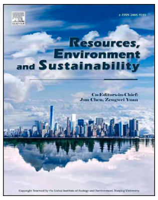
Resources, Environment and Sustainability 25 (2026) 100335

Contents lists available at ScienceDirect

Resources, Environment and Sustainability

journal homepage: www.sciencedirect.com/journal/resources-environment-and-sustainability



Research article

Adopting circular strategies in different vertical farms yields comparable environmental impact reductions

Alicia Invernón-Garrido[a], Anna Petit-Boix[a], Xavier Gabarrell[a,b], Michael Martin[c,d], Joan Muñoz-Liesa[c,e,*]

[a] *Sostenipra Research Group (2021 SGR 00734) Institute of Environmental Science and Technology (ICTA-UAB), Unidad Excelencia Maria de Maeztu CEX2024001506-M, Universitat Autònoma de Barcelona (UAB), Campus UAB, Bellaterra, 08193, Barcelona, Spain*
[b] *Department of Chemical, Biological and Environmental Engineering, Universitat Autònoma de Barcelona (UAB), Campus UAB, Bellaterra, 08193, Barcelona, Spain*
[c] *Department of Sustainable Development, Sustainability Science and Engineering, School of Architecture and the Built Environment, Royal Institute of Technology (KTH), Sweden*
[d] *Life Cycle Management, Sustainable Society, IVL Swedish Environmental Research Institute, Stockholm, Sweden*
[e] *Life Cycle Assessment Research Group, Agroscope, Reckenholzstrasse 191, 8046, Zurich, Switzerland*

ARTICLE INFO

Keywords:
Life cycle assessment
Urban agriculture
Vertical farms
Circular economy
Technological maturity

ABSTRACT

Vertical farms are an emerging industry that can enhance urban food self-sufficiency but must align with environmental goals. This study assesses whether circular economy strategies improve the environmental performance of two European VFs—VF_1 in Spain and VF_2 in Sweden—with differing technological maturity and geographical contexts. Life cycle assessment shows that energy use is the main contributor to environmental impacts, accounting for up to 88% in both cases. Circular strategies such as closed-loop irrigation, waste heat reuse, and material recycling reduce impacts by 7–77%. To compare their maturity level, scenario analyses (Current, Linear, Improvement) reveal that VF_1 offers higher potential for future gains (e.g., 29% reduction in global warming impacts), compared to VF_2 (34% reduction potential). These findings underscore the relevance of broader changes in upstream production systems, technology maturity and site-specific conditions in shaping the sustainability of VFs, and emphasize the need for further research into context-dependent factors influencing their environmental performance.

1. Introduction

Food security is crucial in a context of increasing population, continuous urbanization, and climate change (Li et al., 2020). Generally, food is produced beyond urban areas, sometimes even overseas, creating long and ineffective supply chains. Urban agriculture (UA), in contrast, produces food near the point of consumption in urban or peri-urban areas, which reduces food transportation and develops local economies (Kortright and Wakefield, 2011; Specht et al., 2014), while potentially reducing the environmental impacts of food systems (Hu et al., 2025).

UA encompasses several methods and approaches, one of which is vertical farming (Despommier, 2009). Vertical Farms (VFs) are indoor food production systems where crops are vertically or horizontally stacked in a controlled environment that strictly monitors growth conditions, including temperature, humidity, CO_2, lighting, water and nutrients (Butturini and Marcelis, 2020; van Delden et al., 2021). In recent years, the number of VFs has dramatically grown (Weidner et al., 2022), especially to produce leafy greens and herbs, although they currently represent a small percentage of the food supply. VFs have attracted significant interest and funding from all over the world as a means of securing food supply, extending seasonal availability of regional foods, reducing the need for resources, agricultural land and transportation, and producing more sustainable foods (Martin et al., 2023a; van Delden et al., 2021). However, while VFs are helping to improve hydroponic technologies, the claims around their environmental sustainability can be misleading. Many of these systems actually follow a linear approach to resource use consumption, as they mostly rely on imported resources and lack recycling or reuse strategies (Martin et al., 2022). Coupled with the high energy requirements of artificial

---

* Corresponding author. Department of Sustainable Development, Sustainability Science and Engineering, School of Architecture and the Built Environment, Royal Institute of Technology (KTH), Sweden.
E-mail addresses: joan.munozliesa@agroscope.admin.ch, jmunozliesa@gmail.com (J. Muñoz-Liesa).

https://doi.org/10.1016/j.resenv.2026.100335
Received 15 September 2025; Received in revised form 31 March 2026; Accepted 31 March 2026

lighting and climate control, this raises concerns regarding their overall environmental sustainability (Blom et al., 2022; Graamans et al., 2018; Li et al., 2020).

However, as an emerging industry, VFs hold great potential to experiment with resource efficiency strategies in their closed, controlled environment. Being at the early stages of development, there is room for rethinking their relationship with natural resources and situating themselves as examples of sustainable resource management amongst more consolidated food production systems. For this reason, research has started to explore the main challenges and opportunities of environmental improvements in VFs; for instance, through the implementation of circular economy (CE) strategies (Muñoz-Liesa et al., 2020; Specht et al., 2014; van Delden et al., 2021). Some studies have already assessed the potential of CE to reduce the environmental impacts of VFs. Prominent examples feature the symbiotic relationships between VFs and their surroundings to exchange residual energy, water and nutrient flows (Blom et al., 2023; Chance et al., 2017; Martin et al., 2019). Nevertheless, the application of CE strategies remains highly variable due to differences in VF scale, type, available capital, and local environmental factors that directly affect their feasibility and effectiveness within each VF (Kalantari et al., 2018). This leads to considerable heterogeneity in the CE adoption levels across VFs; that is, the extent to which each VF has developed, adapted and improved available CE strategies and technologies within its own controlled environment.

Ideally, combining a wide range of CE strategies in every existing VF or other UA types is expected to reduce the environmental impacts of the production system (Qiu et al., 2024), but every case needs an individual assessment (Rufí-Salís et al., 2021). Acknowledging VF heterogeneity and CE adoption levels across VFs can prevent potentially misleading conclusions around UA (e.g., Hawes et al., 2024). For instance, Martin et al. (2023a) illustrate the progressive implementation of improvement strategies in a Swedish VF, with a starting point that may be different in other contexts. Not only is the trajectory of the VF towards circularity important, but also the gap between current efforts and the CE adoption potential. We pose that addressing the environmental impact reduction potential of the CE adoption gap can reveal the maturity level of a VF. This can help to minimize the environmental impacts of the VF industry and support the prioritization of CE strategies.

This study aims to analyze the extent to which CE strategies can improve the environmental sustainability of two European VFs, considering their CE adoption level and geographical context. We address the CE adoption gap from a life cycle perspective in two steps. We first assess the environmental performance of the VFs at their initial linear stage—where no CE strategies are applied—and evaluate environmental improvements once CE strategies are progressively implemented to reach their current CE adoption level. We then estimate the potential impact reductions of adopting additional strategies in the future, which shall reveal the CE maturity of the VFs. By doing so, our study provides practical recommendations for the emerging VF industry, enabling it to reassess its current practices and consolidate as a food production industry that can transform its relationship with natural and urban resources in the future.

2. Methodology

The following sections outline the structure of the analysis: Section 2.1 introduces the two VFs assessed in this study; Section 2.2 details the life cycle assessment (LCA) methodology; and Section 2.3 presents various CE strategies to be modelled in the selected VFs.

2.1. Case study description

The VFs under study are located in two different geographical areas: Barcelona, Spain (VF_1), and Stockholm, Sweden (VF_2). This enables the evaluation of their environmental impacts considering local factors such as access to renewable resources, transportation distances, and climate conditions. Doing so offers insights into the adaptability and sustainability of VF practices under different environmental conditions. Additionally, the two VFs present different CE adoption levels, which depend on the stage of technological development. Heterogeneity is also represented in the different crop types, with basil and lettuce as the target crops in VF_1 and VF_2, respectively. This is deemed compatible with the study, as we do not aim to compare the impacts of producing the same crop in different contexts, but to trace the CE adoption potential and associated impacts in two contrasting VFs.

2.1.1. Vertical Farm 1 (VF_1)

VF_1 was created in 2018 as a small-scale VF. After reaching full capacity with 20,000 plants by mid-2021, it was relocated to a larger facility in an industrial zone within the Metropolitan Area of Barcelona, where it continues to expand. The VF has 3024 m^2 of floor space and operates year-round, with production evenly distributed (see Table 1). A variety of leafy greens and herbs are cultivated, such as lettuce, basil and other aromatics. For this study, we assessed the basil crop production, as it represents the main marketable products of the farm. As such, VF_1 has a potential maximum production capacity of 30 tons of basil per year. The production process starts in the Germination room and once plants are germinated, they are placed in horizontal shelves in the Growth room. Finally, they are transferred to the Vertical Tower room, where they grow in vertical tower systems. The plants are cultivated using a hydroponic drip system with coconut fiber as the substrate and vertical LED lights. Climate conditions such as light, temperature and humidity are controlled and optimized for basil production in both the Growth and the Vertical Tower rooms. Once harvested, basil is marketed in various forms, such as fresh and dried herbs, and ready-made products. Packaging options range from paper or plastic bags to reusable plastic bulk containers, depending on the final consumer.

VF_1 implements various circularity and improvement practices

Table 1
Overview of the main characteristics of the two VFs under study.

	VF_1	VF_2
Location	Metropolitan Area of Barcelona, Catalonia, Spain	Between Stockholm and Gothenburg, Sweden
Operative since	2018	2017
Total floor area	3024 m^2	7000 m^2
Cultivation area	668 m^2	1700 m^2
Main crop assessed	Basil	Lettuce
Annual production capacity	~30 tons of basil (~10t during 2024)	~520 tons of lettuce
Cultivation system	Hydroponic drip system with coconut fiber substrate; horizontal shelves + vertical towers	Hydroponic system with coconut fiber and peat plugs; vertical cultivation towers
Production process	Germination (7 days, no light) → Growth room (15–21 days) → Vertical towers (15–21 days)	Germination (high humidity, 1 day) → Growing room (≈14 days) → Vertical towers (14–21 days)
Lighting & climate control	Vertical LED lighting; controlled temperature and humidity	Horizontal LED lighting; controlled climate conditions
Circular economy strategies currently applied	Closed-loop irrigation (S3), condensed water recovery (S4), material recycling (S7), solar panels (S8)	Closed-loop irrigation (S3), condensed water recovery (S4), material recycling (S7),
Packaging	Paper or plastic bags; reusable plastic bulk containers	Bags and reusable plastic boxes
Functional unit in LCA	1 kg of fresh basil ready for commercialization	1 kg of fresh lettuce ready for commercialization
Data source	Primary data (2023–2024, extrapolated to annual production figures)	Secondary data from previous LCA studies: Martin et al. (2023b)

within its operations, including a closed-loop irrigation system and a condensed water recovery mechanism through a dehumidifier to minimize water usage, material recycling strategies, and the use of solar panels for energy generation.

2.1.2. Vertical Farm 2 (VF_2)

VF_2, founded in 2017, has since evolved into a large-scale VF located between Stockholm and Gothenburg. It has 7000 m^2 of floor space, dedicated exclusively to lettuce production throughout the year. In this system, lettuce is first seeded in plugs of coconut fiber and peat and then transferred to a high-humidity Germination room. Then, they are moved to a Growing room, where they reach a height of 8 cm. Finally, they are transferred to vertical cultivation towers before harvesting. Once harvested, the lettuce is washed and packaged in bags and reusable plastic boxes. All information and inventory data from this farm has been retrieved from previous assessments based on Martin et al. (2023b).

VF_2 also incorporates CE strategies into its operational framework, encompassing a condensed water recovery system, material recycling, and closed-loop irrigation. According to Martin et al. (2023b) and personal communications with the farm owners, other improvement strategies are currently being explored in VF_2, such as reusing residual heat from the system, and implementing circular strategies for the growing medium within the VF to reduce their impacts.

2.2. Life cycle assessment

The environmental impacts of the VFs are evaluated using the life cycle assessment (LCA) methodology (ISO, 2006). LCA is a widely used, standardized method for assessing the environmental performance of products, services and systems, enabling comparisons between different processes based on their overall environmental impacts throughout their life cycle. The use of LCA in VFs offers transparent, science-based metrics that support a more strategic and informed approach to sustainability (Martin et al., 2023b).

2.2.1. Goal and scope definition

The aim of this study is to evaluate the extent to which the environmental performance of two European VFs can be improved through the implementation of CE strategies, considering their CE adoption level and geographical context.

Comparing VFs can be challenging, as they often do not produce the same outputs. Thus, rather than directly comparing both VFs, we focus on assessing their CE maturity level compared to a linear system, which depends on the effectiveness of the CE strategies each VF is currently implementing, and to explore the potential for additional case-specific improvements to reduce their environmental impacts. Both VFs are analyzed using a functional unit (FU) of 1 kg of fresh product; for VF_1, FU_1 is the production of 1 kg of basil ready for commercialization, whereas for VF_2, FU_2 is the production of 1 kg of lettuce ready for commercialization.

The study follows a cradle-to-gate perspective, including all upstream processes involved in cultivation, material inputs, energy usage, transportation of materials, harvesting, packaging and end of life (EoL) of waste produced within the VFs (Fig. 1). Transport of the product to consumers, use and post-consumer waste handling are excluded from the system boundaries. The evaluation also incorporates all infrastructure and supporting systems of the VFs, such as LEDs, pumps, pipes and hoses, tanks, and other necessary electronics. The building envelope is not considered, as both VFs are installed within existing buildings.

2.2.2. Life cycle inventory

Data for VF_1 consists of primary data sourced directly from the VF throughout the year 2023, initially based on theoretical projections for that year. Between February and May 2024, the data was reviewed and updated to adjust the theoretical estimates to the production recorded from November 2023 to February 2024, providing a more accurate representation of the VF performance. Data for one full year was unavailable due to ongoing improvements and technical difficulties within the farm. While yield is a critical parameter that determines the total environmental impacts of the VFs, our assumptions do not compromise the goal of comparing the CE adoption levels in each VFs.

Data for VF_2 consists of secondary data sourced from Martin et al. (2023b), which was revised and supplemented with additional information for this study to ensure data harmonization and equivalent system boundaries with VF_1. Data for both VFs was adjusted to align with the same system boundaries and classified into the following categories:

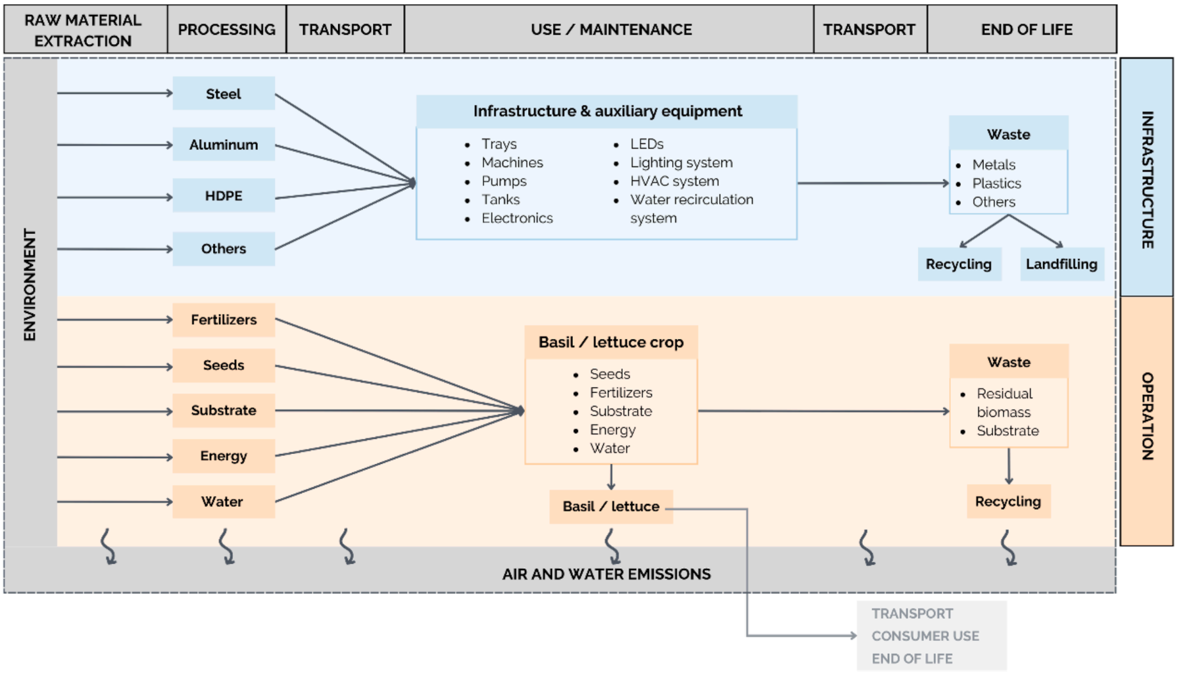


Fig. 1. System boundaries for the environmental life cycle assessment of VF_1 and VF_2. Dashed box represents the boundaries of the system.

seeds and substrate, fertilizers, other materials, water, energy, infrastructure, packaging, transport and waste handling. Background life cycle inventory (LCI) data to match all materials and processes was obtained from ecoinvent v. 3.9.1 (Wernet et al., 2016). More detailed information on the LCI can be found in Tables S1 and S2 of the Supplementary Materials.

Some assumptions were necessary to fill the gaps in the available data. For VF_1, data on the quantities of cleaning agents, packaging materials, and the required operational machineries within the facility were proportionally scaled to the FU using inventory data from Martin et al. (2023b). Such gaps were filled to make sure inventory datasets were updated and harmonized across VFs, using the same foreground categories, system boundaries and system completeness (i.e. level of inventory details) is used. EoL considerations for all materials used within the VF were assumed to involve recycling processes. Assumptions for VF_2 are detailed in the Supplementary Materials section of Martin et al. (2023).

To model the CE strategies, secondary data was used as described in section 2.3. Further detail can be found in the Supplementary Material, where for each of the CE strategies, the modelling approach is given when adapting secondary data to each of the VFs assessed. The integration of all CE strategies in all scenarios considered (see 2.3.3) was developed at the inventory level, considering the synergies between strategies (e.g., closed-loop irrigation reduced the water demand and this was considered when modelling rainwater flows).

2.2.3. *Impact assessment*

Life cycle impact assessment (LCIA) was conducted following the mandatory classification and characterization steps. For this assessment, the LCIA Scores tool was used to perform the LCIA (Muñoz-Liesa et al., 2024). LCIA Scores is based on a Microsoft Excel tool with built-in macros that calculates the impact assessment results for biosphere and technosphere processes using ecoinvent 3.9.1 as background data following a cut-off approach and impact assessment methods as implemented in Brightway 2.5 (Mutel, 2017). We studied the following ReCiPe 2016 Midpoint (H) (Huijbregts et al., 2017) impact categories as suggested by similar UA and VF studies to cover VF impacts and the influence of CE strategies applied (Rufí-Salís et al., 2020, 2021; Martin et al., 2022; Dorr et al., 2021; Van Delden et al., 2021). These included Global Warming (GW, kg CO_2 eq), Freshwater Eutrophication (FE, kg P eq), Marine Eutrophication (ME, kg N eq), freshwater, marine and terrestrial ecotoxicity (ET, kg 1,4-DB eq), Terrestrial Acidification (TA, mol H^+ eq), Mineral Resource Scarcity (MRS, kg Cu-eq) and water consumption (WC, m^3 water-eq consumed), along with the Cumulative Energy Demand (CED, MJ) (Frischknecht et al., 2007).

2.3. *Identification and modelling of CE strategies*

This section outlines the methodology used to identify and model CE strategies aimed at reducing the environmental impact of VFs.

2.3.1. *Identification of strategies through literature*

There is a wide range of management strategies aiming to reduce the resource use and environmental impacts of agricultural systems. As VFs are new food production systems, modelling strategies that directly apply to them is crucial, but a comprehensive overview is missing. To evaluate the potential environmental benefits of CE implementation, a non-systematic literature review was first conducted to identify suitable strategies for VFs. Initially, key terms such as "urban agriculture," "vertical farming," "sustainability," "circularity," "resource efficiency," “case study” and "life cycle assessment" were employed in Google Scholar and Scopus to identify a wide range of articles discussing sustainable practices published until March 2024. Articles focusing on real-case VF studies, LCA and those with an LCI available were prioritized to facilitate the environmental assessment of the CE strategies. Other relevant sources were found by following a snowball approach, tracing citations and references within the initial set of articles (Badampudi et al., 2015). Additionally, communication with experts in the field provided further insights and strategies.

2.3.2. *CE strategies assessed*

Fourteen CE strategies were identified and synthesized (see Table S3 of the Supplementary Materials). These strategies were classified into six categories: optimization of growing media, minimization of tap water input, replacement of conventional fertilizers, reuse of CO_2 and waste heat, material recycling, and utilization of renewable energy. From these, a subset of eight strategies, with at least one representative from each category, was selected to create scenarios and evaluate their impacts. Overlapping strategies within the same category were excluded (i.e., if growing media is replaced by compost, it cannot simultaneously be replaced by beer-derived-residue). CO_2 reuse was not evaluated due to the lack of modelling data and its building specificity. The use of recycled materials for the infrastructure and auxiliary systems was not considered since the VFs under study were already built following the modelling criteria from previous assessments (Martin et al., 2023b).

2.3.3. *Scenarios assessed*

Several scenarios were built and analyzed through LCA to evaluate their environmental performance (Table 2). First, a Current Scenario (CS) using the data provided by each VF allowed for an assessment of

Table 2
Overview of vertical farming scenarios and improvement strategies.

N.	Scenario	Description	References
CS	Current Scenario	Scenario with unmodified data. The following CE strategies are already being applied in each VF: (1) VF_1: S3, S4, S7, S8. (2) VF_2: S3, S4, S7.	Primary data from VF_1 and Martin et al. (2023)
LS	Linear Scenario	Scenario with no CE strategies (S1-S8).	Modelled in this study.
S1	Compost	Replacement of substrate by compost produced from organic municipal solid waste.	Barrett et al. (2016); Martin et al. (2019); Rufí-Salís et al., 2021.
S2	Rainwater harvesting system	Collection of rainwater from the rooftop of the facility to be used as the main water source within the VF.	Jurga et al., 2021; Rufí-Salís et al., 2020; Sucozhañay et al., 2024.
S3	Closed-loop irrigation system	Nutrient recirculation by re-introducing the leached water and nutrients from plants back into the same system.	Rufí-Salís et al., 2020, 2021; Savvas and Gruda (2018).
S4	Condensed water recovery system	Collection of condensed water from the air with a dehumidification system and reintroduction into the system.	De Gelder et al., 2012; Opdam et al., 2005; Tsafaras et al., 2022; Van Kooten et al., 2008.
S5	Struvite	Replacement of conventional phosphate fertilizers with struvite recovered from wastewater treatment plants.	Arcas-Pilz et al., 2022; Rufí-Salís et al., 2021.
S6	Waste heat	Reuse of waste heat generated in the VFs in nearby facilities. Waste heat is assumed to be 15% of total energy used in the VF.	Blom et al., 2023; Gentry (2019); Graamans et al., 2018; Martin et al., 2019, 2022.
S7	Recycling of materials	Recycling of materials generated or disposed of in the vertical farm.	Rufí-Salís et al., 2021.
S8	Photovoltaic (PV) panels	Installation of photovoltaic panels to generate renewable energy for the VFs.	Blom et al., 2022; Li et al., 2020; Martin et al., 2022.
IS	Improvement Scenario	Scenario incorporating all CE strategies (S1-S8)	Modelled in this study.

their present environmental performance. Next, acknowledging that the VFs under study were already implementing some CE strategies, a Linear Scenario (LS) was created to compare their environmental performance against a fully linear benchmark and to analyze the CE adoption level in each VF. This allows for a retrospective assessment of the different CE strategies implemented in both VFs without considering when they were implemented. To understand the environmental improvement potential of each strategy, they were translated into individual scenarios (S1 – S8) by modifying the target processes within the LS. Finally, an Improvement Scenario (IS) integrating all strategies was created to cover prospective improvements in each VF that might be adopted in the future. The IS was modelled by accounting for the combined effect of each individual scenario improvement at the inventory level, i.e., considering the synergetic effects when applying multiple scenarios at once to ensure compatibility. For instance, the PV solar electricity production (S8) was considered together with waste heat potentials (S6), both ultimately contributing to reduce the use of electricity from the grid. All material inputs and outputs and its related processes (e.g. transport) were also modified accordingly. Details regarding all strategies and scenarios, including a brief description of each CE strategy, the theoretical background supporting them, the assumptions made for their application, and a step-by-step guide for estimating their environmental performance when applied to any VF, can be found in Sections 2 and 3 of the Supplementary Materials.

3. Results and discussion

3.1. Environmental performance of the current scenario (CS)

To determine the impact reduction potential of CE strategies, the

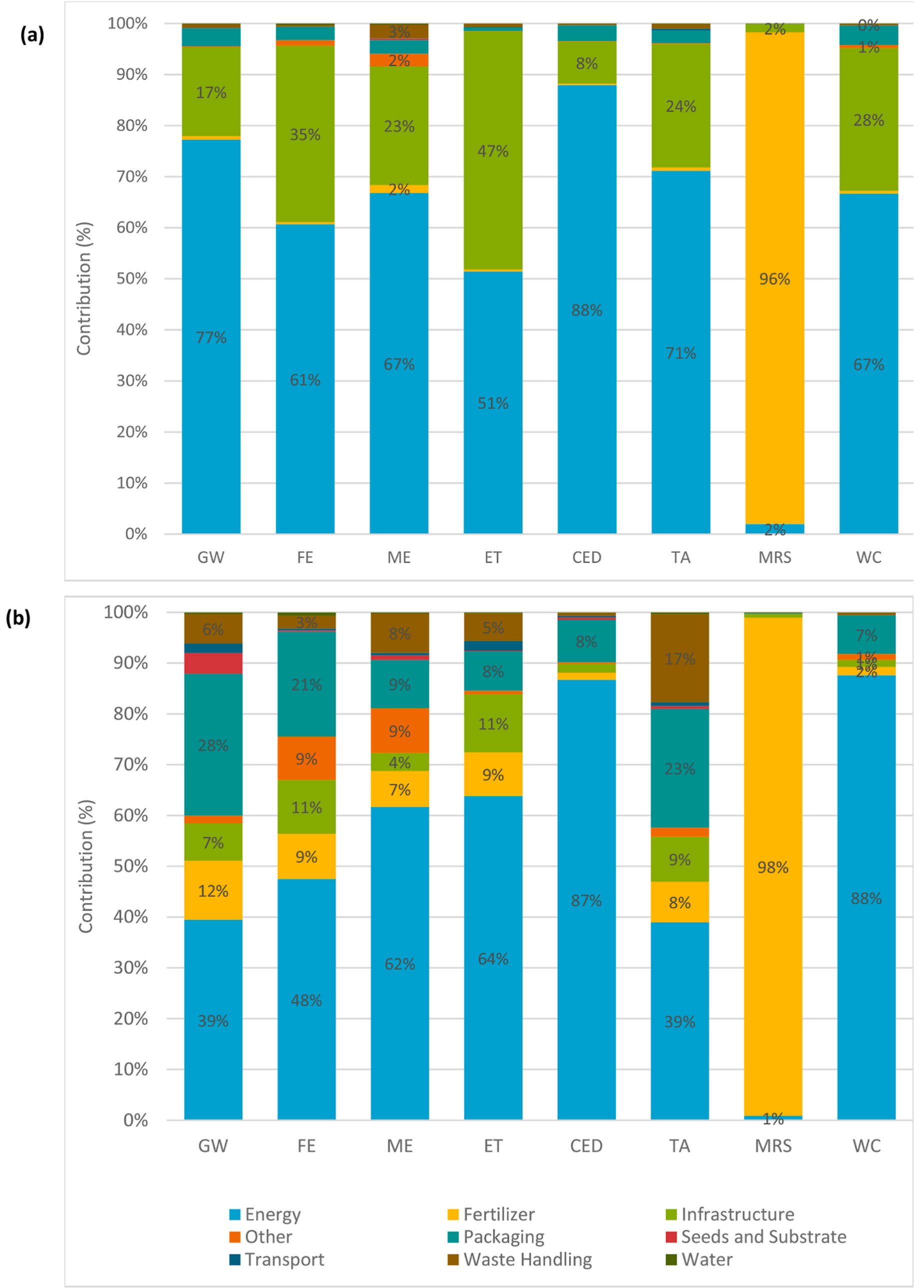
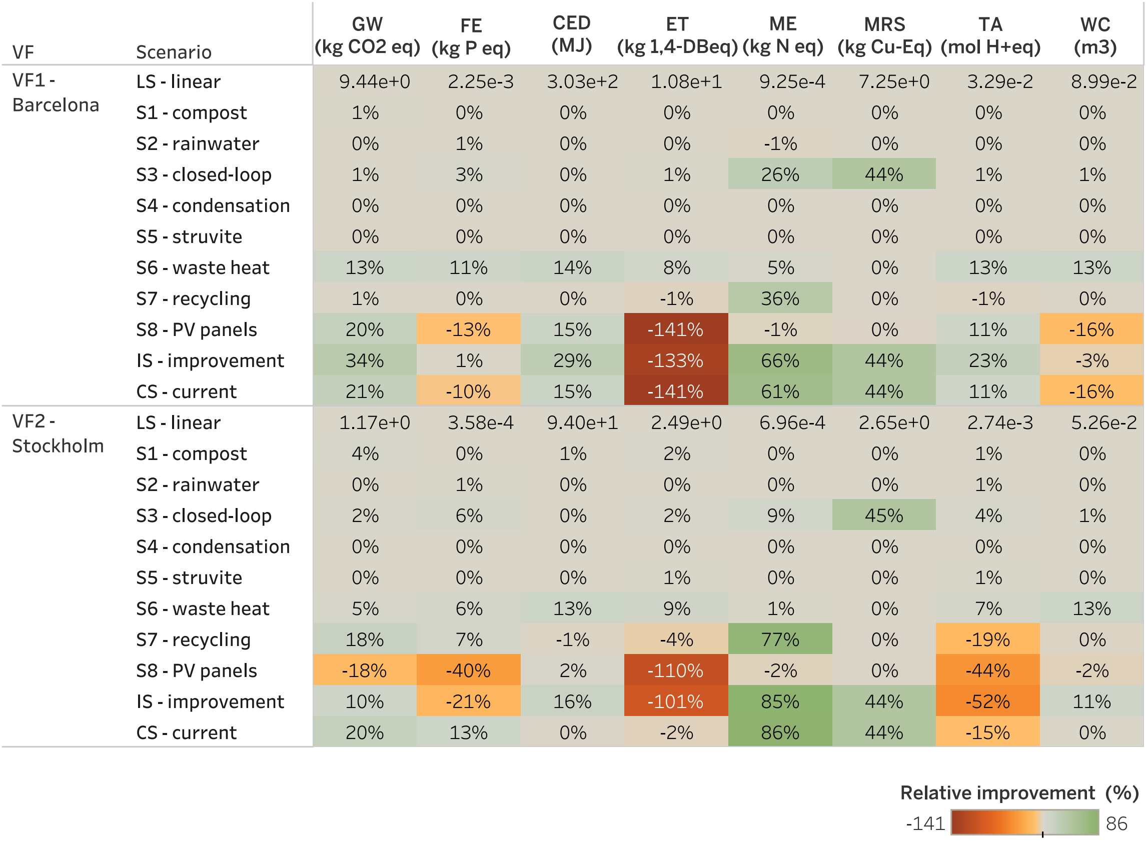


Fig. 2. Contribution analysis of different processes to the environmental impacts of (a) 1 kg of basil production in VF$_1$ and (b) 1 kg of lettuce production in VF$_2$ for Current Scenario. GW: Global Warming; FE: Freshwater Eutrophication; ME: Marine Eutrophication; ET: Ecotoxicity; CED: Cumulative Energy Demand; TA: Terrestrial Acidification; MRS: Mineral Resource Scarcity; WC: Water Consumption. Data labels are included for processes that contribute more than 2% to the impacts in each impact category.

current environmental impact profiles of the VFs were assessed by means of contribution analysis. Fig. 2 shows the relative environmental impact contributions of all materials and processes in VF$_1$ and VF$_2$, grouped into nine categories. In VF$_1$ (Fig. 2a), energy is the predominant contributor, accounting for more than 50% of the impacts across all impact categories except for mineral resource scarcity (MRS), due to the mineral extraction associated with fertilizers (resulting in 96% of SO impacts). In terms of GW, FE, ME and TA, energy accounts for 60-77% of impacts and >50% for the rest of impact categories except for SO. Infrastructure is the second most significant factor, contributing to 17-35% of impacts, followed by packaging, which accounts for less than 4% across all categories. ET presents a different distribution, with energy and infrastructure accounting for a similar share of impacts: 51% and 47%, respectively. CED is dominated by energy consumption, which represents 88% of the total impact, with infrastructure and transport each contributing less than 2%.

In VF$_2$ (Fig. 2b), the environmental impact contributions are more evenly distributed among all categories compared to VF$_1$. Energy remains the primary contributor, but it accounts for less than half of the total impacts in three impact categories: 39% in GW and TA, and 48% in FE. Packaging is the second largest contributor to GW and FE and is responsible for 20-30% of the impacts. In ME and ET, energy accounts for approximately 60% of impacts, while CED is dominated by energy, representing 87% of total impact. Packaging contributes 8-9% in ME, ET and CED, being the only category other than energy to contribute more than 2% to CED. Infrastructure and fertilizers have similar contributions across most impact categories, ranging from 4% to 12%, except for CED (where their contributions are minimal) and SO, with 98% of impacts due to mineral extraction needs. Waste handling also has a notable impact, especially in TA, where it accounts for 17% of the impacts. Seeds and substrate contribute 4% to GW impacts, while other items such as water and transport have relatively minor contributions across all categories.

Our results align with previous studies and can be attributed to the LED lighting system, which contributes to more than 80% of energy consumption, as well as the HVAC system necessary for maintaining controlled climate conditions (Graamans et al., 2018; Martin et al., 2022; van Delden et al., 2021; Weidner et al., 2022). Our analysis adds another layer to this evidence by showing the heterogeneity of environmental impact profiles in different VFs. In VF$_1$, the share of energy contribution in all categories is higher than in VF$_2$. The reasons can be twofold. First, VF$_1$ uses a higher amount of electricity per kilogram of crop produced (30 kWh/kg) compared to VF$_2$ (10 kWh/kg) because the biomass of lettuce crops is about three times the biomass produced for basil crops, according to the experimental trials at VF$_1$. This is in line with Pennisi et al. (2019), since basil crops in VFs can use 34-50 kWh/kg while a lettuce crop uses 14-25 kWh/kg according to the red-blue ratios, indicating that VF$_2$ is more efficient than the average VF basil production in terms of electricity use. Second, the impact assessment results are highly sensitive to the source of electricity used, and the environmental impacts of electricity generation vary significantly among countries (Martin and Molin, 2019). In 2023, Sweden and Spain generated electricity at 41 and 218 g CO$_2$/kWh, respectively, due to differences in their energy production mixes, including renewable, nuclear, and gas sources. Consequently, even if both VFs used the same amount of energy per FU, environmental impacts would be greater for VF$_1$ due to the higher impacts of producing Spain's electricity.



VF	Scenario	GW (kg CO2 eq)	FE (kg P eq)	CED (MJ)	ET (kg 1,4-DBeq)	ME (kg N eq)	MRS (kg Cu-Eq)	TA (mol H+eq)	WC (m3)
VF1 - Barcelona	LS - linear	9.44e+0	2.25e-3	3.03e+2	1.08e+1	9.25e-4	7.25e+0	3.29e-2	8.99e-2
	S1 - compost	1%	0%	0%	0%	0%	0%	0%	0%
	S2 - rainwater	0%	1%	0%	0%	-1%	0%	0%	0%
	S3 - closed-loop	1%	3%	0%	1%	26%	44%	1%	1%
	S4 - condensation	0%	0%	0%	0%	0%	0%	0%	0%
	S5 - struvite	0%	0%	0%	0%	0%	0%	0%	0%
	S6 - waste heat	13%	11%	14%	8%	5%	0%	13%	13%
	S7 - recycling	1%	0%	0%	-1%	36%	0%	-1%	0%
	S8 - PV panels	20%	-13%	15%	-141%	-1%	0%	11%	-16%
	IS - improvement	34%	1%	29%	-133%	66%	44%	23%	-3%
	CS - current	21%	-10%	15%	-141%	61%	44%	11%	-16%
VF2 - Stockholm	LS - linear	1.17e+0	3.58e-4	9.40e+1	2.49e+0	6.96e-4	2.65e+0	2.74e-3	5.26e-2
	S1 - compost	4%	0%	1%	2%	0%	0%	1%	0%
	S2 - rainwater	0%	1%	0%	0%	0%	0%	1%	0%
	S3 - closed-loop	2%	6%	0%	2%	9%	45%	4%	1%
	S4 - condensation	0%	0%	0%	0%	0%	0%	0%	0%
	S5 - struvite	0%	0%	0%	1%	0%	0%	1%	0%
	S6 - waste heat	5%	6%	13%	9%	1%	0%	7%	13%
	S7 - recycling	18%	7%	-1%	-4%	77%	0%	-19%	0%
	S8 - PV panels	-18%	-40%	2%	-110%	-2%	0%	-44%	-2%
	IS - improvement	10%	-21%	16%	-101%	85%	44%	-52%	11%
	CS - current	20%	13%	0%	-2%	86%	44%	-15%	0%

Fig. 3. Absolute impact assessment scores for LS for VF1 and VF2 and relative improvement rate for all CE strategies applied, with positive values indicating environmental impact reductions. GW: Global Warming; FE: Freshwater Eutrophication; ME: Marine Eutrophication; ET: Ecotoxicity; CED: Cumulative Energy Demand; TA: Terrestrial Acidification; MRS: Mineral Resource Scarcity; WC: Water Consumption.

3.2. *Environmental impacts of CE adoption*

Both VFs follow similar impact reduction trends when addressing the CE adoption gap. Regardless of the heterogeneity of VF configurations in terms of geographical context, crop type or current CE adoption level, their trajectories from linear (LS) to current CE adoption (CS) and potential CE adoption (IS) yield comparable results (Fig. 3).

In VF_1, IS outperforms CS across all categories, suggesting that VF_1 still has potential for improvement and further reduction of the environmental impacts to match those of the IS. The environmental impacts of applying the individual CE strategies S1, S2, S4, S5, and S7 show minimal differences compared to LS, except for a 36% reduction in ME impacts in S7 due to the recycling of all materials (Fig. 3). The use of a closed-loop irrigation system (S3) results in a 3% reduction in FE and a 26% reduction in ME impacts, due to decreased wastewater production through leachate recirculation. Moreover, it also reduces 45% of SO impacts due to reduction of mineral fertilizers. Reusing waste heat in nearby facilities (S6) reduces impacts across all categories by an average of 11%, mainly by decreasing the system's overall energy consumption, the primary factor influencing environmental performance. The use of PV panels (S8) presents a trade-off: while it reduces GW, CED and TA by 20%, 15% and 11%, respectively, the environmental costs associated with PV manufacturing lead to a 13% and 141% increase in FE and ET impacts, respectively. When comparing the three main scenarios, LS shows the highest impacts across all categories except for ET, due to the environmental costs of installing PV panels in the CS and IS. In terms of maturity, CS shows improved performance over the LS in four out of six impact categories, with reductions ranging from 10% to 61% in GW, ME, CED, TA.

In VF_2, CS shows the best performance in most categories compared to both the LS and IS, influenced by the environmental results of S8 that worsen IS results. The environmental impacts derived from CE strategies follow a similar pattern to VF_1, although some differences can be observed due to the diverse distribution of impacts among various categories rather than being predominantly influenced by the electricity needs and its respective country grid mixes (see section 4.1). The use of compost (S1) to replace coconut husk and peat results in a 4% reduction in GW, compared to the 1% observed in VF_1, where only coconut husk is used as substrate. S6 presents a lower improvement across all impact categories, with an average reduction of 7% due to decreased initial energy impacts. S8 proves unfavorable, as it increases impacts across all categories—ranging from 2 to 110%—except for CED. This is primarily driven byb the higher environmental impacts of onsite renewable energy production compared to grid-sourced energy. Unlike VF_1, LS does not present the worst performance across most categories, showing the highest impacts only in GW and ME. In contrast, the IS presents the highest impacts in FE, ET and TA due to the addition of PV panels.

3.3. *Understanding the potential of individual CE strategies*

3.3.1. *Compost (S1)*

The choice of growing media significantly influences the environmental impact of a system. Substituting conventional soil, often rich in peat, with alternative materials such as recycled paper, compost, and brewers' spent grains has proven to decrease GW impacts by over 60% (Barrett et al., 2016; Martin et al., 2019). Here we replaced the growing media —coconut husk in VF_1, and coconut husk and peat in VF_2—with municipal solid waste compost, a promising substitute for peat in soilless cultivation systems (Hargreaves et al., 2008). Despite the previous claims, only small changes—a reduction of 1% and 4% GW impacts in VF_1 and VF_2, respectively—were observed when comparing this strategy to LS due to the low contribution of the growing medium to the overall impacts. The greater reduction in VF_2 is likely due to peat, which studies have shown has high environmental impacts, whereas by-products such as coir present lower impacts (Martin et al., 2019, 2022; Toboso-Chavero et al., 2021; Vinci and Rapa, 2019).

3.3.2. *Water targeting strategies (S2, S3, S4)*

Direct water savings from applying strategies S2, S3, and S4 are not reflected in any impact category as the current contribution of water in both VFs is below 1%. Added infrastructure for the RWHS (S2) has no noticeable impact on either VF, in contrast to the 36% increase in GW impacts reported by Rufí-Salís et al. (2020). However, using a closed-loop irrigation system (S3) reduces the amount of fertilizers and prevents the discharge nutrients into the environment, thereby almost halving the impacts on eutrophication associated with linear systems (Christie, 2014; Grewal et al., 2011; Kumar and Cho, 2014). This is also in line with other recirculating techniques applied to aquaculture systems using biochar as natural filters (Behjat et al., 2025).

3.3.3. *Struvite (S5)*

Replacing conventional fertilizers with struvite in VF_1 and VF_2 showed no significant changes in environmental impacts compared to LS. The use of struvite as a slow-release phosphorus source has proven effective in mitigating freshwater eutrophication by reducing phosphorus leaching into water bodies (Arcas-Pilz et al., 2022; Rufí-Salís et al., 2021). However, Li et al. (2020) and Martin et al. (2022) suggest that switching to organic fertilizers may result only in minor reductions in the overall impacts of VFs. Nonetheless, using residue-derived fertilizers promotes waste valorization and enhances circular economy, contributing to sustainable practices (Li et al., 2020).

3.3.4. *Heating (S6)*

The excess heat generated by artificial lighting in VFs can be effectively utilized as a low-temperature heat source. In both VF_1 and VF_2, reusing 15% of total energy as waste heat decreased environmental impacts across all categories by 1% to 14%. These findings align with prior research highlighting the benefits of integrating urban farms with energy systems (Blom et al., 2023; Gentry, 2019; Sanjuan-Delmás et al., 2018; Sanyé-Mengual et al., 2018). Graamans et al. (2018) reported that the effectiveness of this strategy is greater in cold and temperate climates due to higher heating demands. However, research by Muñoz-Liesa et al. (2022) demonstrated that heat exchange can still result in energy savings in warmer Mediterranean climates. Future studies should evaluate the specific heating requirements of VF_1 and VF_2 locations to improve the regional application of this strategy.

3.3.5. *Recycling (S7)*

Numerous studies globally have explored the various benefits of recycling solid waste (Ayodele et al., 2018; Jang et al., 2020; Razzaq et al., 2021), and research shows that recycling can significantly reduce GW impacts (Ferronato et al., 2021; Meys et al., 2020). In this study, recycling practices greatly lowered ME impacts −36% and 77% in VF_1 and VF_2, respectively—being the only strategy, alongside S3, to address benefits in this impact category. This highlights the importance of considering diverse strategies, as each may offer different benefits across the analyzed environmental impact categories.

3.3.6. *PV panels (S8)*

The use of renewable energy technologies, such as PV panels, can reduce the environmental impact of VFs (Blom et al., 2022). However, this approach involves trade-offs associated with the life cycle of PV materials, including extraction, transportation, production, waste treatment, and installation (Jungbluth et al.). The findings for VF_1 align with these observations: while installing PV panels reduces GW impacts by 20%, it results in 13% and 141% more impacts than LS in FE and ET impact categories. In VF_2, the application of this strategy shows no environmental improvement due to the higher impacts associated with the production of photovoltaic electricity compared to the Swedish electricity mix (Martin et al., 2022). Research by Blom et al. (2022) and Casey et al. (2022) indicates that renewable energy systems significantly benefit VFs in regions with high-carbon electricity grids. In contrast, in areas with existing low-carbon electricity sources, such as Sweden, the environmental advantages are less significant and impacts can even be higher, as is the case for VF_2. Additionally, local irradiation levels affect PV efficiency (Blom et al., 2022), with Spain achieving greater energy output per unit of PV panel than Sweden.

3.4. Overall environmental VF performance

The overall results of the CE implementations provide insights into the circular economy (CE) maturity of the studied VFs. Using global warming (GW) impacts as an illustrative example, Fig. 4 summarizes the environmental performance associated with past, current, and potential future implementations in each farm, as assessed in Fig. 3. However, for VF_2, the installation of photovoltaic (PV) panels (S8) was not included in the Improvement Scenario (IS) from Fig. 4, as it did not lead to environmental benefits (due to the Swedish electricity grid already relying on low-carbon energy sources). This finding highlights the importance of jointly improving background systems (such as electricity generation) and foreground technologies (such as vertical farming systems) when aiming to reduce environmental impacts in LCA modelling (Mendoza et al., 2020). In this case study, since improvements have already occurred in the background system (the electricity grid), further foreground interventions yield counterproductive outcomes, worsen by the economies of the scale too (as it could happen with PV installations in small rooftops).

Hence, improvements obtained of 20-21% for CS compared to LS when strategies S3, S4 and S7 were applied for both case studies. Thus, they yield similar environmental results regardless of their specific contexts and environmental impact contributions. For the Improvement Scenario (IS), GW reductions were up to 34% compared to the LS, demonstrating that VFs have already been evolving and will likely continue to improve in the future to achieve better environmental performances. Such environmental improvements at system-level are in line with the resulting impacts in literature. For instance, a greenhouse herb production which implemented a set of improvement strategies lowered GW impacts between 32 and 38% (Martin et al., 2023a). Assessing these improvements is important to consider when conducting the LCA of emerging technologies, since environmental reductions over 90% could be achieved (Gavankar et al., 2015). It is also important to detect the main contributors of environmental impacts (as is the case when comparing CS with LS for VF_2 due to change of waste handling impacts), aiding to effectively direct future VF improvements (i.e., energy use and packaging for IS at VF_2). Moreover, eco-design approaches applied at early stages of product and technology designs can be useful to detect and minimize environmental hotspots (Muñoz-Liesa et al., 2025), helping to achieve improved levels of environmental and economic competitiveness (Bey et al., 2013).

3.5. Limitations and outlook

Overall, this study demonstrates the potential of various CE strategies to reduce environmental impacts in VFs and underscores the need for more case-specific studies that consider the intrinsic characteristics of each system. However, assessing the environmental impacts of CE adoption relies on data and modelling assumptions that need to be further explored in the future:

- **PV panels:** Current inventory data from the ecoinvent database dates back to 2005, while the PV technology increased the efficiency from 14 to 19.8% in 2020, since it is a rapidly evolving industry (Müller et al., 2021). This leads to environmental impacts up to 2 times higher than the current estimated impacts for silicon-based PV panels (Besseau et al., 2023). This would potentially decrease environmental impacts observed in IS for VF_2 since PV panels can yield impacts as low as 0.05 kg CO_2 eq/kWh (for instance, in the GW category), which is lower than the electricity impacts of the Swedish electricity mix (0.07 kg CO_2 eq/kWh). However, this greatly depends on the PV type of installation, production potential and PV technology, among other assumptions, calling for additional assessments of VFs with different PV configurations.
- **Building envelopes:** VF_1 and VF_2 are hosted in existing buildings that were excluded from the LCI. Their environmental impacts would likely be higher when allocating the impacts of building infrastructure to the VF. Studies indicate that the environmental footprint of infrastructure can range from a relatively minor contribution to 10-15% of total impacts (Barge, 2020; Martin and Molin, 2019). However, the literature shows that the integration of VFs into existing buildings helps to mitigate environmental impacts compared to the construction of new facilities (Gentry, 2019; Romeo et al., 2018). Guidelines for more harmonized inventories including lifetime assumptions and methodological approaches are needed. By doing so, we could highlight the importance of using existing urban spaces and synergies within urban infrastructure to enhance the sustainability of vertical farming practices.
- **Machinery and infrastructure**: Many LCAs on VFs use simplified or generalized LCI data, which affects system completeness. This is often the case for capital goods (Font-Vivanco, 2020) as it is the case for VFs' machinery and infrastructure. Evidenced through the different relative contributions between VF_1 and VF_2, (and particularly due to the high energy environmental impacts of VF_1), omitting significant details in the LCI phase can potentially lead to underestimations or misrepresentations of actual impacts (Guinée et al., 2011).

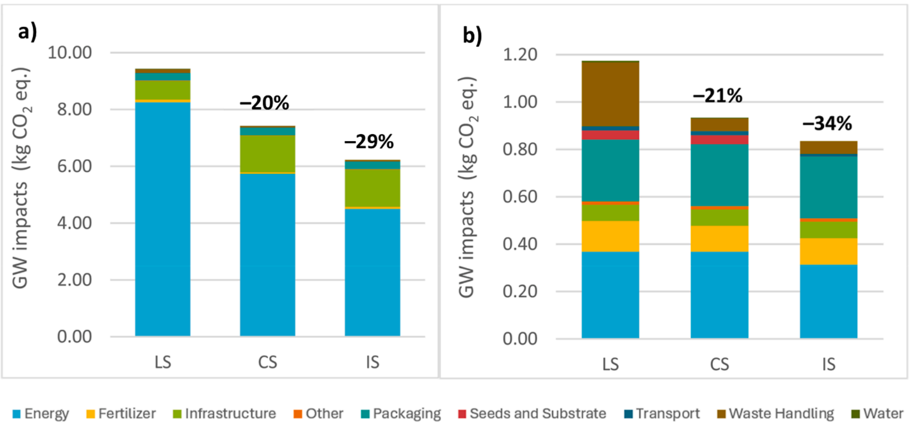


Fig. 4. Contribution of different processes to the GW impacts of (a) 1 kg of basil production in VF_1 and (b) 1 kg of lettuce production in VF_2 within Linear (LS), Current (CS) and Improvement Scenario (IS). Note IS* for VF_2 does not include strategy S8 (solar panels).

- **Packaging:** Many studies have excluded packaging from their environmental assessments (Graamans et al., 2018; Romeo et al., 2018; Weidner et al., 2022). However, the total annual consumption of packaging materials can lead to relevant environmental footprints, as seen in VF_2, accounting for roughly 20% of GHG, FE and TA impacts, which aligns with Cellura et al. (2012), Dias et al. (2017) and Martin et al. (2023). Reducing material usage, particularly plastics, and developing recyclable or compostable alternatives could mitigate these impacts (Blom et al., 2022). This could be further analyzed in the future.
- **Case studies:** the effects of CE adoption in the VFs was developed at a theoretical level using real operational data. Since CE applications are highly design-specific, further studies are necessary to evaluate the feasibility and actual impacts of these CE strategies through real-world pilot projects and close monitoring, as well as to explore additional strategies to further enhance the environmental performance of these emerging urban food production systems. This will validate the robustness of our results. A more practical assessment of the implementation challenges of a portfolio of CE strategies is also needed. This shall address issues such as the availability of financial resources, technical feasibility or compatibility of waste resources with food safety standards (Zambrano-Prado et al., 2021).
- **Future assessments:** Beyond environmental impact reduction, future scenarios also might shift the environmental contributions of the subsystems assessed. This might reveal new environmental hotspots to tackle from a CE perspective while the global economy decarbonizes. Nevertheless, some CE strategies in vertical farming may still be relevant for broader urban sustainability objectives, such as resource recirculation and waste flow management, even when their environmental benefits are limited.

4. Conclusions

Vertical Farms (VFs) are still an emerging technology aiming to improve resource use efficiency of crop growing needs in a climate change context. Moreover, VF integration within cities through circular economy (CE) strategies is also in its infancy, and the their environmental impacts are still not fully understood. This study conducted an LCA of two commercial VFs to evaluate how CE strategies can improve environmental performance, considering their distinct characteristics, maturity levels and geographical context: Spain and Sweden. Several takeaways stand out from this assessment:

First, energy use is the primary contributor to environmental impacts, accounting for 70% of all impacts in VF_1 (Barcelona) and 57% in VF_2 (Stockholm) at the current VFs status, with variations attributed to energy efficiency and sourcing.

Second, the implementation of CE strategies provided considerable potential but context-dependent benefits when enhancing the environmental sustainability, with reductions of ~20% from linear to current systems and up to ~30% in future scenarios in terms of GW impacts. Strategies such as closed-loop irrigation, material recycling, and waste heat reuse consistently reduced impacts, particularly in marine eutrophication (up to 36% in VF_1 and up to 77% in VF_2). However, not all strategies are universally beneficial due to geographical and technological differences: for example, photovoltaic integration improved impacts in VF_1 but increased them in VF_2, highlighting environmental trade-offs. Thus, circular strategies and its derived context-specific environmental impacts should be jointly assessed to ensure resource circularity does not worsen environmental impacts.

Finally, results showed that environmental improvements in the foreground reflect the maturity level of the VFs, but their effectiveness depends on the state of background systems as well (i.e., the broader changes in upstream production systems). VF_1 CS showed a lower maturity level, with environmental reductions of 10% to 61% in GW, ME, CED and TA impacts compared to LS. However, it also showed higher potential for improvement through additional CE strategies within the IS. In contrast, since VF_2 is already operating in a low-environmental impact electricity grid, it exhibited limited gains and even burden shifting for some interventions. This demonstrates that advancing VF sustainability requires aligning foreground technological improvements with background system conditions, as improvements in one without the other may limit or counteract overall environmental benefits.

Overall, this study highlights the importance of combining CE strategies with a system-wide perspective to identify the most effective pathways towards the sustainable development of food systems.

CRediT authorship contribution statement

Alicia Invernón-Garrido: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Anna Petit-Boix:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Xavier Gabarrell:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Investigation, Funding acquisition. **Michael Martin:** Writing – review & editing, Writing – original draft, Supervision, Resources, Investigation, Funding acquisition. **Joan Muñoz-Liesa:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

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.

Acknowledgements

This work has been supported by the Swedish Research Council for Sustainable Development (FORMAS) for the funding received for J. Muñoz-Liesa to the ECO-FARM CITY project (Circular vertical farms to reduce environmental impacts in cities, grant number 2022-02850) and M. Martin for the project (Improving the resource-efficiency and environmental performance of urban-vertical farms through circular-based production methods, grant number 2021-02447). We also thank the Ministerio de Ciencia y Innovación (MCIN/AEI/10.13039/501100011033/FEDER, UE) and the EU founding “Next Generation” for funding the projects MOVE4EDU (PID2021-126845OB-C21) and BINAFET (TED2021-130047B-C21). This research is also supported by María de Maeztu Unit of Excellence (CEX2019-0940-M) and the Department of Research and Universities of the Generalitat de Catalunya and the Department of Agriculture, Livestock, Fisheries and Food for the financial support for the WEF4build project (Clima Fund). The authors would like to acknowledge Carlos Gómez, Alejandro Rueda and Victor Noriega from the VF in Barcelona, together with the Sostenipra Research group and the ICTA-UAB staff for their support, advice, and their valuable insights and assistance throughout the project.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.resenv.2026.100335.

Data availability

Data will be made available on request.

References

Arcas-Pilz, V., Parada, F., Rufí-Salís, M., Stringari, G., González, R., Villalba, G., Gabarrell, X., 2022. Extended use and optimization of struvite in hydroponic cultivation systems. Resour. Conserv. Recycl. 179, 106130. https://doi.org/10.1016/j.resconrec.2021.106130.

Ayodele, T.R., Alao, M.A., Ogunjuyigbe, A.S.O., 2018. Recyclable resources from municipal solid waste: assessment of its energy, economic and environmental benefits in Nigeria. Resour. Conserv. Recycl. 134, 165–173. https://doi.org/10.1016/j.resconrec.2018.03.017.

Badampudi, D., Wohlin, C., Petersen, K., 2015. Experiences from using snowballing and database searches in systematic literature studies. In: Proceedings of the 19th International Conference on Evaluation and Assessment in Software Engineering, pp. 1–10. https://doi.org/10.1145/2745802.2745818.

Barge, U., 2020. Analyzing the environmental sustainability of an urban vertical hydroponic system. Environ. Sci. Agricult. Sci. Food Sci. 89.

Barrett, et al., 2016. Achieving environmentally sustainable growing media for soilless plant cultivation systems – a review. Scientia Horticulturale 212, 220–234. https://doi.org/10.1016/j.scienta.2016.09.030.

Behjat, M., Svanström, M., Peters, G., Wennberg, N., 2025. Life cycle assessment of recirculating aquaculture systems with innovative biochar filter for enhanced nutrient recirculation. Resour. Environ. Sustain. 21, 100233. https://doi.org/10.1016/j.resenv.2025.100233.

Besseau, R., Tannous, S., Douziech, M., Jolivet, R., Prieur-Vernat, A., Clavreul, J., Payeur, M., Sauze, M., Blanc, I., Pérez-López, P., 2023. An open-source parameterized life cycle model to assess the environmental performance of silicon-based photovoltaic systems. Prog. Photovoltaics Res. Appl. 31, 908–920. https://doi.org/10.1002/pip.3695.

Bey, N., Hauschild, M.Z., McAloone, T.C., 2013. Drivers and barriers for implementation of environmental strategies in manufacturing companies. CIRP Ann. 62, 43–46.

Blom, T., Jenkins, A., van den Dobbelsteen, A., 2023. Synergetic integration of vertical farms and buildings: reducing the use of energy, water, and nutrients. Front. Sustain. Food Syst. 7. https://doi.org/10.3389/fsufs.2023.1227672.

Blom, T., Jenkins, A., Pulselli, R.M., van den Dobbelsteen, A.A.J.F., 2022. The embodied carbon emissions of lettuce production in vertical farming, greenhouse horticulture, and open-field farming in the Netherlands. J. Clean. Prod. 377. https://doi.org/10.1016/j.jclepro.2022.134443.

Butturini, M., Marcelis, L.F.M., 2020. Chapter 4 - vertical farming in Europe: present status and outlook. Plant Factory 77–91. https://doi.org/10.1016/B978-0-12-816691-8.00004-2.

Casey, L., Freeman, B., Francis, K., Brychkova, G., McKeown, P., Spillane, C., Bezrukov, A., Zaworotko, M., Styles, D., 2022. Comparative environmental footprints of lettuce supplied by hydroponic controlled-environment agriculture and field-based supply chains. J. Clean. Prod. 369. https://doi.org/10.1016/j.jclepro.2022.133214.

Cellura, M., Longo, S., Mistretta, M., 2012. Life Cycle Assessment (LCA) of protected crops: an Italian case study. J. Clean. Prod. 28, 56–62. https://doi.org/10.1016/j.jclepro.2011.10.021.

Chance, E., Ashton, W., Pereira, J., Mulrow, J., Norberto, J., Derrible, S., Guilbert, S., 2017. The plant—an experiment in urban food sustainability. Environ. Prog. Sustain. Energy 37, 82–90. https://doi.org/10.1002/ep.12712.

Christie, E., 2014. Water and Nutrient Reuse Within Closed Hydroponic Systems. Electronic Theses and Dissertations. https://digitalcommons.georgiasouthern.edu/etd/1096.

De Gelder, A., Dieleman, J.A., Bot, G.P.A., Marcelis, L.F.M., 2012. An overview of climate and crop yield in closed greenhouses. J. Hortic. Sci. Biotechnol. 87 (3), 193–202. https://doi.org/10.1080/14620316.2012.11512852.

Despommier, D., 2009. The rise of vertical farms. Sci. Am. 301 (5), 80–87. https://www.jstor.org/stable/26001595.

Dias, G.M., Ayer, N.W., Khosla, S., Van Acker, R., Young, S.B., Whitney, S., Hendricks, P., 2017. Life cycle perspectives on the sustainability of Ontario greenhouse tomato production: benchmarking and improvement opportunities. J. Clean. Prod. 140, 831–839. https://doi.org/10.1016/j.jclepro.2016.06.039.

Dorr, E., Koegler, M., Gabrielle, B., Aubry, C., 2021. Life cycle assessment of a circular, urban mushroom farm. J. Clean. Prod. 288, 125668. https://doi.org/10.1016/j.jclepro.2020.125668.

Ferronato, N., Portugal Alarcón, G.P., Guisbert Lizarazu, E.G., Torretta, V., 2021. Assessment of municipal solid waste collection in Bolivia: perspectives for avoiding uncontrolled disposal and boosting waste recycling options. Resour. Conserv. Recycl. 167, 105234. https://doi.org/10.1016/j.resconrec.2020.105234.

Font-Vivanco, D., 2020. The role of services and capital in footprint modelling. Int. J. Life Cycle Assess. 25, 280–293. https://doi.org/10.1007/s11367-019-01687-7.

Frischknecht, R., Jungbluth, N., Althaus, H.-J., Bauer, C., Doka, G., Dones, R., Hischier, R., Hellweg, S., Humbert, S., Köllner, T., Loerincik, Y., Margni, M., Nemecek, T., 2007. Implementation of life cycle impact assessment methods. Ecoinvent Report No. 3, Data v2. 0. Swiss Centre for Life Cycle Inventories.

Gavankar, S., Suh, S., Keller, A.A., 2015. The role of scale and technology maturity in life cycle assessment of emerging technologies: a case study on carbon nanotubes. J. Ind. Ecol. 19, 51–60. https://doi.org/10.1111/jiec.12175.

Gentry, M., 2019. Local heat, local food: integrating vertical hydroponic farming with district heating in Sweden. Energy 174, 191–197. https://doi.org/10.1016/j.energy.2019.02.119.

Graamans, L., Baeza, E., van den Dobbelsteen, A., Tsafaras, I., Stanghellini, C., 2018. Plant factories versus greenhouses: comparison of resource use efficiency. Agric. Syst. 160, 31–43. https://doi.org/10.1016/j.agsy.2017.11.003.

Grewal, H.S., Maheshwari, B., Parks, S.E., 2011. Water and nutrient use efficiency of a low-cost hydroponic greenhouse for a cucumber crop: an Australian case study. Agric. Water Manag. 98 (5), 841–846. https://doi.org/10.1016/j.agwat.2010.12.010.

Guinée, J.B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., Rydberg, T., 2011. Life cycle assessment: past, present, and future. Environ. Sci. Technol. 45 (1), 90–96. https://doi.org/10.1021/es101316v.

Hargreaves, J.C., Adl, M.S., Warman, P.R., 2008. A review of the use of composted municipal solid waste in agriculture. Agric. Ecosyst. Environ. 123 (1), 1–14. https://doi.org/10.1016/j.agee.2007.07.004.

Hawes, J.K., Goldstein, B.P., Newell, J.P., Dorr, E., Caputo, S., Fox-Kämper, R., Grard, B., Ilieva, R.T., Fargue-Lelièvre, A., Poniży, L., Schoen, V., Specht, K., Cohen, N., 2024. Comparing the carbon footprints of urban and conventional agriculture. Nat. Cities 1, 164–173. https://doi.org/10.1038/s44284-023-00023-3.

Hu, Y., Pradhan, P., Zhang, H., Wang, Z., Huang, Q., Jia, Q., Lian, X., Xu, C., Yang, R., Tian, Y., Xu, Z., Jiao, L., Kropp, J.P., 2025. Urban agriculture supports China's vegetable supply without raising greenhouse gas emissions. Resour. Environ. Sustain. 21, 100254. https://doi.org/10.1016/j.resenv.2025.100254.

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

ISO, International Organitzation for Standarization, 2006. Environmental Management - Life Cycle Assessment - Principles and Framework (ISO 14040:2006).

Jang, Y.-C., Lee, G., Kwon, Y., Lim, J., Jeong, J., 2020. Recycling and management practices of plastic packaging waste towards a circular economy in South Korea. Resour. Conserv. Recycl. 158, 104798. https://doi.org/10.1016/j.resconrec.2020.104798.

Jungbluth, N., Dones, R., & Frischknecht, R. (s. f.). Life Cycle Assessment of Photovoltaics; Update of the Ecoinvent Database | MRS Online Proceedings Library (OPL). Cambridge Core. https://doi.org/10.1557/PROC-1041-R01-03.

Jurga, A., Pacak, A., Pandelidis, D., Kaźmierczak, B., 2021. A long-term analysis of the possibility of water recovery for hydroponic lettuce irrigation in an indoor vertical farm. Part 2: rainwater harvesting. Appl. Sci. 11 (1), 1. https://doi.org/10.3390/app11010310.

Kalantari, F., Tahir, O.M., Joni, R.A., Fatemi, E., 2018. Opportunities and challenges in sustainability of vertical farming: a review. Journal of Landscape Ecology 11 (1), 35–60. https://doi.org/10.1515/jlecol-2017-0016.

Kortright, R., Wakefield, S., 2011. Edible backyards: a qualitative study of household food growing and its contributions to food security. Agric. Hum. Val. 28 (1), 39–53. https://doi.org/10.1007/s10460-009-9254-1.

Kumar, R.R., Cho, J.Y., 2014. Reuse of hydroponic waste solution. Environ. Sci. Pollut. research 21 (16), 16. https://doi.org/10.1007/s11356-014-3024-3.

Li, L., Li, X., Chong, C., Wang, C.-H., Wang, X., 2020. A decision support framework for the design and operation of sustainable urban farming systems. J. Clean. Prod. 268, 121928. https://doi.org/10.1016/j.jclepro.2020.121928.

Martin, M., Molin, E., 2019. Environmental assessment of an urban vertical hydroponic farming system in Sweden. Sustainability 11 (15), 15. https://doi.org/10.3390/su11154124.

Martin, M., Bengtsson, E., Carotti, L., Orrestig, K., Orsini, F., 2023a. Environmental assessment of greenhouse herb production: a case of longitudinal improvement options in Sweden. Resour. Conserv. Recycl. 193, 106948. https://doi.org/10.1016/j.resconrec.2023.106948.

Martin, M., Elnour, M., Siñol, A.C., 2023b. Environmental life cycle assessment of a large-scale commercial vertical farm. Sustain. Prod. Consum. 40, 182–193. https://doi.org/10.1016/j.spc.2023.06.020.

Martin, M., Poulikidou, S., Molin, E., 2019. Exploring the environmental performance of urban symbiosis for vertical hydroponic farming. Sustainability 11 (23), 23. https://doi.org/10.3390/su11236724.

Martin, M., Weidner, T., Gullström, C., 2022. Estimating the potential of building integration and regional synergies to improve the environmental performance of urban vertical farming. Front. Sustain. Food Syst. 6. https://www.frontiersin.org/articles/10.3389/fsufs.2022.849304.

Mendoza, A., Cox, B., Mutel, C., Vuuren, D.P., Vivanco, D.F., Deetman, S., Edelenbosch, O.Y., Guinée, J., Tukker, A., 2020. When the background matters: using scenarios from integrated assessment models in prospective life cycle assessment. J. Ind. Ecol. 24, 64–79. https://doi.org/10.1111/jiec.12825.

Meys, R., Frick, F., Westhues, S., Sternberg, A., Klankermayer, J., Bardow, A., 2020. Towards a circular economy for plastic packaging wastes – the environmental potential of chemical recycling. Resour. Conserv. Recycl. 162, 105010. https://doi.org/10.1016/j.resconrec.2020.105010.

Müller, A., Friedrich, L., Reichel, C., Herceg, S., Mittag, M., Neuhaus, D.H., 2021. A comparative life cycle assessment of silicon PV modules: impact of module design, manufacturing location and inventory. Sol. Energy Mater. Sol. Cells 230, 111277. https://doi.org/10.1016/j.solmat.2021.111277.

Muñoz-Liesa, J., Navarro-Segarra, M., Sierra-Montoya, M., Esquivel, J.P., Peiró, L.T., 2025. Bio-based materials and customized energy supply as key drivers to ecodesign primary portable batteries. Sustain. Prod. Consum. 54, 202–214. https://doi.org/10.1016/j.spc.2024.12.011.

Muñoz-Liesa, J., Royapoor, M., Cuerva, E., Gassó-Domingo, S., Gabarrell, X., Josa, A., 2022. Building-integrated greenhouses raise energy co-benefits through active ventilation systems. Build. Environ. 208, 108585. https://doi.org/10.1016/j.buildenv.2021.108585.

Muñoz-Liesa, J., Royapoor, M., López-Capel, E., Cuerva, E., Rufí-Salís, M., Gassó-Domingo, S., Josa, A., 2020. Quantifying energy symbiosis of building-integrated agriculture in a mediterranean rooftop greenhouse. Renew. Energy 156, 696–709. https://doi.org/10.1016/j.renene.2020.04.098.

Muñoz-Liesa, J., Talens, L., Gabarrell, X., 2024. LCIA scores: an open-source tool to facilitate environmental assessments for LCA practitioners. Benelux Office Intellectual Property, iDEPOT number 145093. https://doi.org/10.5281/zenodo.14003415.

Mutel, C., 2017. Brightway: an open source framework for life cycle assessment. J. Open Source Softw. 2 (12), 236. https://doi.org/10.21105/joss.00236.

Pennisi, G., Sanyé-Mengual, E., Orsini, F., Crepaldi, A., Nicola, S., Ochoa, J., Fernandez, J.A., Gianquinto, G., 2019. Modelling environmental burdens of indoor-grown vegetables and herbs as affected by red and blue LED lighting. Sustainability 11 (15), 15. https://doi.org/10.3390/su11154063.

Qiu, J., Zhao, H., Chang, N.-B., Wardropper, C.B., Campbell, C., Baggio, J.A., Guan, Z., Kohl, P., Newell, J., Wu, J., 2024. Scale up urban agriculture to leverage transformative food systems change, advance social–ecological resilience and improve sustainability. Nat. Food 5, 83–92. https://doi.org/10.1038/s43016-023-00902-x.

Razzaq, A., Sharif, A., Najmi, A., Tseng, M.-L., Lim, M.K., 2021. Dynamic and causality interrelationships from municipal solid waste recycling to economic growth, carbon emissions and energy efficiency using a novel bootstrapping autoregressive distributed lag. Resour. Conserv. Recycl. 166, 105372. https://doi.org/10.1016/j.resconrec.2020.105372.

Romeo, D., Vea, E.B., Thomsen, M., 2018. Environmental impacts of urban hydroponics in Europe: a case study in Lyon. Proced. CIRP 69, 540–545. https://doi.org/10.1016/j.procir.2017.11.048.

Rufí-Salís, M., Petit-Boix, A., Villalba, G., Gabarrell, X., Leipold, S., 2021. Combining LCA and circularity assessments in complex production systems: the case of urban agriculture. Resour. Conserv. Recycl. 166, 105359. https://doi.org/10.1016/j.resconrec.2020.105359.

Rufí-Salís, M., Petit-Boix, A., Villalba, G., Sanjuan-Delmás, D., Parada, F., Ercilla-Montserrat, M., Arcas-Pilz, V., Muñoz-Liesa, J., Rieradevall, J., Gabarrell, X., 2020. Recirculating water and nutrients in urban agriculture: an opportunity towards environmental sustainability and water use efficiency? J. Clean. Prod. 261, 121213. https://doi.org/10.1016/j.jclepro.2020.121213.

Sanjuan-Delmás, D., Llorach-Massana, P., Nadal, A., Ercilla-Montserrat, M., Muñoz, P., Montero, J.I., Josa, A., Gabarrell, X., Rieradevall, J., 2018. Environmental assessment of an integrated rooftop greenhouse for food production in cities. J. Clean. Prod. 177, 326–337. https://doi.org/10.1016/j.jclepro.2017.12.147.

Sanyé-Mengual, E., Martinez-Blanco, J., Finkbeiner, M., Cerdà, M., Camargo, M., Ometto, A.R., Velásquez, L.S., Villada, G., Niza, S., Pina, A., Ferreira, G., Oliver-Solà, J., Montero, J.I., Rieradevall, J., 2018. Urban horticulture in retail parks: environmental assessment of the potential implementation of rooftop greenhouses in European and South American cities. J. Clean. Prod. 172, 3081–3091. https://doi.org/10.1016/j.jclepro.2017.11.103.

Savvas, D., Gruda, N., 2018. Application of soilless culture technologies in the modern greenhouse industry – a review. Eur. J. Hortic. Sci. 83, 280–293. https://doi.org/10.17660/eJHS.2018/83.5.2.

Specht, K., Siebert, R., Hartmann, I., Freisinger, U.B., Sawicka, M., Werner, A., Thomaier, S., Henckel, D., Walk, H., Dierich, A., 2014. Urban agriculture of the future: an overview of sustainability aspects of food production in and on buildings. Agric. Hum. Val. 31 (1), 33–51. https://doi.org/10.1007/s10460-013-9448-4.

Sucozhañay, A., Pesántez, J., Guerrero-Coronel, R., Guerrero-Coronel, R., Peña, D., Célleri, R., 2024. Rainwater harvesting as a sustainable solution for the production of urban hydroponic crops. Water Reuse 14 (2), 177–189. https://doi.org/10.2166/wrd.2024.151.

Toboso-Chavero, S., Madrid-López, C., Villalba, G., Gabarrell Durany, X., Hückstädt, A. B., Finkbeiner, M., Lehmann, A., 2021. Environmental and social life cycle assessment of growing media for urban rooftop farming. Int. J. Life Cycle Assess. 26 (10), 10. https://doi.org/10.1007/s11367-021-01971-5.

Tsafaras, I., Campen, J.B., de Zwart, H.F., Voogt, W., Harbi, A.A., Assaf, K.A., Abdelaziz, M.E., Qaryouti, M., Stanghellini, C., 2022. Quantifying the trade-off between water and electricity for tomato production in arid environments. Agric. Water Manag. 271, 107819. https://doi.org/10.1016/j.agwat.2022.107819.

van Delden, S.H., SharathKumar, M., Butturini, M., Graamans, L.J.A., Heuvelink, E., Kacira, M., Kaiser, E., Klamer, R.S., Klerkx, L., Kootstra, G., Loeber, A., Schouten, R. E., Stanghellini, C., van Ieperen, W., Verdonk, J.C., Vialet-Chabrand, S., Woltering, E.J., van de Zedde, R., Zhang, Y., Marcelis, L.F.M., 2021. Current status and future challenges in implementing and upscaling vertical farming systems. Nat. Food 2 (12), 12. https://doi.org/10.1038/s43016-021-00402-w.

Van Kooten, O., Heuvelink, E., Stanghellini, C., 2008. New developments in greenhouse technology can mitigate the water shortage problem of the 21st century. Acta Hortic. 767, 45–52. https://doi.org/10.17660/ActaHortic.2008.767.2.

Vinci, G., Rapa, M., 2019. Hydroponic cultivation: life cycle assessment of substrate choice. Br. Food J. 121 (8), 1801–1812. https://doi.org/10.1108/BFJ-02-2019-0112.

Weidner, T., Yang, A., Forster, F., Hamm, M.W., 2022. Regional conditions shape the food–energy–land nexus of low-carbon indoor farming. Nat. Food 3 (3), 3. https://doi.org/10.1038/s43016-022-00461-7.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.

Zambrano-Prado, P., Orsini, F., Rieradevall, J., Josa, A., Gabarrell, X., 2021. Potential key factors, policies, and barriers for rooftop agriculture in EU cities: barcelona, Berlin, Bologna, and Paris. Front. Sustain. Food Syst. 5, 733040. https://doi.org/10.3389/fsufs.2021.733040.