution of this urban food production method to reduce the climatic impacts of food production and distribution in urban areas and provide evidence for policy intervention to promote more sustainable urban food systems.

Following, the methodology of this research is presented in Section 2, and the results are exhibited and discussed in Section 3; finally the conclusions are shown in Section 4.

2. Methodology

The Life Cycle Assessment (LCA) methodology has been chosen to carry out the environmental assessment of this study, following the framework defined by the ISO 14040/44 guidelines (ISO, 2006a, 2006b), applying an attributional approach. This methodology has been widely used to assess

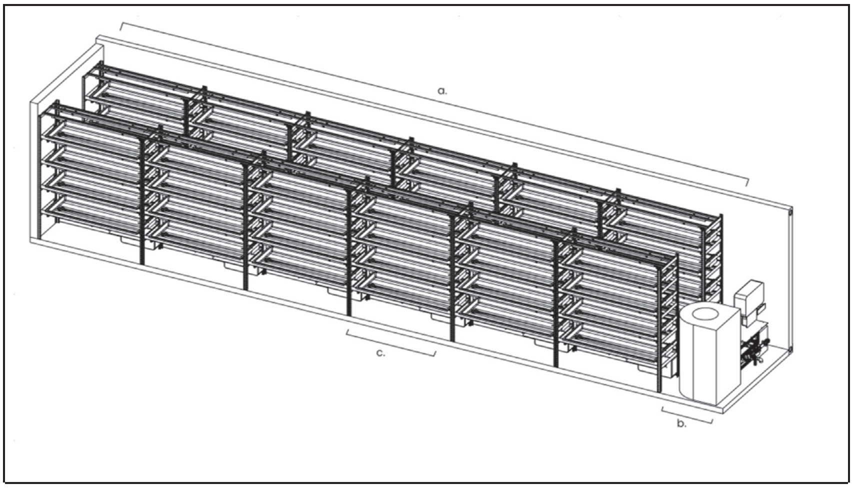


Fig. 1. Angled view of the layout within the shipping container. a). the growing area, b). the water system comprising a reservoir, filter, and nutrient dosing system (water chiller).

the environmental impacts of a system, product, or service (Schmidt Rivera et al., 2021).

The following sections describe in detail the 4-steps of the LCA methodology, starting with the definition of the goal and scope in Section 2.1, followed by the life cycle inventory Section 2.2 and the impact assessment Section 2.2.3. The last step – interpretation of results – has a full section dedicated to it (Section 3).

2.1. Goal and scope

The goal of this study is to estimate the environmental impacts of aeroponic container farm food production systems in the UK, as an urban food production method, and to compare them with conventional food production systems (e.g., open fields and greenhouses) and other vertical farming options (e.g., hydroponic). A further goal is to estimate the potential contribution of aeroponic container farm to reduce the climatic impacts of food production and distribution in urban areas of the UK.

The functional unit (FU) consists of 'the production of 1 kg of pea shoots at farm gate'; this FU allows comparison between studies assessing different food production and distribution methods. The scope of the study is from cradle to farm gate, including the extraction and processing of the infrastructure materials, growing inputs and energy, and the waste management of all inputs at their end of the life. To determine the contribution to reduce the impacts of food production and distribution in urban areas, different transportation methods and distances will be analysed for imported salads and herbs in the UK. A full description of the system and the inventory is presented in Section 2.1.1.

2.1.1. Description of the system

The hydroponic container farm system can be divided up into a growing space and a water system. The growing area consists of twelve modular stacks each made up of four aeroponic grow beds and LED lights arranged vertically. The beds are connected to the water system via piping. The total growing area of these twelve modules is equivalent to 48 m^2. A HVAC system maintains the temperature and relative humidity of the growing area and air is distributed across the surface of the plants with additional fans. In the water system, the water is stored in a reservoir and circulated throughout the system with pumps. The nutrient composition of the water is monitored by an automated dosing system. The water is also pumped through particulate and UV filters. The whole system is controlled and automated by a farm computer (see Figs. 1 and 2).

For the purpose of the study, the system has been divided in five life cycle stages namely pea shoot production, facilities, hardware, energy demand and waste management, as described in Fig. 3. These stages are used in the design and operation of the system, and therefore to facilitate the integration of the outcomes of this study in the day-to-day activities, they have been used as life cycle stages too. The inventory provides a description of each stage and data used.

2.2. Inventory

Data was collected in-situ and supported using economic models and manuals, laboratory analysis and specific measurements. For developing inventories, a process flow diagram was produced detailing the method of growing pea shoots within an aeroponic container farm. Each life cycle

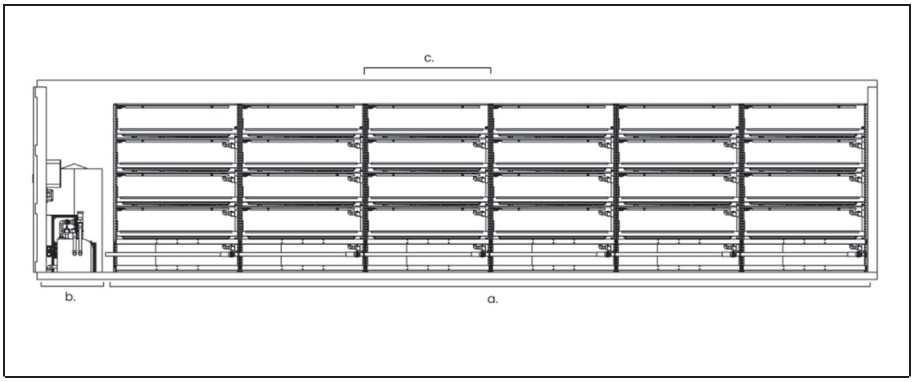


Fig. 2. Lateral view of the layout within the shipping container. a). the growing area, b). the water system comprising a reservoir, filter, and nutrient dosing system (water chiller).

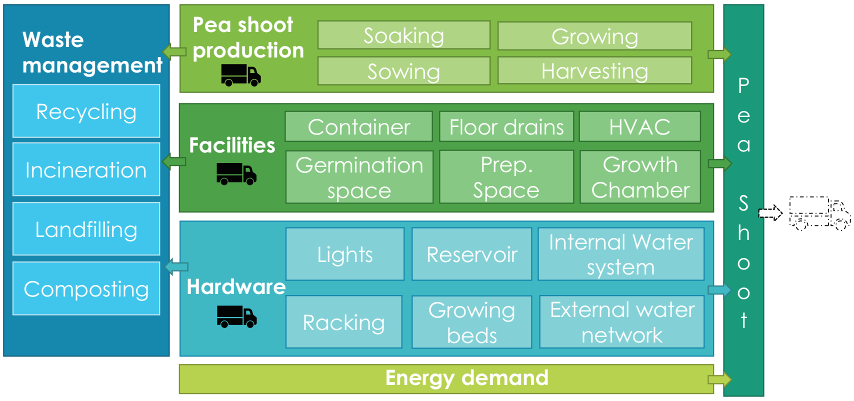


Fig. 3. Life cycle stages of the aeroponic container system.

stage was broken down into their main infrastructure and activities (Fig. 3), which then help identifying all components and processes; from this a database was then populated listing all materials and utilities required throughout the process. Manufacturers and distributors manuals and website were used to identify and quantify materials of each component, as well as operational aspects of the infrastructure (e.g., energy consumptions of pumps, etc.). Details of the inventory of each stage are presented below.

2.2.1. Pea shoot production

The pea shoot production stage consists of all the steps and inputs required to produce the pea shoots (salads); starting with preparing medium (mats) and soaking and sowing the seeds; then the growing phase includes the nutrient requirements and water, and finally harvesting. This stage also includes emissions to water from the disposition of exhausted water after the recirculation cycles. Ecoinvent 3.6 database (Moreno Ruiz et al., 2019) has been used for background information and in-situ measurements were used for emissions. Table 1 details the inputs accounted for in this stage.

Table 1
Inventory of the pea shot production stage, values per functional unit.

Sub-system	Components	Quantities [kg or kWh]	Transport	Cargo [tkm]
Soaking	Pea seed	1.9E−01	Lorry	1.98E−02
	Polyethylene	5.20E−05	Lorry	5.20E−06
	Acrylonitrile-butadiene-styrene copolymer, ABS	1.59E−04	Lorry	1.75E−04
	Polypropylene	1.92E−04	Lorry	2.02E−04
	Polyvinylchloride	3.22E−05	Lorry	2.25E−05
	Water	1.73		
Sowing	Polypropylene	3.04E−03	Lorry	3.04E−03
	Recycled polypropylene	3.17E−05	Lorry	3.17E−05
	Mat - Recycled Wool Rich Fibres[a]	6.20E−02	Lorry	6.20E−03
	Water	5.54E−01	–	–
Growing	Phosphoric acid, fertiliser grade	7.67E−04	–	–
	Ammonium nitrate	5.37E−04	–	–
	Monoammonium phosphate	1.84E−04	–	–
	Potassium hydroxide	1.03E−03	–	–
	Potassium nitrate	8.28E−04	–	–
	Tap water	5.72	–	–
	Wastewater treatment	−2.12E−01	–	–
Emissions to water	Ammonium	7.65E−07	–	–
	Bicarbonate	1.30E−06	–	–
	Boron	3.40E−08	–	–
	Calcium	3.14E−05	–	–
	Chloride	5.95E−06	–	–
	Copper	1.05E−08	–	–
	Iron	1.66E−07	–	–
	Magnesium	7.65E−06	–	–
	Manganese	5.10E−08	–	–
	Molybdenum	4.43E−09	–	–
	Nitrate	7.12E−05	–	–
	Phosphorus	2.00E−05	–	–
	Potassium	1.17E−05	–	–
	Silicon	1.70E−07	–	–
	Sodium	5.31E−06	–	–
	Sulphide	1.08E−05	–	–
	Zinc, ion	5.10E−08	–	–

[a] LCIA data was provided from manufacturer, only carbon footprint was accounted for.

2.2.2. Facilities and hardware stages

The facilities and hardware stages refer to the surrounding infrastructure and auxiliary equipment that enable the functioning of the aeroponic container farm. The hardware stage includes the lighting system, water network and the infrastructure to support the growing system such as racking and grow bed container, which include metal structures, plastic containers, pumps, and pipes, etc. The facilities refer to the infrastructure itself such as the container, the growth chamber, HVAC system and working spaces

Table 2
Inventory of hardware and facilities stages by functional unit.

System	Sub-system	Parts/components	Quantities [kg - kWh]	Transport	Cargo [tkm]
Hardware	Lights	LED lights	5.84E−04	Shipping	1.20E−02
		Aluminium	2.13E−04	Lorry	2.13E−05
		A4 steel	9.05E−06	Shipping	1.86E−04
	Racking	Steel	1.03E−03	Lorry	1.76E−03
	Grow bed	ABS	6.82E−04	Lorry	4.29E−04
		Copper	4.43E−04	Shipping	9.08E−03
		Steel	1.81E−05	Shipping	3.71E−04
		PP	1.14E−03	Lorry	1.25E−03
	Internal water network	PVC	3.27E−04	Shipping	2.29E−04
		Steel	3.22E−06	Shipping	6.60E−05
		ABS	3.32E−04	Shipping	6.81E−03
	External water network	PVC	8.77E−05	Lorry	6.14E−05
		Stainless	5.99E−05	Shipping	1.23E−03
		Aluminium	6.09E−05	Lorry	6.70E−05
	Reservoirs	MDPE	1.59E−03	Lorry	1.59E−04
		Steel	2.77E−04	Lorry	4.15E−04
Facilities	Container	Steel	4.49E−03	LOrry	9.21E−02
	Growth chamber	PIR	2.13E−03	Lorry	2.13E−04
		Steel	4.67E−05	Lorry	4.67E−06
	In floor drains	Steel	9.22E−07	Lorry	9.22E−08
		PVC	2.59E−06	Lorry	2.59E−07
	HVAC system	Galvanised steel	9.81E−05	Lorry	1.26E−04
		Aluminium	3.69E−06	Lorry	6.27E−06
	Prep space	Steel	8.01E−04	Lorry	1.23E−03
		Copper	2.77E−06	Lorry	4.15E−06
		Titanium steel	1.94E−05	Lorry	2.91E−05
	Germination space	Aluminium	2.49E−04	Lorry	6.98E−04

to carry out different activities, such as germination. This stage mainly accounts for metal structures and auxiliary materials. The inventory was built using information from existing farms, while the background information for all inputs was sourced from Ecoinvent 3.6 (Moreno Ruiz et al., 2019). Table 2 details the inventory of these stages.

2.2.3. Energy demand

The energy demand refers to the energy requirements to operate the system. As seen in Table 3, this includes the energy required by the bed controllers, environment, facilities, fertigation, irrigation, lighting, operations, and soaking equipment. The UK electricity mix was sourced from Ecoinvent 3.6 database (Moreno Ruiz et al., 2019). A thorough discussion of decarbonization pathways as well as the implication of Green Tariffs are presented in Section 3.2.1.

2.2.4. Waste management

The waste management stage includes the common practices of end-of-life resource management of the UK, incineration, and landfilling (DEFRA, 2021), which complements the recycling practices for the different materials (e.g., metals and plastics). In this study, landfilling of metals, and incineration and landfilling of plastics are assumed for the shares not recycled. The mats, with the leftover salad roots and seeds, are the only composting waste in the system. The wastewater treatment is also included. Background information was sourced from Ecoinvent 3.6 (Moreno Ruiz et al., 2019). Table 4 shows the details of recycling rates of each material considered in this study.

2.2.5. Assumptions

The critical assumption in vertical farming production methods is that there are no emissions coming from the nutrients used. All the reviewed studies state that vertical farming systems do not emit emissions. In this study, we have also assumed that there are no direct emissions to air from the oxidation of the nitrogen-based nutrients, due to lack of studies to model this and resources to measure this otherwise. However, emissions to water were possible to measure, hence they are accounted for based on water sampling of the system; details of the emissions are displayed in Table 1.

2.2.6. Scenarios

Scenario analysis will aid understanding of potential improvements in both the aeroponic container farm system and broader food system; these scenarios were informed by hotspot analysis and by the company (e.g., to test suppliers). The scenarios include different energy sources, solar and wind energy, and plant-based growing mats, which includes cotton, jute and kenaf. Table 5 summarises the scenarios considered, and data used.

2.3. Life cycle impacts assessment

This study uses GaBi ThinkStep software (Thinkstep, 2019) to model the system while the environmental impacts are estimated using ReCiPe impact assessment method (Huijbregts et al., 2017). This method has been selected because it is widely used across LCA practitioners and published studies, which enables direct comparison for validation, and due to provides a comprehensive set of indicators. Primary energy demand (PED) has been also included to complement the study (Thinkstep, 2019). A full set of impacts are considered and assessed by groups, namely 'common impacts', 'toxicity related impacts' and 'resource related impacts'. Common impacts include Climate change (CC), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Photochemical Ozone Formation, Ecosystems (POFe) and Human Health (POFh), Stratospheric Ozone Depletion (OD), Terrestrial Acidification (TA). The toxicity related impacts include Freshwater ecotoxicity (FEC), Human toxicity related to cancer (HTc) and non-cancer (HTnc), Marine ecotoxicity (MEC), Terrestrial ecotoxicity (TEC). Finally, the resource related impacts are Primary energy demand (PED), Fossil depletion (FD), Land use (LU), Metal depletion (MD), and Freshwater Consumption (FWC).

Table 3
Energy demand of the aeroponic container farm.

Activity	kWh/f.u.	Share
Bed controllers	0.63	13 %
Environment	1.06	22 %
Facilities	0.12	2 %
Fertigation	0.04	1 %
Irrigation	1.25	26 %
Lighting	1.69	34 %
Operations	0.11	2 %
Soaking	0.001	0.01 %
Total	**4.9**	**100 %**

Table 4
Waste management practices per materials.

Materials	Recycling rate	Reference
Steel	96 %	Steelcontruction.info (2022)
Aluminium	95 %	ALFED (2020)
Copper	70 %	Copper Alliance (2019)
Plastics	32 %	BPF (2020)
Concrete	91 %	MPA (2020)

3. Interpretation of results

The results section first presents overall environmental impacts including the whole life cycle stages in Section 3.1, to then assess the contribution by stage in Section 3.2. The assessment of different scenarios will be shown in Section 3.3 and the validation of the results in Section 3.4. Finally, the contribution of aeroponic container systems to improving sustainability of local food systems is assessed in Section 3.5.

3.1. Environmental impacts

The environmental impacts of producing 1 kg of pea shoot using aeroponics container system will be discussed first for the common impacts in Section 3.1.1 including climate change, to then assess the toxicity related impacts in Section 3.1.2 and finally the resource related impacts in Section 3.1.3.

3.1.1. Common impacts

Fig. 4 shows the environmental impacts of aeroponic container farm production system. Climate change (CC) is estimated at 2.29 kg CO_2eq. per 1 kg of pea shoot (fu). The energy requirements of the system to operate, in this case supplied by the electricity from the UK grid, are the main contributor to CC (82 %). TA is calculated at 6.74 g SO_2eq./fu with the energy demand being the main contributor too (67 %). Similarly, the energy

Table 5
Scenario description.

Scenarios	Data source	Reference
Solar energy[a]	GB: electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted GB: electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted	Ecoinvent 3.6 (Moreno Ruiz et al., 2019)
Wind energy	GB: electricity production, wind, <1 MW turbine, onshore	Ecoinvent 3.6 (Moreno Ruiz et al., 2019)
Cotton	GLO: market for textile, cotton	Ecoinvent 3.6 (Moreno Ruiz et al., 2019)
Jute	Manufacturing of mats made of recycled and virgin Jute	Information provided by manufacturers
Kenaf	GLO: market for textile, kenaf	Ecoinvent 3.6 (Moreno Ruiz et al., 2019)

[a] Equal share of technology has been considered.

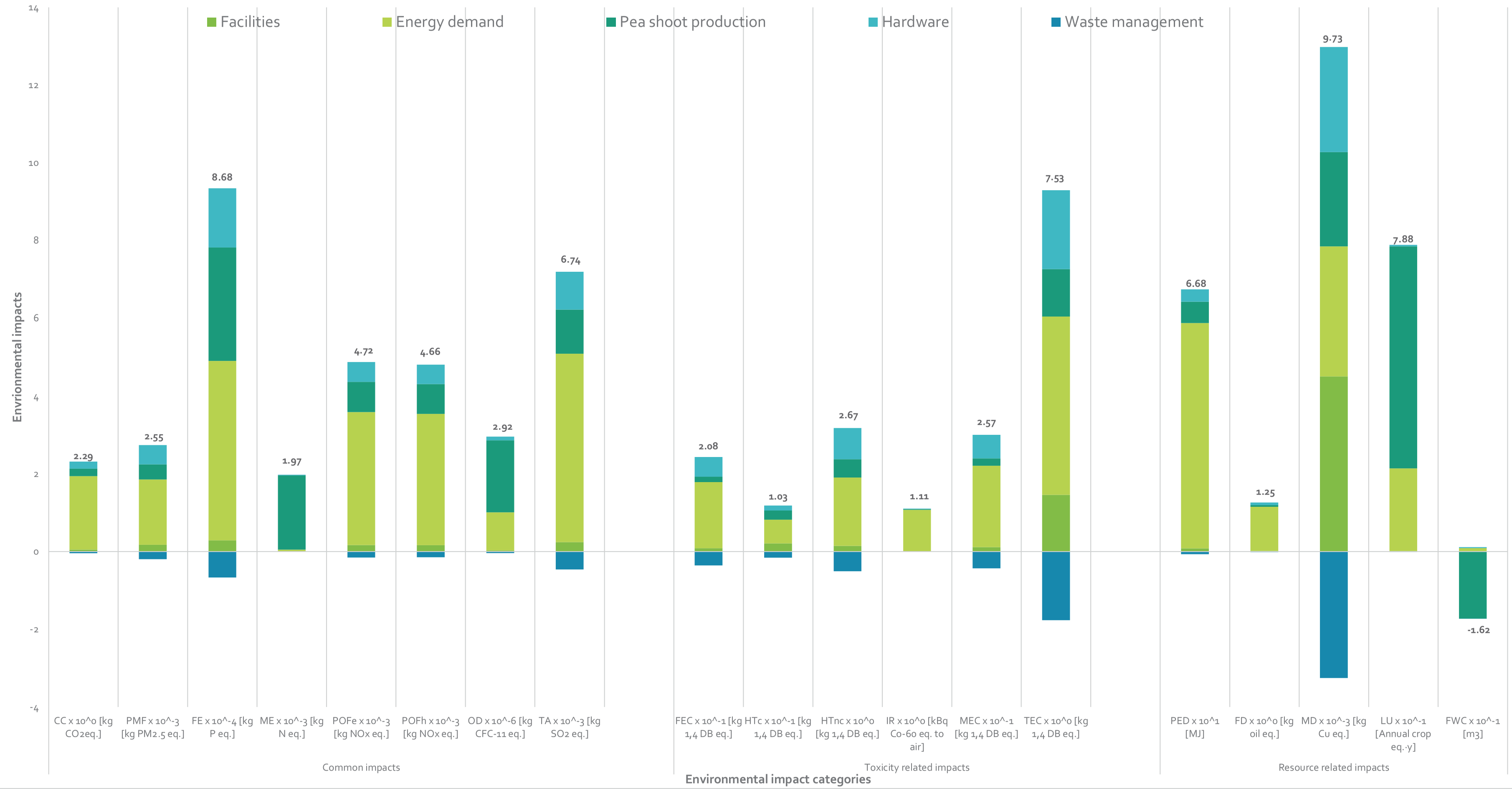


Fig. 4. Environmental impacts of 1 kg of pea shoot produced in aeroponic container farm system.

demand is the main contributor (>60 %) for most of the impacts, namely PMF, estimated at 2.55 g PM2.5 eq./fu, and POFe and POFh calculated at 4.72 and 4.66 g NOx eq./fu, respectively. FE is 0.868 g P eq./fu, with energy demand contributing by 49 % and the pea shoot production adding 31 %. these results align with previous studies performed by Al-Chalabi (2015), Molin and Martin (2018) and Wildeman (2020), where they concluded that the energy demand is the main contributor to impacts like CC, TA, and others.

A different trend is seen in ME (1.97 g N eq./fu) and OD (2.92 mg CFC-11 eq./fu); the pea shoot production stage is the main contributor adding 97 % and 63 % of the impacts, respectively. This is mainly associated to the nutrients used in the growing stage (see Table 1). For OD, the energy demand is also an important contributor adding a third of the impacts (33 %). Overall, the facilities and hardware stages contribute on average 3 % and 10 %, respectively. Only for FPM and FE, the facilities show a larger contribution, adding 18 % and 16 % to the impacts, respectively. Recycling practices in the waste management stage aid reducing the impacts by on average 4 % by avoiding the burdens of producing new materials; this is particularly important for PFM, FE and TA where the waste management stage saves around ~7 % of the original impacts.

3.1.2. Toxicity related impacts

Fig. 4 exhibits the toxicity related impacts. FEC and MEC are estimated at 208 and 257 g 1,4 DB eq./fu with the energy demand being the largest contributor (70 %). IR, estimated at 1.11 kg Co-60 eq./fu, also shows a similar trend in terms of main contributor, with the energy demand being almost the only driver (97 %). Energy demand is the largest contributor due to the emissions associated to the life cycle of the production and operation of the energy technologies, especially those fossil fuel based (e.g., coal, natural gas), which represented ~50 % of the 2017 UK energy grid (BEIS, 2022). Similarly, HTc, calculated at 103 g 1,4 DB eq./fu, is mainly driven by the energy requirements (and source), which represents 52 % of the impacts, but pea shoot production and hardware stages add 20 % and 11 %, respectively. TEC (7.53 kg 1,4 DB eq./fu) and HTcn (2.67 kg 1,4 DB eq./fu) show similar patterns in terms of stage contribution, however with different shares from the previous impacts. For them, the energy demand corresponds on average to ~52 % for both impacts, while the pea shoot production stage adds ~14 % and the facilities stage contributes ~24 %.

Across all the impact categories, the hardware stage contributes on average 17 %, with the largest contribution found in HTnc (25 %). Correspondingly, the facilities stage adds on average 8 % while the pea shoot production is responsible for 10 % on average. Waste management options, specifically the recycling of materials, contribute reducing the impacts by avoiding the burden of producing virgin materials, also called credits. These credits decrease the absolute impacts by between 13 % in the case of HTc and 20 % in the case of TEC. IR is the only impact not affected by the credits.

3.1.3. Resource related impacts

Fig. 4 also displays the impacts associated with resources such as energies (PED, FD), metals (MD), water (FWC) and land (LU). PED and FD are estimated at 66.8 MJ/fu and 1.25 kg oil eq./fu, and as expected, the energy demand leads these impacts (86&90 %, respectively). These results are explained by the large contribution from fossil fuel-based technologies into the UK energy mix in 2017 (~50 % of the generation is from coal and natural gas) (BEIS, 2022). This is explored further in Section 3.2.1 and in the scenario analysis (Section 3.3). MD, calculated at 9.76 g Cu eq./fu, shows a shared contribution from all the stages, being the facilities the larger contributor with 35 %, followed by the energy demand (26 %), and then the pea shoot production (19 %) and hardware (21 %) stages. This is mainly because of the metals used in the infrastructure and components of the system. For the last resources, LU and WFC, the impacts are estimated at 0.79 annual crop eq. y/fu and -0.16 m^3 with only two stages contributing - pea shoot production and energy demand. In the case of the former, the use of water for soaking, sowing, and growing is the main and obvious reason of such contribution (see Table 1), while in the case of the energy demand, it is due to the water use within the life cycle of the energy generation technologies. The net negative water consumption is due to the treatment of wastewater, which enable the recovery of water for other uses. For these impacts, the credits from the waste management stage, namely recycling of the different materials avoiding the burden of extracting and processing virgin materials, mainly affects MD, reducing the impacts by 25 % from its absolute values.

3.2. Life cycle stage contribution

As seen in Section 3.1, the contribution of the life cycle stages varies depending on the impacts. This section assesses the contribution of key life cycle stages of the aeroponic container farm system. It is important to note that although the energy requirements of the system are by far the main contributor for almost all the impacts, it is essential from an operation and design perspective to also understand how the components and activities of each stage contribute to the impacts of the overall system.

3.2.1. Energy demand

Table 3 shows the breakdown of the activities associated with the energy demand. A third of the energy demand (34 %) is associated with the lighting system, which is key to produce pea shoot (or any other food product), as this system generates the photons of light needed for plant photosynthesis, hence powering the plants growth cycle, and directly affecting yield. Nearly half of the energy demand is related to the irrigation system and the environment, another important aspect of this technology. Bed controllers are responsible for 13 % of the energy demand. Finally, the facilities, fertigation, the operation, and the soaking activities add together 5 % of the energy demand.

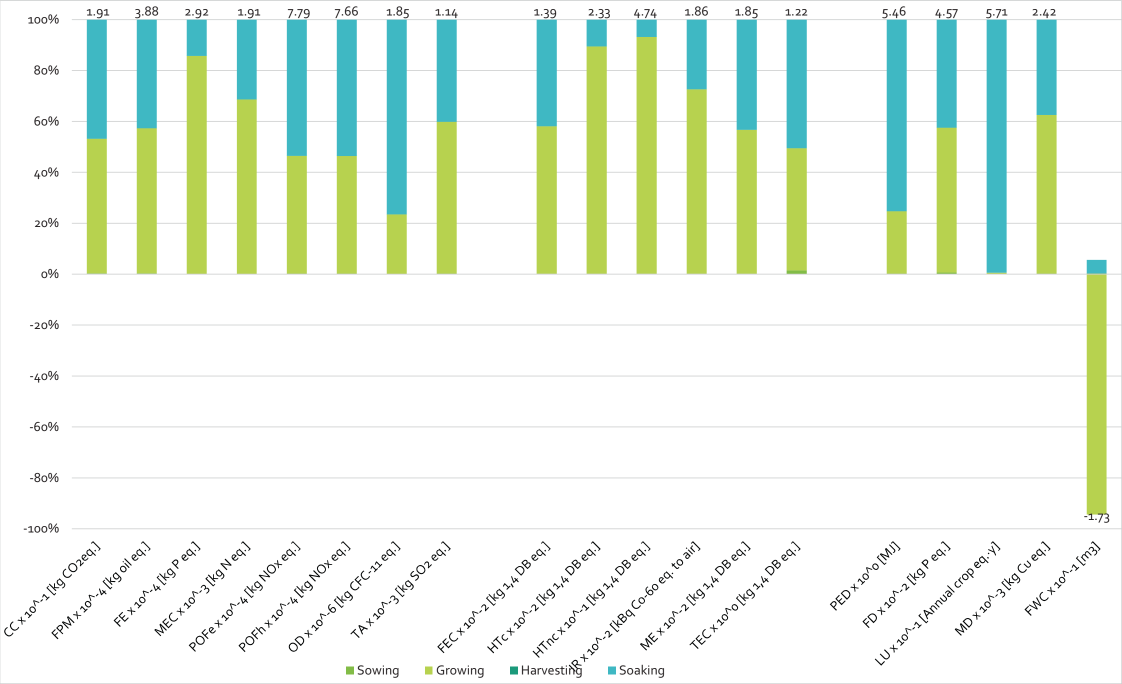
The impacts of the energy demand stage are solely driven by the electricity mix of the UK, which even though has increased its share of renewables to 29 % (BEIS, 2018), it still consists of a large fossil fuel basis (e.g., 6.7 % coal, 40 % natural gas). For this study, we have used the UK 2017 energy mix from Ecoinvent 3.6 (Moreno Ruiz et al., 2019), as it provides information to assess a large set of indicators. However, in the last four years, the UK grid have increased the use of renewable technologies, hence decreasing, in particular, the greenhouse gas emissions associated to energy generation. Table 6 displays the changes in CC using the latest UK energy carbon intensity factors. As can been seen, using the 2021 estimates of the UK electricity mix improves CC by 33 %, with the production of 1 kg of pea shoot estimated at 1.36 kg CO_2eq. Table 6 also shows the potential reduction associated to the future decarbonization of the UK energy grid based on Government's commitments; the decarbonization plans for the next 15-years offer great opportunities to reduce the impacts of aeroponic food production systems, with reduction of up to 77 % by 2034, equivalent to 0.64 kg CO_2 eq. per 1 kg of pea shoot produced.

Table 6
Analysis of the influence of different UK energy mixes.

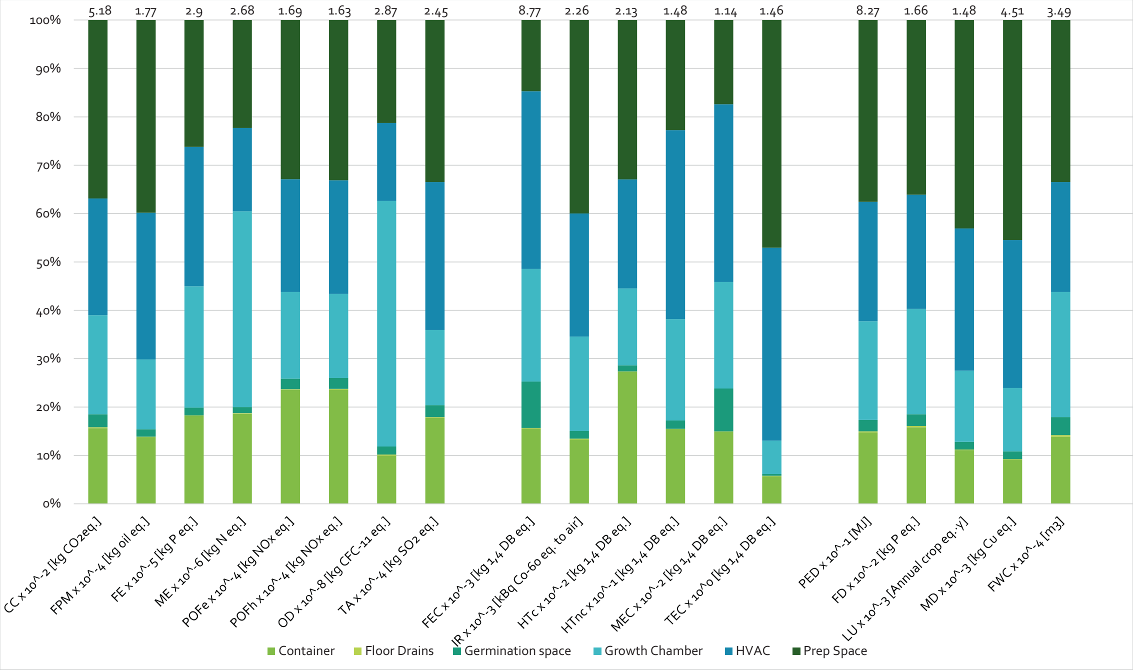
Year	Carbon intensity [kg CO_2eq./kWh]	CC of aeroponic production [kg CO_2eq./fu]	Improvement
2017	0.384	2.28	This study
2018	0.307	1.89	17 %
2019	0.277	1.75	23 %
2020	0.253	1.63	28 %
2021	0.231	1.52	33 %
2024	0.111	0.93	59 %
2026	0.098	0.87	62 %
2028	0.100	0.88	61 %
2030	0.085	0.80	65 %
2032	0.064	0.70	69 %
2034	0.051	0.64	72 %
Green Tariff[a]	0	0.39	83 %

[a] For the calculations, 0 kg CO_2 eq./kWh of energy acknowledging that this value might be under Scope 1 for reporting GHG emissions while the system accounts for scope 3.

It is important to note that the aeroponic container system of this study uses green electricity tariffs. Although green tariffs have been seen as a good solution for businesses to reduce their environmental impacts associated to energy consumption, there is a large debate of how green these tariffs actually are, and how to report them. The main issue is related to the Renewable Energy Guarantee of Origin (REGO) certificates, which

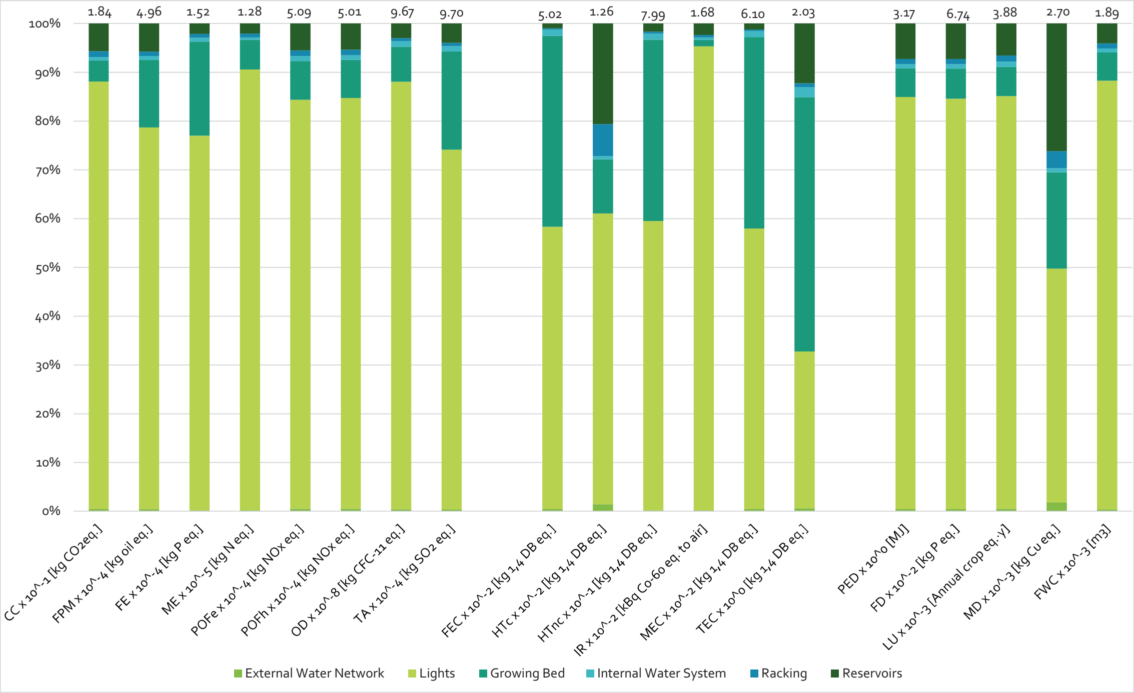


a) Pea shoots production stage



b) Facilities stage

Fig. 5. Contribution of activities and components to the environmental impacts of each life cycle stage the aeroponic container system.



c) Hardware stage

Fig. 5 (*continued*).

are allocated to every Mega-Watt hour (MWh) of electricity generated by renewable sources. The electricity generated and REGOs are traded separately across energy providers, hence companies could purchase REGOs together with the energy acquired or separately (GHG Insight n.d., Centre for Sustainable Energy, n.d., Green Electricity Markets, n.d.). This means that energy suppliers could buy energy from the grid (with shares of renewables and fossil fuel sources) and offset the emission with REGOs (representing units of electricity) to then claim the provision of "100% renewable energy". In addition to being able to claim green electricity, companies could even save money, as REGOs are usually cheaper than electricity, while green tariffs are usually premium products for customers. On the contrary, those companies that are genuinely providing green tariffs usually work with Power Purchase Agreements (PPA) – a mechanism that keeps REGOs together with the energy purchased (CCS, 2020). If so, energy suppliers using PPAs could encounter higher costs by investment in supply-demand forecasting processes and by working with small, usually independent, energy generators such as community-owned projects (CCS, 2020; Centre for Sustainable Energy, n.d.). A large debate has arisen from the misleading nature of the green tariff, with a recent report concluding that nearly 30 % of the UK energy green tariff suppliers could be labelled as "greenwashing" (Scottish Power, 2021). There are efforts to support consumers with their decision making from private sector; for example, defining a Green Accreditations (Uswitch, 2021) or Green Tariffs Levels (Ecotricity, 2021). However, these mechanisms are not standardised, leaving the consumers and small and medium businesses to do their own research. The complexities of green tariffs highlight how more clear policies and real investments are required to get to net zero. With investment in the decarbonization of energies being the basis; it is clear that market-based mechanisms enable businesses with the opportunities for "greenwashing", which leads to confusing consumers who are detrimental players to face the climate crisis (The Guardian, 2022).

As expected, issues around green tariffs make the reporting of the greenhouse gas emissions very complicated, no matter the scope that is used – scope 1, 2, 3, with opposite perspectives between governmental bodies (e.g., GGC and DEFRA) (CCS, 2020). For the reasons mentioned above the complexities of tracking down what the real sources of electricity generation are used by green tariff providers, to then define the whole life cycle (GHG reporting scope 3) and assess the emissions will be another project altogether; hence this study does not fully assess the green tariff using scope 3 or a full life cycle assessment. Instead, the use of electricity generated by solar and wind power systems is discussed in Section 3.3. However, it is important to have an overview of what an ideal green tariff could offer to the aeroponic container system. As seen in Table 6, calculations show that if the carbon intensity of the electricity use is 0 kg CO_2eq./kWh, the impacts of producing 1 kg of pea shoots by aeroponic container system will be ~5 times lower than the current impact, reducing it to 0.39 kg CO_2eq./fu (see Table 6).

3.2.2. Pea shoot production

Fig. 5a shows the contribution of the pea shoots production stage, which is mainly driven by two activities – soaking the seeds and the growing phase, which on average represent 99.8 % of this stage. The growing phase is the largest contributor adding on average 55 % of the impacts. The main reason for such large contribution is the emissions to water and the associated with the wastewater treatment; this is particularly important for impacts such as FE, ME, HTc&nc, IR and MD, where this activity represents over 70 % of the impacts. However, the wastewater treatment also provides benefits recovering water for further use, hence the negative values associated with FWC. Overall, the growing activities contribute between 45 and 62 % to the majority of the impact categories (10 out 19 categories). The production of seeds is the main contributor to the impacts of soaking, being the main contributor to categories such as LU (99 %), PED (75 %), and OD (77 %). Overall, this stage adds between 38 and 55 % to most of the impacts (9 out of 19) including CC, while for nearly a third (6 out of 19) the contribution is lower than 38 %.

3.2.3. Facilities

Fig. 5b displays the impacts associated to the facilities stage, showing a breakdown of the contribution by component. As described in the inventory, this stage mainly accounts for infrastructure, hence the materials used and the extraction and processing of them that constitute the facilities. On average, the preparation space, and the HVAC, each account for around a third of the impacts of the facilities stage. In the case of the prep space, the impact contribution varies from up to 47 % in the case of TEC to around 15 % in the case of FEC. The prep space contributes by between 27 % and 39 % for most of the impacts (8 out 19), while to the rest it adds between 15 and 26 % (5 out 19 impacts, including CC), and between 40 and 47 % for six out 19 impacts. HVAC contributes by between 16 and 24 % in over half of the impacts (9 out 19), including CC; while in nearly a third of the impacts, HVAC adds between 25 %–34 %. Finally, HVAC contributes between 35 and 43 % in 4 out 19 impacts. The steel required for both the prep space and the HVAC is the main responsible for the contribution of this stages. The growing chamber and the container add on average 21 % and 16 %. For nearly half of the impacts (9 out 19), the growth chamber contributes between 7 and 19 % while in other eight impacts, including CC, it adds between 20 and 26 %. The largest contribution (up to 50 %) is seen at ME and OD. The container itself adds on average 16 % to the impacts of the facilities, with a contribution of between 13 and 19 % for 12 out of 19 impacts, including CC. The floor drains and the germination space together contribute on average 3 %.

3.2.4. Hardware

Fig. 5c exhibits the contribution of the hardware stage, which is mainly led by the lighting system. The contribution of LED lighting is estimated at 74 % on average across all the impacts, varying from 32 % for TEC and 95 % for IR. The lighting system contributes by ~80 % in 10 impacts including CC, where it adds 88 %. For four impacts (FPM, FE, TA & HTc), the LED lighting contributes by between 79 % and 60 %, while adds between 59 % and 40 % for the other four categories, namely FEC, HTnc, MEC and MD. The growing bed components also show an important contribution to this stage, adding on average 16 % of the impacts. The largest contribution is seen in TEC, where this system is responsible for half of the impacts (52 %). Similarly, growing beds are responsible for around ~40 % of the impacts in the case of FEC, HTnc and MEC, while adds around ~20 % in the case of FE, TA, and MD. In the rest of the impacts, the growing bed components contributes <10 %, with the only exception of FPM (14 %). The reservoirs contribute by on average 7 % across all the impacts of this stage, with the exceptions of HTcn and MD, where it is responsible for around 20 %, and for TEC where it adds 12 %. The other three components – external water network, internal water system and racking – contribute by <1 % across all the impact categories.

3.3. Scenario analysis – energy sources and mat materials

The results of the scenario analysis are shown in Fig. 6a for the energy options and Fig. 6b for the mat options. Description of the scenarios and the assumptions are detailed in Section 2.2.6 and summarised in Table 5.

3.3.1. Energy scenarios

As expected, in the case of the energy generation, the use of renewable sources– solar and wind energy - to power the system provide large improvements across most of the environmental impact categories (14 out 19). For example, CC improves by 68 % and 80 % when replacing the use of the UK grid electricity with solar and wind energy, respectively. Using wind power improves other four categories, namely FEC (65 %), HTnc (57 %), TEC (46 %) and MD (8 %). The avoidance of emissions associated to the life cycle of fossil-based electricity generation technologies (they represent ~50 %), especially the direct emissions from operation, are the reasons of the large improvement across most of the impacts. On the contrary, other five impacts increase when using solar energy, which are FEC (31 %), HTnc (25 %), TEC (148 %), MD (63 %) and FWC (276 %). In the case of wind energy, the only impact that increased is FWC (183 %). The use of anaerobic digestion to generate electricity has been also assessed, however little improvements were offered as only four impacts improve, namely CC (39 %), TEC (94 %), PED (90 %) and FD (58 %). The need of precious metals in the solar power technologies (e.g., panels) increase impacts associated to resources and toxicities, as the extraction and manufacturing of those require the use of energy and water, while at the same time emit emissions that has the potential to affect human health, water, and soil.

3.3.2. Mat scenarios

In the case of alternative plant base mats, the scenarios do not offer significant opportunities for improvements; only one out 19 impacts improved when using the cotton mat (MEC) and kenaf (e.g., MEC and HTnc); all the rest of the impacts increased. For example, in the case of CC, using kenaf and cotton increases the impacts by 8 % and 29 %, respectively. For jute, the scenario increases the impact by between 2 and 8 %. The main reason of this is the production of raw materials (e.g., cotton, kenaf) and manufacturing of mats, which in this case is assumed (as proxy) as the production of textiles. In the case of the base scenario, the current system uses recycled wool, but only information for CC was obtained from manufacturers. For jute, virgin and recycled, information from manufacturers was used, but again only accounted for CC.

3.4. Validation

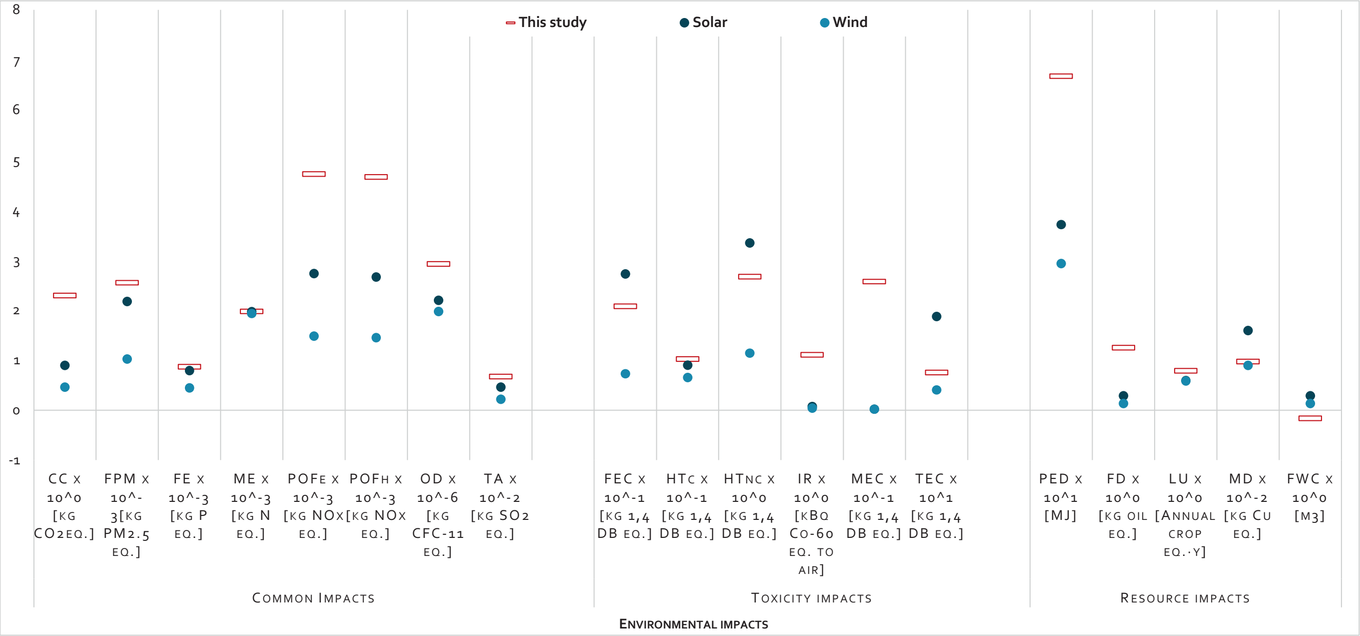
As seen in the introduction (Section 1), as far as the authors are aware, there are no studies assessing the environmental impacts of any kind of aeroponic production systems nor about microgreens such as pea shoots. Therefore, to validate the results, studies about vertical farming found in the literature are used, which mainly use leafy greens such as lettuce and herbs. Additionally, other production methods such as greenhouse and open field are included, in addition to the average impacts of lettuce in the UK. To account for the variation of the crops, dry basis is used, as has been done by previous studies (Wildeman, 2020). There are not many studies assessing a full set of environmental impacts; therefore, only a selection of impacts is available for comparison and are presented in Fig. 7 for CC and in the Supplementary information in Table S1 for the rest of the impacts. Additionally, the results are validated and compared by nutrient content against different production methods, looking at energy content (calories) and proteins. See details in Fig. S1 in the Appendix A.

When comparing with hydroponic systems, the CC of the base scenario is nearly a third of the mean across the hydroponic studies (0.64 kg CO_2eq./kg product (DM)), ranging from nearly four times higher CC than Martin and Molin (2019) to nearly five times lower CC than Al-Chalabi (2015). Using solar energy in the aeroponic system improves the impacts; the system shows almost the lowest CC (up to 12 times lower), except against Martin and Molin (2019), where the solar-powered aeroponic system still shows 54 % higher impacts. When comparing with greenhouse production systems, all the aeroponic container system scenarios exhibit lower CC than the mean across the studies (0.62 kg CO_2eq./kg food (DM)).

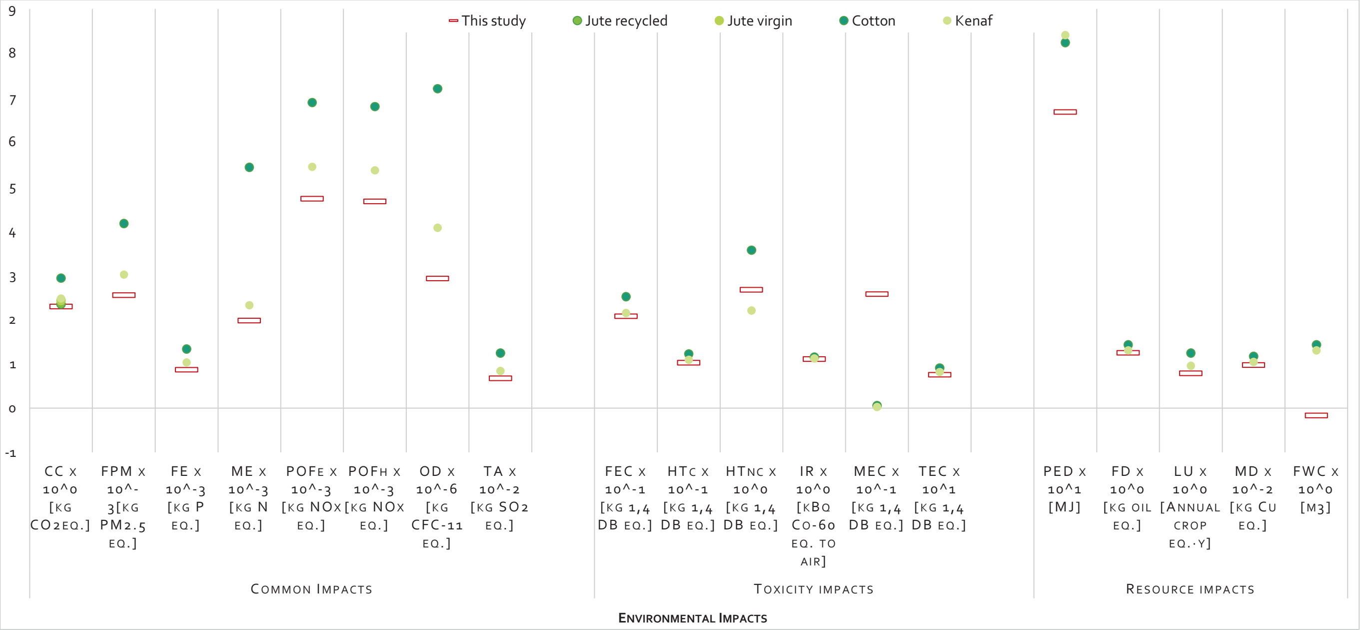
In general, the results of this study are within the range of those found in literature across all the productions systems (Bartzas et al., 2015; Fiteinis and Chatzisymeon, 2016; Frankowska et al., 2019; Plawecki et al., 2014; Romero-Gámez et al., 2014). In terms of CC, the base scenario of aeroponic container system ranks 11th across the 17 studies, while when using the 2021 UK energy grid, the CC is in the 10th position. However, when using solar energy, the aeroponic container system shows some of the lowest impacts, sitting in the 8th position after almost all the studies assessing the open-field systems. Finally, when comparing the CC of aeroponic production systems with the average impacts of UK lettuce, which includes 59 % imports, the results show lower CC than the UK average, with impacts varying by between 1 %, in the case of the baseline scenario, to 2.62 times lower impacts in the case of solar powered aeroponic container system.

3.5. Contribution to local food systems: food imports v/s local aeroponic container production

As presented in the introduction, there are several claims about the contribution of vertical farming to reduce impacts to the environment while providing opportunities to increase local food security. This section looks



a) *Scenario analysis of energy sources*



b) *Scenario analysis of mat options*

Fig. 6. Comparison of the environmental impacts of the scenario analysis.

to provide evidence to some of these claims by assessing the impacts to climate change (CC) of food imports versus aeroponic.

Aeroponic container farming systems are mainly used to produce herbs and microgreens. In the UK, these food products are grown locally in greenhouses, but when imported, they mainly come from Spain, Kenya, Jordan, and Mexico (CBI, 2020). Due to the fragile nature and short life span of these products, they are mostly transported by air freight (see Table 7), but some could be also imported through refrigerated lorries. To understand the environmental benefits, it is important to put the previous results (see Section 3.1) in context, in terms of implications of importing foods and the overall impacts of producing and distributing them to the UK. Hence, this section first compares the impacts of the aeroponic container system

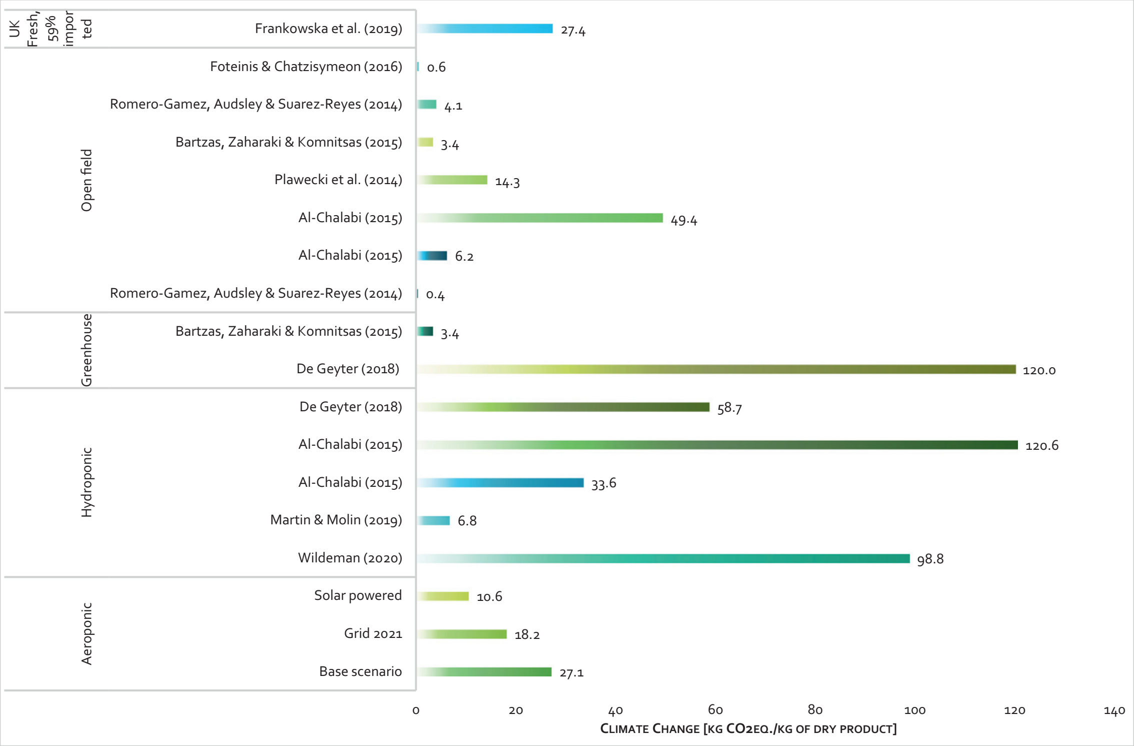


Fig. 7. Validation of climate change (CC) impact of pea shoot produced by aeroponic container system in comparison with hydroponic system, greenhouse, and open field. Results presented per kg of dry mater (DM). See appendix Table A1 for a larger set of indicators.

against the impacts from transporting herbs and microgreens to the UK using different transport modes. Table 7 summarises the assumptions made for the analysis.

As seen in Fig. 8a, if only the impacts of transporting herbs and microgreens is assessed, the results show that aeroponic container production system has lower CC than the impacts of transporting food from Kenya by road, using either refrigerant (R134a & RCO_2), and by air freight, and by air freight from Mexico, which represents between 15 %–24 % (Kenya) and 70 % (Mexico) lower impacts. On the other hand, the transportation of food from closer places, such as Spain and Jordan, still shows lower impacts than the production of microgreens from the aeroponic container system when using the baseline (2017), while the 2021 grid scenario shows nearly the same impacts than the impacts of transport by air from Jordan (1.52 vs 1.57). However, when comparing with solar- and wind-powered aeroponic container systems the results vary. For example, the solar-powered aeroponic system exhibits lower impacts than transporting food from Mexico, Kenya and Jordan, however still higher impacts than the transport from Spain. Wind-powered aeroponic system shows the lowest impacts. Hence, regardless the impacts of the herbs and microgreens production methods, for long distance travel the aeroponic container system is a viable and preferred option, in particular when powered by wind, showing lower impacts than any mean of transport assessed; therefore, it does contribute to reduce impacts of the food system.

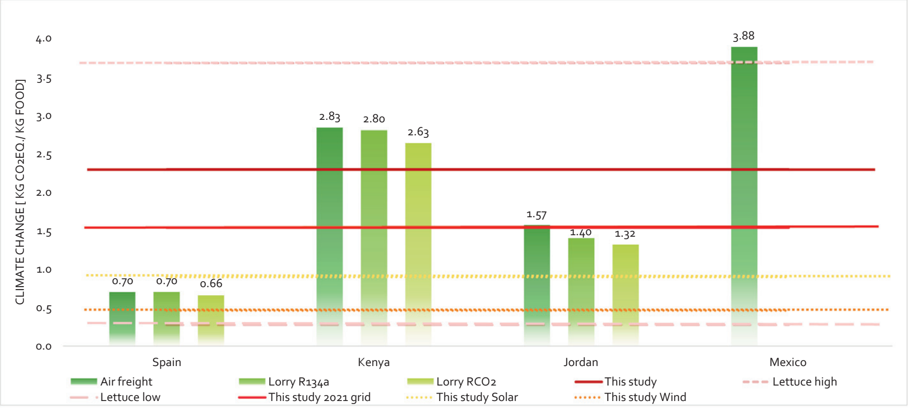
Table 7
Distance of imported herbs in the UK by country and mode of transport.

Mode of transport	Carbon intensity [kg CO_2eq./tkm][a]	Spain [km]	Kenya [km]	Jordan [km]	Mexico [km]
Lorry[b]		2500	10,000	5000	–
[Refrigerated CO2]	0.263				
[Refrigerated R134a]	0.28				
Air freight[c]	0.436	1600	6500	3600	8900

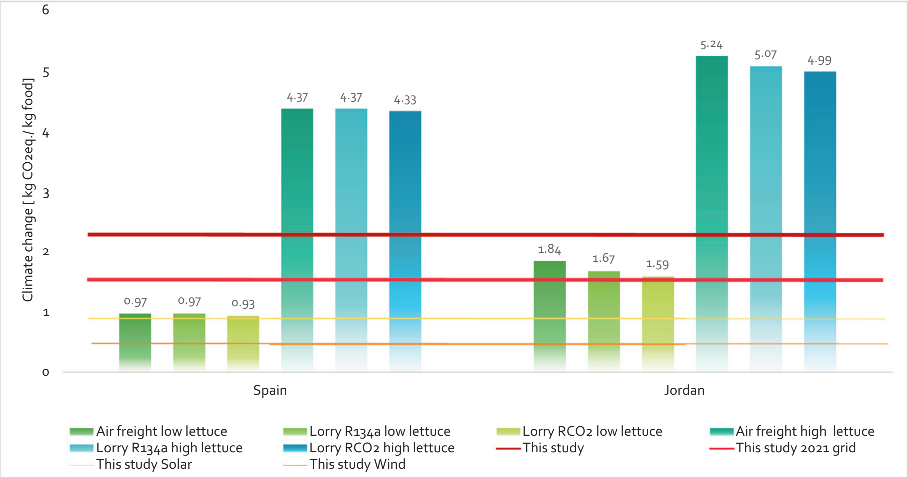
[a] Carbon intensity is sourced from Ecoinvent 3.6 (Moreno Ruiz et al., 2019).
[b] Road routes were calculated using Google maps https://maps.google.co.uk/.
[c] Flight routes were estimated using https://flight-distance.com/.

Fig. 8b compares the production and transportation of imported food (salads) from Spain and Jordan (best scenarios) versus the impact of producing food (salads) by aeroponic container system; for comparison two representative food production methods are used: high (3.67 kg CO_2eq./kg product) and low (0.27 kg CO_2eq./kg product) lettuce production systems, based on global data. The aeroponic container system provides a competitive performance when the food production method is high, regardless the location and transportation type. When comparing with the low impact lettuce, aeroponic container system is not as competitive, especially when using the UK grid electricity; it only shows lower CC than the lettuce from Jordan when using the 2021 UK grid scenario, but still higher impacts than low lettuce from Spain, regardless the mode of transport. However, the solar- and wind-powered aeroponic container systems show the lowest impacts; the solar-powered system exhibits ~10 % lower CC than importing lettuce from Spain by any transport type, while in the case of wind-powered aeroponic container system, the impacts are nearly half (0.45 vs 0.97) of those from imported food from Spain.

It is then important to determine parameters to aid decision making toward when aeroponic container systems will have a preferable advantage. Fig. 9 helps to determine the breaking point when aeroponic container system will offer a competitive advantage from imported food. It is clear that aeroponic container system will be better than any imported food with similar or greater carbon intensity than the aeroponic container system itself, estimated at 2.29 kg CO_2 eq./kg of pea shoot. So, when using the lowest food impact value, "low lettuce", for the three modes of transport options (air freight, lorry with refrigerants R134a and RCO_2), the aeroponic container system will be equal or better with the following distance: 2863 km in the case of air freight, 4458 km in the case of using lorry with R134a as refrigerant and 4747 km for lorries with CO_2 as refrigerant. The solar-powered aeroponic container system nearly halves the



a) Comparison of impacts of aeroponic production method against the impacts of transportation from different importing locations



b) Comparison of impacts of aeroponic production method against the impacts of production and transportation from imports

Fig. 8. Comparison of climate change impact between aeroponic container system and the transportation and production of food in example locations; two different refrigerant systems are used for comparison in the case of lorries.

distances as seen in Table 8, while for the wind-powered aeroponic container system the distances get constraint to almost national level only (<658 km).

To contextualise the findings, the following maps (Fig. 10a–c) exhibit the critical distances – using London as a starting point – for which aeroponic container system powered by 2021 UK power grid, solar power, and wind power, are better than importing food, respectively. The figures show the service areas of R134a and RCO_2 refrigerated lorries travelling along roads, and a buffer area for air freight. For example, Fig. 10a shows importing food from the whole of Europe, some places in the middle east, and Northern Africa (specifically Morocco, Algeria, Tunisia, and Libya), has less impacts than using 2021 UK grid-powered aeroponic containers. This is valid for road (both refrigerated lorry types) and air freight. On the other hand, Fig. 10b shows that it is better to use solar-powered aeroponic containers than to import foods (in this case salads) from North Africa, and some places in East Europe and the Balkans, for all transport modes. Finally, Fig. 10c shows that if wind-powered aeroponic containers are used, producing in this way is better than importing food from almost any part in Europe, except for the North of France, Belgium, Netherlands, and a small part of West Germany (for all transport modes). These findings provide key examples when understanding the opportunities of urban farming methods, especially for delicate and short-lived crops such as salads and herbs, which are the target crop for such container farms. The authors however anticipate that the methodology evidenced for vertical farm LCA in this paper will be replicable to bigger vertical farms, which are currently growing larger crops ranging from strawberries, to tomatoes, to tree seedlings and mushrooms. More needs to be done to quantify the impacts of this nascent industry within all the above crops, especially as vertical farming is expanding so rapidly. Good environmental practice must be established early to ensure the sector provides net positive contributions to the climate crisis and regional food security, rather than a net negative.

4. Conclusions

This research has evaluated for the first time the environmental impacts of an aeroponic container farm system through the assessment of 19 environmental impact categories. Among other categories, for example, it was estimated that the production of 1 kg of pea shoot accounts for 1.52 kg CO_2eq. when using electricity from the 2021 UK energy grid.

The analysis also shows that the energy required by the system, and the source of this energy, are the main contributors to almost all the impact categories assessed. Therefore, the selection of the energy source is critical to improve the environmental performance of food grown in aeroponics. On this note, the study proves that the decarbonization of the UK energy grid

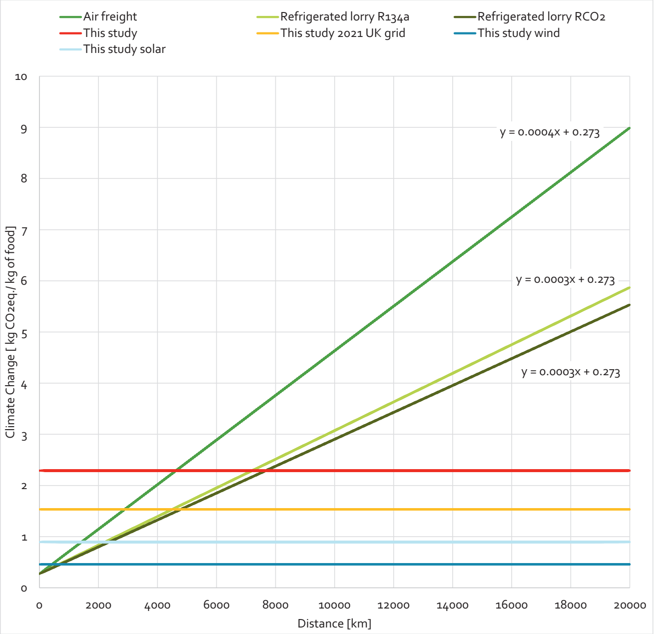


Fig. 9. Perspective of climate change of production of pea shoot by aeroponic container system against imported lettuce by different mode of transport.

provides large opportunities to reduce the impacts of the food grown by aeroponics (up 72 % reductions), and that the use of 100 % renewable sources such as solar- and wind-power renders the system competitive with all the similar products imported in the UK, most of the hydroponic grown salads found in literature, and some of the greenhouse and open field salads grown elsewhere.

Furthermore, this research reveals that although the use of a ‘Green Tariff’, equivalent to zero GHG emission, would clearly reduce the impacts to climate change (by 83 %); there are currently several uncertainties about how to account for the green tariff's emissions and the reliability of these mechanisms. Direct access to renewable power is therefore suggested as a priority for users of such production systems.

In relation to food security, the study demonstrates that aeroponic systems in urban areas have potential to contribute to local food security, by offering stability and resiliency of supply, availability, and all-year accessibility to nutritious and fresh foods which could reduce or avoid the dependency on imports, and that offers a competitive environmental performance. However, it is important to note that vertical farming is used for growing specific types of crops, mainly herbs and salads, with an average high of 40 cm (Kozai et al., 2016). Other crops that are being currently explored include berries, peppers and tomatoes, and flowers. Hence, vertical farming, in this case aeroponic, does not intend to replace conventional agriculture, but supplement the food systems with high-value crops (Kozai et al., 2016). This study supplies a valuable methodology for impact assessment of vertical farms (large and small), as the industry lacks an established methodology within the academic literature. Such quantification is key if this young industry is to fulfil its stated promise to reduce the environmental impact of fresh produce, rather than increase it. This research provides evidence for policymakers and decision makers to understand the benefits and trade-offs of aeroponics when compared with imported foods, showcasing examples of when the aeroponic production system delivers foods with competitive (and sometimes better) environmental performance than similar imported products. The methodology can also be reapplied within different countries to evaluate the value of utilising an aeroponic production system for supplying fresh produce, representing a valuable tool for evaluating the impact of vertical farming projects before they are built. Additionally, this study provides information for aeroponic farming experts to look for improvement opportunities such as energy saving measures to reduce the impacts and costs of the systems.

Table 8
Critical distance to define the benefits provided by aeroponic container system using low lettuce values as reference and three transport modes.

	Distance [km]		
	Air freight	Refrigerated lorry R134a	Refrigerated lorry RCO_2
This study 2017 UK grid	4629	7208	7673
This study 2021 UK grid	2894	4506	4798
This study Wind	397	618	658
This study solar	1394	2171	2312

Another important aspect, and one of the limitations of this study, is the affordability issue of aeroponic grown foods, in particular in times of high-energy costs and potential energy shortages and blackouts. Future work will need to explore the economic and social sustainability aspects, to offer a more comprehensive assessment of this system. Finally, this study considers a monocropping system, only growing pea shoot, as at the time of the assessment this was the most studied crop. Future work will include a multi-grown approach including a diverse portfolio of crops grown in vertical farms of different scales.

CRediT authorship contribution statement

XSR: Funding acquisition; Conceptualization, Methodology, Formal analysis, Software, Writing- Original draft preparation, Review & Editing final draft, Project administration. **BR**: Conceptualization; Data collection, Visualization; review & editing, manuscript. **TO**: Data collection; **FJV**: Visualization, Software, review & editing, manuscript. **JF**: Conceptualization; Data curator, Funding acquisition; Visualization; review & editing, manuscript.

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Data availability

All the inventories and data use are displayed in the main document.

Declaration of competing interest

XSR reports financial support was provided by Innovate UK. JF, BR, TO report a relationship with LettUs Grow Ltd. that includes: board membership, employment, and equity or stocks. FJV does not have any conflict of interest.

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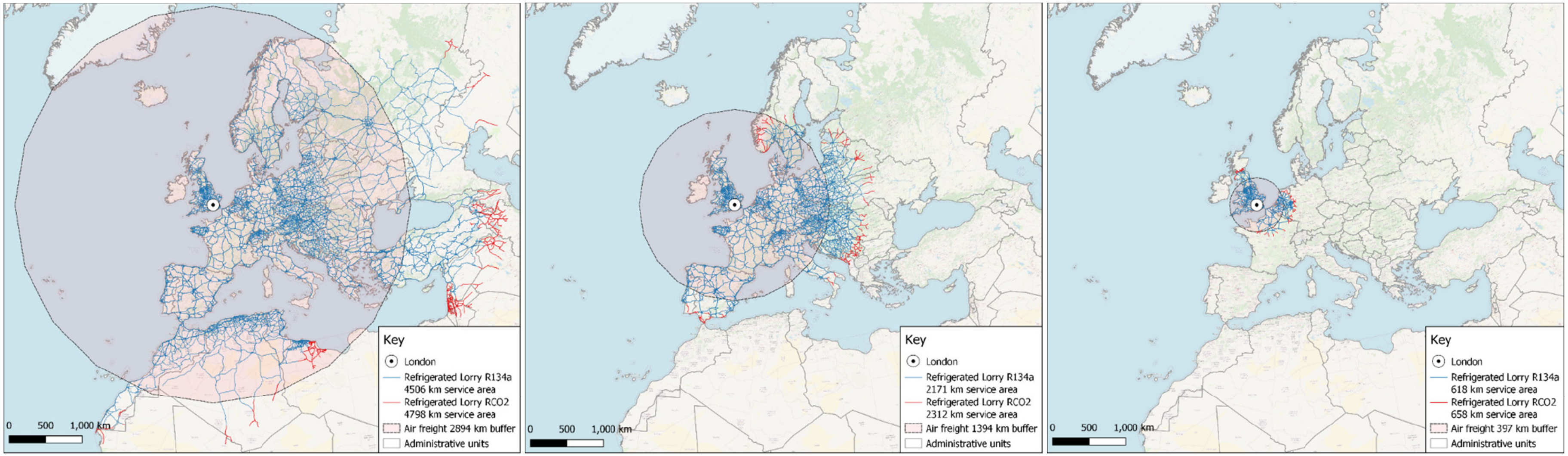
Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.160420.



a) 2021 UK grid-powered aeroponic containers

b) Solar-powered aeroponic containers

c) Wind-powered aeroponic containers

Fig. 10. Critical distances from London as a starting point using 2021 UK grid-powered aeroponic containers (a), solar-powered aeroponic containers (b), wind-powered aeroponic containers(c) (all scenarios used low-lettuce values as a reference).

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