BURLEIGH DODDS SERIES IN AGRICULTURAL SCIENCE

Advances in plant factories

New technologies in indoor vertical farming

Edited by Emeritus Professor Toyoki Kozai, Chiba University, Japan
and Dr Eri Hayashi, Japan Plant Factory Association, Japan

burleigh dodds
SCIENCE PUBLISHING

Life cycle assessment of indoor vertical farms

Michael Martin, IVL Swedish Environmental Research Institute and KTH Royal Institute of Technology, Sweden; and Francesco Orsini, University of Bologna, Italy

1 Introduction

It is becoming increasingly important to find solutions for more resilient food production methods closer to urban environments with less vulnerability to supply-chain shocks (Benke and Tomkins, 2017; O'Sullivan et al., 2020; Pulighe and Lupia, 2020). Indoor vertical farming (IVF[1]) systems have emerged worldwide as a result of the need for more resilient food provisioning. IVF has been promoted for its potential to extend seasonal availability, produce more sustainable food, secure food supplies, and reduce pressure on agricultural land (Graamans et al., 2018; Martin and Molin, 2019; Thomaier et al., 2014; van Delden et al., 2021). Furthermore, IVF has seen a dramatic increase in recent years, attracting considerable interest and funding (Agritecture, 2022; Orsini et al., 2020; Weidner et al., 2019).

IVFs are relatively new in the context of food supply chains, and thus it is an expanding subject of inquiry. A large share of the scientific and grey literature promotes vertical farming as a sustainable solution for food provisioning

1 The acronym IVF henceforth refers to the verb 'indoor vertical farming' to denote the practice and the noun 'indoor vertical farm' to denote the sites.

http://dx.doi.org/10.19103/AS.2023.0126.06

Chapter taken from: Kozai, T. and Hayashi, E. (ed.), *Advances in plant factories: New technologies in indoor vertical farming*, Burleigh Dodds Science Publishing, Cambridge, UK, 2023, (ISBN: 978 1 80146 316 4; www.bdspublishing.com)

(Al-Chalabi, 2015; Benke and Tomkins, 2017; Despommier, 2011). However, assessments of the environmental implications of IVFs remain limited in scientific literature, with few cases applying systematic environmental assessments (Dorr et al., 2021; Martin and Molin, 2019; Martin et al., 2022; Romeo et al., 2018). A number of theoretical studies have assessed IVFs to compare their performance against competing systems such as open-field production and greenhouses, see e.g. Graamans et al. (2018) and Weidner et al. (2021, 2022). Nonetheless, empirical evidence from real case studies is lacking in the literature, which may be due in part to their novelty and evolving nature. As such, there are few studies that validate claims made by vertical farming of their resource efficiency and reduced environmental impacts, which are often focused primarily on the farm-level metrics.

Consumers, businesses, and decision-makers are becoming increasingly attentive to the use of feedback and information through credible systems to communicate and evaluate the environmental impacts of goods and services. In particular, the food sector has been increasingly employing life cycle assessment (LCA) for highlighting the 'footprint' of their products (Freidberg, 2014). Employing LCAs may be an important methodology for IVFs to meet the criticism of many of the claims in the industry and provide knowledge for working with sustainability more strategically, providing transparent and scientifically based metrics.

This chapter aims to provide insights on conducting an environmental sustainability assessment of an IVF employing LCA methodology and outline important considerations during the process. The chapter is designed to provide an overview of the method, and thereafter describes the different phases of conducting a LCA, providing guidance specifically for IVFs. It also outlined the limitations of employing LCA and provides knowledge on challenges, important aspects, and possibilities to improve the environmental performance of IVFs based on previous research. The methodology and insights are applicable to different forms of IVF. This includes assessments of, for example, the production of edible crops, mushrooms, and production of crops for other purposes (e.g. pharmaceutical applications).

2 Life cycle assessment and its application in indoor vertical farms

LCA is a broadly employed and accepted method in which the environmental impacts related to a product system or service are quantified and illustrated during its life cycle, i.e. from raw material extraction via production and use phases to waste management and transportation (Finnveden et al., 2009). The method has been used for several decades and has even been standardized by the International Standards Organization (ISO, 2006). It is used by organizations

Published by Burleigh Dodds Science Publishing Limited, 2023.

to identify so-called 'hot-spots' in their life cycle which can be used to improve processes and make strategic decisions on the best course of action to improve. LCA also provides information that can be used for labeling and decision-making.

According to ISO 14044 (2006), the process of conducting an LCA is based on four required steps (also referred to as phases), including (1) goal and scope definition, (2) inventory analysis, (3) environmental impact assessment, and (4) interpretation; see Fig. 1. These steps are specifically reviewed in subsequent sections with application to applying LCA of IVFs.

2.1 Goal and scope of the study

In the first step, the goal and scope of the LCA are defined to ensure that the outcome is consistent with the objectives, setting the context for the study. For this step, it is important that the purpose of the study is clearly defined in the documentation but also agreed upon between those conducting the LCA and the receiver (typically the client). For example, this can include the intended application of the study, such as communication, comparative assertions, product improvement, planning processes, strategic decisions, or policy-making. It is also important to highlight the conditions and assumptions for which the results of the assessment are valid, which are of utmost importance to the study.

In the scope description, the definition of the functional unit, i.e. the service delivered by the product system, is critical to agree upon. Specifically for IVFs this is typically associated with the production output, e.g. one kilogram of the edible portion (fresh weight) of a particular food available to consumers.

The definition of system boundaries should also be set. This includes what is to be included and what is to be omitted. Ideally, the system boundaries cover the full life cycle, with both upstream and downstream inputs and outputs, including all material, energy, and processes. However, often simplifications are done in order to match the scope of the study and reduce the complexity. In the

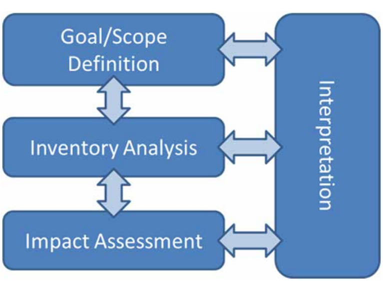

Figure 1 Elements of the Life Cycle Assessment Method (based on ISO, 2006).

LCA field, the system boundaries are typically referred to as being e.g. a cradle-to-gate study versus a cradle-to-grave study.[2] Cradle-to-gate assessments include all inputs and processes up to the availability of a product at retail or availability at the consumer. Cradle-to-grave assessments include the same as the cradle-to-gate studies but also include the use and waste management of the product after consumption, e.g. the waste handling methods for the growing media and packaging. Figure 2 illustrates an example of the system boundaries for a cradle-to-gate and a cradle-to-grave perspective applicable for an IVF. Note that the waste handling from the farm is included in the cradle-to-gate boundaries and that retail is often not included. However, the 'gate' can also be extended to include the availability of the product at the retail location, but not the use and final disposal of the product. This should be clear in the system boundaries of the study. Typically, the retail phase for food products has only a minor contribution to the environmental performance compared to other processes along the life cycle and is often omitted given this motivation.

2.2 Life cycle inventory

The life cycle inventory (LCI) is used to collect data necessary for the quantification of the environmental impacts of the service or product. This is done by mapping the applicable material and energy flows and processes involved along the life cycle confined within the system boundaries set in the scope of the project.

For IVFs, data collection includes all material and energy inputs, all transportation requirements, processes, infrastructure, and processes required for cultivation and waste handling. Figure 2 outlines many of these for a typical IVF. This is often the most tedious part of conducting any LCA, and will require a number of iterations between the LCA practitioner and the IVF, i.e. if the LCA is performed by an external source.

In order to alleviate the data collection, especially for IVFs, often a timeframe is chosen to collect data, e.g. based on annual production[3] figures. For the LCI, data quality issues can also be noted. For example, data should be as accurate as possible. Nonetheless, assumptions may need to be made when the availability of accurate data is limited, which may require a sensitivity analysis later in the assessment to see the influence this has on the results. When assumptions are made by the LCA practitioner, these should be reviewed by the IVF representative involved with the LCA in order to assure the assumptions are realistic.

2 In agricultural LCAs, cradle-to-gate can also be referred to as 'farm-to-gate' and the cradle-to-grave approach, referred to as a 'farm-to-fork' assessment.

3 It is recommended to conduct the study using annual values if a screening of impacts from the system is to be done. If the production and energy demand are consistent, a monthly value may be used. If more details on how to improve seasonally are required, monthly data can be important.

Published by Burleigh Dodds Science Publishing Limited, 2023.

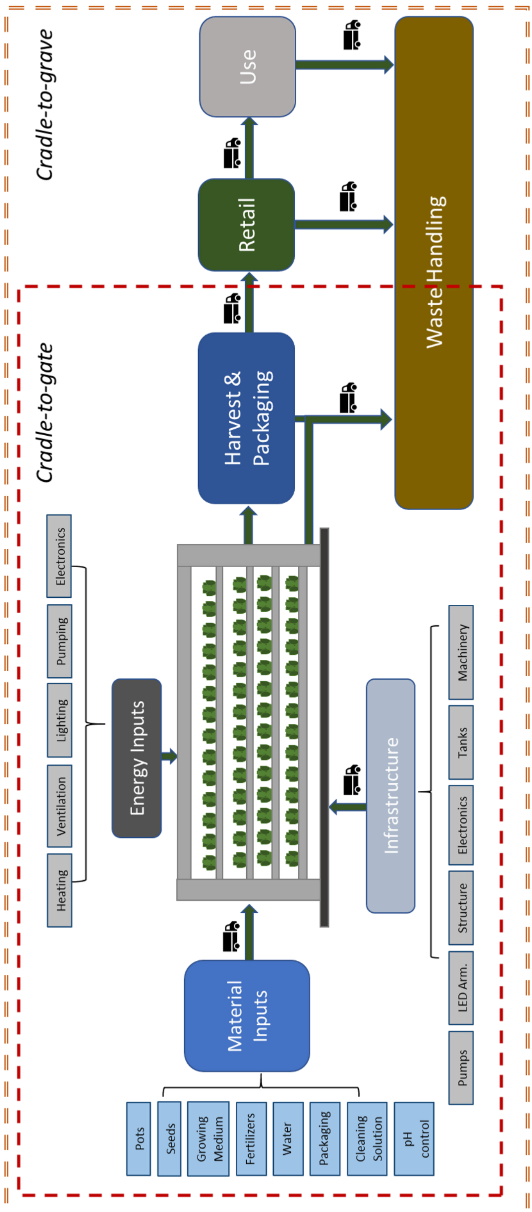

Figure 2 System boundaries for the life cycle assessment of an IVF, including inputs, outputs, of the system. Based on Martin et al. (2022).

2.2.1 Material inputs

For IVFs, a number of material inputs, or consumables, are required. Depending upon the system, this can include all consumable inputs such as, packaging for inputs (e.g. cardboard, plastics, etc.), growing media, water, fertilizers, pH control, protective wear, seeds, CO_2 enrichment, cleaning supplies, other chemicals, and packaging for products (including pots, outer wrapping, cardboard, plastics). For some materials, there may be more thorough data available. Assumptions can be made and documented on the amounts employed based on the total outputs. Practically, it may also be possible to review expenses and make estimates on the amounts used annually.

2.2.2 Energy

For IVFs, the energy demand is of key importance to the environmental impacts. As such, it is crucial that data is collected on the amount of energy employed, in addition to its sourcing. For electricity, information on the source is important for the LCA and relevant information on certificates of origin for the electricity should be reviewed.

Energy consumption may be primarily related to electricity demand for LED lighting, pumps, HVAC[4] systems, monitoring equipment, and other processes. If external heating sources from other energy carriers than electricity are used, these should also be included in the study, e.g. natural gas or district heating.

2.2.3 Transportation

For the LCA, information on the transportation distance of all materials into the farm, and products and waste leaving the farm, are included in the assessment. Important information here includes the distances from the sourcing of the materials and supplies. While detailed information can be included, assumptions can be made on the distances. Furthermore, for transportation of the products to markets, a breakdown of different markets can be provided, or an average travel distance could be provided.

For LCAs, the transportation of materials and products is typically assessed as tonne-kilometers (tonne-km) as the LCI datasets for transportation logistics are provided in these units. As such, the distance is then multiplied by the mass (in tonnes) of the material or product. See, e.g. the row 'Transportation-Inputs' in Table 1, which sums up all the tonne-km for all material inputs; similarly this is also done for the outputs and infrastructure. If transportation of items to and from the farm is conducted in other forms, datasets, e.g. for driving a car or van, can also be included, and are typically related to the number of kilometers driven.

4 Heating, ventilation, and air-conditioning (HVAC).

Table 1 Simplified input-output table employed for the LCI in LCAs of IVFs. Values are arbitrarily included.

Type	Category	Specific category	Inputs	Amount (annually)	Unit	Transport distance (km)
Inputs	***Material inputs***	**Growing medium**	Growing media	10	kg	100
		Fertilizers	Fertilizer 1	1	kg	50
			Fertilizer 2	2	kg	50
		Seeds	Seeds	5	kg	100
		Water	Tap Water	100	m^3	–
		Other	CO_2 (enrichment)	60	kg	45
		Packaging	Polystyrene (PS)	3	kg	50
			PET	5	kg	50
			Polypropylene	5	kg	50
			Cardboard	20	kg	50
	Transportation-inputs		Material inputs (Truck)	6	tonne-km	–
	Energy inputs		Electricity	5000	kWh	–
			Heat	1000	kWh	–
Outputs	**Production outputs**		Plant (Type 1)	400	edible kg	50
			Plant (Type 2)	500	edible kg	20
	Cultivation and packaging wastes		Packaging waste (Plastic)	5	kg	50
			Packaging waste (Cardboard)	15	kg	50
			Organic waste	10	kg	50
	Transportation-outputs/market		Market (Truck)	30	tonne-km	–
			Waste handling (Truck)	1.5	tonne-km	–
Infrastructure	**Infrastructure**		Steel tray structures	1500	kg	100
			Plastic	50	kg	100
			Pipes (Polyethylene)	15	kg	100
			LED light fixtures	50	units @ 1.5 kg	100
			Tanks	2	units	100
			Seeding machine	1000	kg	100
			Other electronics	25	kg	100
	Transportation-infrastructure		Truck	359	tonne-km	–

2.2.4 Infrastructure

Infrastructure for IVF is an important input in the assessment of the system. For an IVF, this can include steel structures, tanks, tubing, pumps, electronics, machinery (seeding, packaging, etc.), HVAC equipment, LED armatures, etc. It is also important to take into account the lifetime of the infrastructure. As such, the entire infrastructure does not affect the environmental impacts of the vertical farm on one specific year but is distributed over the lifetime. An example is the assumed steel structures which have a long lifetime. As 1500 kg of steel is assumed to be included in the structure, with a lifetime of 25 years, the impact on the annual system would be related to employing 60 kg of steel. The infrastructure also may have varying durability, i.e. associated lifetimes. While steel structures may have an assumed long lifetime, LED lighting fixtures and other active equipment, such as pumps, tubing, and various plastics may have a much shorter lifetime due to their active use. Maintenance and added equipment and infrastructure can also be included if the information is available. The LCA practitioner and the IVF firm should make assumptions on the lifetime of all infrastructures based on evidence from both practical experience, information from the producer, scientific literature, and ensure to document this in the study.

2.2.5 Outputs

While some producers specialize in a single or a handful of outputs, others may have a large span of different products. These can be accounted for differently, depending on the type of output (e.g. salad, herbs, mushrooms, etc.). Furthermore, while some farms may sell harvested crops, others may sell as potted plants with packaging and growing media. As such it is important for an LCA to take into account the type of product sold. Typically this is done by accounting for the edible portion, e.g. in kilograms, of the product to retail. For potted plants, the total number annually can be used. Furthermore, waste from the farm should also be accounted for, see subsequent section.

2.2.6 Waste handling

Besides the edible portion of the products sold to market, there may be a number of waste and residual streams produced from the farm. This includes, but is not limited to, biowastes (e.g. growing media and plants), packaging wastes, wastewater to drain, equipment, and any other consumables (e.g. protective wear). For each of these flows, the amount and their method of waste handling should be accounted for. The waste handling methods for different waste streams may vary depending upon the location and IVF. This can include

Published by Burleigh Dodds Science Publishing Limited, 2023.

sending the waste for incineration, landfill, or to recycling for certain materials. If residual streams are included in the output, e.g. products or energy sold to other systems, these are important for the LCA. This can include residual heat which may be used in other applications, e.g. heating of the host building and other co-located spaces (Martin et al., 2022).

In studies with a cradle-to-grave perspective, an important aspect to take into account is the waste handling of the final product and packaging. As such, the materials and design of the packaging may be important at this stage. Once again, methods for the treatment of these waste flows should be accounted for. Practically, after the product leaves the farm this may not be clear, as information on consumer behavior, including how they employ the product, the share of waste, and what they do with the waste may not be available. As such, assumptions can be made based on local conditions and systems available in the region.

2.2.7 Connecting to LCI datasets

Once the inventory is complete, LCI data is gathered to match those flows and processes. Despite the comprehensive nature of LCI databases from sources such as Ecoinvent (Frischknecht et al., 2005) not all datasets are available to match with flows and processes outlined in the inventory. As such, representative datasets can be chosen, although assumptions should be documented. For example, there may not be datasets available for a specific component, e.g. a specific sensor. However, a dataset specifying an 'active electronic component' may be used as a proxy. At this stage, it is important to ensure that the LCI datasets and the inventory listing have similar units. As an example, in the case of the sensors, in the inventory, the number of sensors may be included. However, the LCI data may be provided for the mass of the electronic components, e.g. in kg. As such conversions will be required to allow for these to be used. When conducting an LCA, it is important to always list which LCI datasets we used, which are often listed as a table, in order to improve transparency.

2.3 Life cycle impact assessment

The next phase of conducting an LCA is the life cycle impact assessment (LCIA). In this phase, the environmental impacts associated with all inputs and processes are quantified and provided for different selected environmental impact categories. When conducting this phase, predefined LCIA methods included in LCA software are employed. These are used to aggregate the environmental impacts into different environmental impact categories.

LCIA methods are categorized as midpoint and endpoint approaches. Firstly, midpoint approaches provide quantitative modeling for equivalent emissions of substances. It stops at this point to reduce the uncertainties and does not include weighting. Examples of midpoint categories are global warming potential (kg CO_2-eq.) or acidification potential (e.g. measured in kg SO_2-eq.). Taking this a step further, endpoint approaches model damages caused by the release of different substances and emissions. An example of an endpoint impact includes the Disability-adjusted life years (DALY) impact category which takes into account years lost to premature death due to illness, disability, or early death. For IVFs, the midpoint methods are most appropriate. As an example, for the impact category, Global Warming Potential (also referred to as carbon footprint), an aggregation of all greenhouse gas emissions (GHGs; such as CO_2, CH_4, N_20, etc.) is conducted to assess their impacts on climate change. These are expressed as kg CO_2-equivalent units, denoted as kg CO_2-eq.

While it is often assumed that carbon footprints are LCAs, this is only one impact category in a much broader set of environmental impact categories. Various LCIA methods contain a large number of impact categories. Some of these included the ReCiPe method (Huijbregts et al., 2016) or the ILCD Environmental Footprint v. 3.0 method (ILCD, 2010) with a large range of environmental impact categories available. The ReCiPe method contains 18 environmental impact categories, including agricultural land occupation (m^2a), climate change (kg CO_2-eq.), fossil depletion (kg oil-eq.), freshwater ecotoxicity (kg 1,4-DCB-eq.), freshwater eutrophication (kg P-eq.), human toxicity (kg 1,4-DCB-eq.), ionizing radiation (kg U235-eq.), marine ecotoxicity (kg 1,4-DB-eq.), marine eutrophication (kg N-eq.), metal depletion (kg Fe-eq.), natural land transformation (m^2), ozone depletion (kg CFC-11-eq.), particulate matter formation (kg PM_{10}-eq.), photochemical oxidant formation (kg NMVOC-Eq), terrestrial acidification (kg SO_2-eq.), terrestrial ecotoxicity (kg 1,4-DCB-eq.), urban land occupation (m^2a), and water depletion (m^3 water-eq.).

LCAs of IVFs may choose to include all or a selected number of environmental impact categories. However, for IVFs, several authors have shown that important indicators from LCIA methods include those related to carbon footprint, resource consumption, water depletion, ecotoxicity, acidification, and eutrophication (Dorr et al., 2021; Martin et al., 2022). LCIA methods, however, are regionally specific. Many of the LCIA methods are based on European conditions. As such, regionally specific LCIA methods for different regions can also be used. For example, the ILCD or ReCiPe methods can be used for European conditions, while the TRACI LCIA method is more applicable to North American conditions.

2.4 Partitioning of environmental impacts in multi-functional processes

If an IVF produces several products, referred to as a multi-functional process, the allocation to the functional unit and other products from the system is necessary. The impacts are therefore partitioned to all products of the system, which is done by physical or economic allocation. Physical allocation is done by partitioning impacts to the different products by their physical properties of the overall output, e.g. by their mass or energy. For IVFs, the mass of the products is primarily used, with edible mass preferable. Economic allocation refers to partitioning impacts on the products based on their economic value (e.g. market price). The economic value inherent in the products and by-products may change, or be different depending on the location of an IVF, inhibiting comparisons (Cherubini, 2010; van der Voet et al., 2010).

In the ISO standards, it is recommended that allocation be avoided if possible (ISO, 2006). To do so, a method referred to as system expansion may be used to avoid allocation, by removing impacts from conventional products replaced from by-products of the system (Weidema, 2001). This is done by identifying the equivalent amount of conventional products or materials replaced by a by-product of the system and thereafter finding the environmental impacts of producing that product. In the calculations, the impacts from the avoided system are credited. The system expansion method is a form of consequential modeling, also referred to as partial-consequential modeling (Brander et al., 2009), for the avoidance of processes created in the system affecting markets outside the system (Zamagni et al., 2012).

An example of this can include a mushroom farm, which produces mushrooms as the main outputs, but the spent mushroom substrate is used for soil amendment. Assuming that replaces, e.g. peat, the equivalent amount of peat, either in kilograms of volume (m^3) can be avoided and credited to the mushroom farm. See examples of such calculations for IVFs in Fig. 3 and also in previous assessments of IVFs including by-products that provide credits to the system such as the use of residual heat from IVFs (Martin et al., 2019, 2022).

It should be noted that the allocation in multi-functional processes is a highly controversial topic in the LCA field. There is extensive literature devoted to this (see e.g. Ekvall and Finnveden, 2001; Wardenaar et al., 2012). Nonetheless, as Guinée et al. (2004) suggest, there is no 'correct' way to solve this problem in practice or theory. It should be apparent, that the chosen allocation method is consistent with the research questions addressed and the main methodological choices made. One way to avoid critique on the allocation issue is to conduct the study and illustrate the results by applying different approaches, i.e. including allocation (e.g. mass or economic) and system expansion, thus showing the influence this can have on the results.

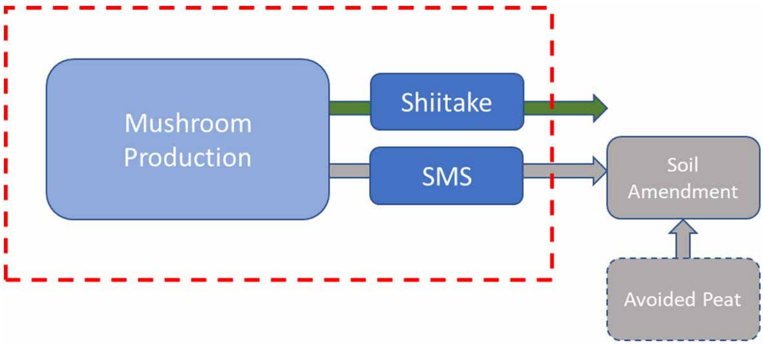

Figure 3 Depiction of system-expansion method to show how the use of spent mushroom substrate (SMS) can lead to avoided peat use.

2.5 Interpretation

The 'last' phase of an LCA is the interpretation phase. In this phase, the practitioner(s) interpret the inventory and impact results in order to assess the consistency, sensitivity, and significant issues to be used to formulate conclusions, recommendations, and limitations for the study. This is important for communication with external parties in order to highlight any limitations and uncertainties.

The process of interpretation is rather iterative in nature, requiring revisions to the model and data. A previous study by Lazarevic (2012, p. 3) describes the iterative nature of conducting the LCA as follows, 'the goal and scope of the study are defined, a life cycle model is developed, impact assessments produced, the goal and scope are then refined or revised if necessary, key data improved, impact assessment characterization factors are improved, results interpreted, reported and subjected to independent review if necessary.'

For LCA studies with IVFs, this may include reviewing the assumptions made on different processes, transportation distances, representative datasets employed, and making any necessary improvements to the model. Processes, inputs, and datasets which were found to have a large influence on the overall environmental impacts can also be analyzed further and sensitivity analyses can be conducted to show their influence. This is often done by changing the datasets, or showing how an increase or decrease in the specified amount can influence the results. As outlined as follows, for IVFs, one important aspect to conduct a sensitivity analysis is the electricity data employed.

3 Strengths and limits of life cycle assessments for indoor vertical farms

LCA's strength lies in its comprehensive approach to evaluate upstream and downstream flows of a product or service (Hermann et al., 2007; Finnveden et al., 2009). This is important, as impacts from a product or service may have impacts unevenly distributed along the life cycle. For assessing the environmental implications of a product or service, LCA cannot completely be replaced, as other stools may not review a cradle-to-grave perspective (Finnveden, 2000).

However, LCA also has some limitations. The objectivity, methodological considerations, and completeness have been debated for decades (Arvidsson et al., 2018; Freidberg, 2014; Heiskanen, 1999). As previously outlined, allocation and other methodological choices have been subject to extensive scientific discussion in the field (Brandao et al., 2017; Ekvall and Finnveden, 2001; Plevin et al., 2014). Data availability can also be a limiting factor for conducting LCAs of IVFs, with limited data on specific materials and infrastructural components, e.g. substrates and components for the infrastructure.

LCA is also limited to environmental impacts. As such, it may be difficult to capture the benefits of IVFs for local food provisioning compared to conventional methods. Despite this, similar assessments can be made to assess the social and economic implications using other life cycle approaches, such as social LCA and life cycle costing. These can even be combined to provide a more holistic approach to assessing sustainability, using life cycle sustainability assessment (Sala et al., 2013; Zamagni et al., 2013). Furthermore, LCAs may not fully model rebound effects and future changes in technology, e.g. the claims by IVF firms that it 'frees' space for conventional agriculture.

4 Insights from life cycle assessments of indoor vertical farms

From previous studies applying LCA to IVFs, a number of processes and parameters are important, or sensitive, for the overall environmental performance. The following sections outline several of these important processes and parameters in order to provide information that can be used to improve the process and environmental performance of LCA practitioners and IVFs.

4.1 Electricity and climate control

Similar to other forms of controlled environment agriculture, energy is of utmost importance for IVFs. From previous research, the largest share of environmental impacts from IVFs has been found to stem from energy demands for LED and HVAC systems; see e.g. findings in Graamans et al. (2018), Martin et al. (2022), and Weidner et al. (2022). Additionally, given the large share of emissions from energy sources, the results are highly sensitive to the source, and subsequent choice of LCI dataset, for electricity. It is advised that when conducting an LCA for IVFs, the regional energy mix, or mixes, should be used.

As an example, Martin et al. (2019, 2022) show the sensitivity of employing the Swedish electricity mix versus a Nordic electricity mix on the environmental performance of an IVF, confirming significant differences between the two options.

Furthermore, if an IVF purchases electricity with certificates of origin, e.g. from hydropower or wind, this should also be compared with the regional system. This is exemplified in a recent study for IVF in Sweden, where the choice of hydropower-based electricity led to lower environmental impacts compared to other studies from Sweden, see e.g. Milestad et al. (2020). As identified by Brander et al. (2018), it is not certain that the electricity is produced from their claimed origins or can lead to changes in the electricity mix of a given region or that the electricity used has the same profile. Additionally, different standards for conducting LCAs handle the use of energy sourcing differently, and it is advisable to show results based on different electricity sources and mixes in order to avoid criticism. In conclusion, it is advised when conducting an LCA to show the sensitivity of different electricity mixes on the results of the study.

4.2 Substrates

For IVFs, the choice of substrate can also have a significant influence on the environmental performance of an IVF. Previous research has shown that substrates such as perlite and peat may have large environmental impacts, while lower environmental impacts are found for by-products such as coir (Martin et al., 2019, 2022; Quantis, 2012; Toboso-Chavero et al., 2021; Vinci and Rapa, 2019). The use of peat also continues to be controversial (Chapman et al., 2003; Hojlund, 2008; Salomaa et al., 2018). However, further research should be conducted on the environmental performance of different substrates as the use of new materials evolves for applications in IVFs. These typically include blends of materials and there has been an increased influx of new substrate materials specifically designed for IVF applications.

Depending on the growing system adopted, the amount of substrate needed by the IVF may also significantly vary, or may even be absent (e.g. when aeroponic farms are using reusable sowing mats, obtained from recycled materials). Accordingly, strategies that account for substrate use reduction should also be envisaged, when comparative scenarios are elaborated.

It should also be noted that the inherent properties of different substrates may also affect their waste handling methods. For inorganic substrates, landfilling or incineration may be the only option, while for other bio-based materials, composting or recycling may be employed. This can also have an influence on waste management and should be considered in the design of the system, e.g. to promote more closed-loop or circular systems.

4.3 Infrastructure

The infrastructure has been shown to have a minor contribution to the overall environmental performance of IVFs. However, the infrastructure can contribute to as high as 10–15% of the overall GHG emissions, and equally contribute significantly to resource depletion, given the amount of metals and electronic components (Barge, 2020; Martin and Molin, 2019). This can be sensitive to the assumed lifetime of certain inputs and components. For example, as the industry is novel, there may not be a large base of experience to base assumptions on the lifetime of products. Creating new buildings for an IVF may have a large influence on the impact of the infrastructure, while employing residual or existing spaces may not require as many resources. However, the materials and processes needed to use existing spaces should also be taken into account. Again, for new structures or intermediate processing required to use residual and existing spaces, the assumed lifetime can have a large influence on the impact of the infrastructure. This suggests that, from a life cycle perspective, choices to improve the lifetime of the materials, have a benefit to the environmental performance of IVFs.

Furthermore, in previous assessments, the results were also found to be sensitive to datasets for the infrastructure, including, e.g. electronics, machinery, and metals (Barge, 2020). For infrastructure, it is crucial to carefully choose representative products in the LCI datasets. Additionally, for reviewers of the LCAs and for ensuring the scientific-based information provided by an LCA, transparently providing information on the assumed lifetimes in addition to the LCI datasets employed is of utmost importance for an LCA.

4.4 Packaging

In previous studies, packaging has been found to contribute only to a small share of the environmental impacts of IVFs. However, a large number of studies have also excluded packaging from their assessment (Graamans et al., 2018; Romeo et al., 2018; Weidner et al., 2022) motivating its minor share of the overall impacts. However, despite its relatively small share to the overall impacts, annually the total consumption of certain materials may contribute to a large environmental footprint (e.g. GHG emissions and resource consumption). Reducing the amount of material, e.g. plastics, and developing approaches to switch from conventional black-colored[5] plastics to other colors, or other bio-based materials, may allow for the possibility of recycling and composting. This is also regionally and context-dependent on the markets for IVF products. As such, the packaging should be carefully chosen as it can also influence its waste

5 Black plastics are often difficult to recognize in sorting systems and often end up in incineration.

handling methods. Further studies are needed to understand this impact, especially as the IVF industry has been quick to address the use of plastics in their work with sustainability.

5 Life cycle management and increasing transparency

A large focus in the IVF industry has been geared to promote sustainability, although there is little documentation on how vertical farming companies work with sustainability beyond claims provided on the packaging and in media. For IVFs, it is important that claims made are substantiated. However, few transparent assessments and studies of their work are available; see e.g. (Agritecture, 2022). In previous research, it was found that IVFs consider environmental performance information important for benchmarking and communicating their environmental performance. However, few were willing to publicly provide the results of their assessments due to the fact that most systems are constantly improving and evolving. As such, the so-called 'snapshot' with an LCA may not be representative of a system in the near future. Claims and comparative assertions on the benefits of IVFs compared to conventional systems also contradict the original intent in the early development of LCA, making comparative assertions and suggesting one system is better than another. When drawing conclusions from LCAs, Finnveden (2000) suggested that conclusions cannot be made on which system is 'better,' though they can lead to decisions leading to a better course of action than would have been followed.

Using the information, however, can be essential to developing improvement options. However, developing prospective approaches can be a beneficial stance to proactively work with sustainability issues at an early stage of development to identify the best technologies for specific contexts, e.g. markets, geographic locations, and infrastructure available (Arvidsson et al., 2018; Martin et al., 2021).

6 Conclusion and future trends in research

The majority of current vertical farming systems employ linear approaches to their production. This entails that they employ imported (often virgin) materials from outside their immediate regions for all their resource and energy demands. In the future, employing recycled materials in addition to renewable and residual energy sources may reduce the environmental impacts of the consumables and other inputs. With cities becoming an important driving force for the circular economy and as a critical stakeholder for developing and improving food security, synergies between IVFs and their urban infrastructure are essential for understanding and planning for future urban food systems.

As such, sustainable solutions for more integrated food, water, energy, and transportation will become increasingly important (Specht et al., 2014; Martin et al., 2019, 2022; Rufi-Salis et al., 2020). There is currently a number of research projects exploring such developments ongoing worldwide, which have the potential to develop more circular approaches for the IVF industry and potentially improve the environmental performance of IVFs.

Furthermore, in the coming years, it is expected that IVF production will gain in terms of product diversification, moving from the current systems, which are mainly based on leafy vegetables, herbs, and microgreens, toward a wide range of agricultural goods. In the future, these are expected to include berries, edible flowers, potted seedlings, etc. For these products, comparative assessments versus conventional production systems (both in terms of cultivation and transportation/storage), may become more relevant to compare the implications of IVFs.

7 Where to look for further information

For further information about life cycle assessment and its application in general, there are a number of standards, guidelines, and helpful resources. A great introduction to LCA and its application can be found in the book by Tillman and Baumann, titled *The Hitch Hiker's Guide to LCA: An Orientation in Life Cycle Assessment Methodology and Application* (ISBN: 9789144023649). Further guidance on LCA methodology can be found from the European Commission's Joint Research Center in The International Reference Life Cycle Data System (ILCD) Handbook, document EUR 24378 EN-2010 (https://eplca.jrc.ec.europa.eu/ilcd.html).

Standards for LCA can also be reviewed, above all the International Standards Organisation (ISO) standards for LCA, through the ISO 14040 series. These provide relevant standards and guidelines on how to conduct LCA as per the industry standard and followed by much of the academic literature for applying LCA to products and services (https://www.iso.org/standard/38498.html).

A number of articles have also been published which assess the environmental performance of indoor vertical farming systems, several of which have been produced by the authors of this chapter, see e.g. Orsini et al. (2020), Martin et al. (2022) and Martin and Molin (2019).

There are also a number of current research projects related to indoor vertical farms and sustainability. The authors' own research projects provide a great reference for outputs and dissemination activities related to the sustainability of vertical and urban farms. These can be found through the Sustainable Urban Farming Lab (www.ivl.se/suf) and the FoodE project (www.foode.eu).

Finally, the Food and Agricultural Organization (FAO), the Association for Vertical Farming (AVF), and the International Society for Horticultural Sciences (ISHS) have developed reports, papers, and webinar series which address the sustainability of indoor vertical farming which are of interest.

8 Acknowledgements

The research leading to this publication was co-financed by the following funding sources: 1) Swedish Innovation Agency (Vinnova), within the Research Program, Innovations for a Sustainable Society, in the project ‘Urban farming for resilient and sustainable food production in urban area,’ grant code: 2019-03178, 2) the Swedish Research Council for Sustainable Development (FORMAS), within the Research Program, Increased mobility between academy and practice project ‘Assessing and Improving the Sustainability of Urban Vertical Farming Systems,’ grant code: 2019-02049, and 3) the Italian Ministry of Research and Education (MUR), within the Research Programmes of National Interest (PRIN) project ‘Sustainable Vertical Farming (VFarm),’ grant code: J33C20002350001.

9 References

Agritecture (2022). The 2021 global CEA consensus. Online, Available at: https://www.waybeyond.io/census, Accessed [2022 February 10].

Al-Chalabi, M. (2015). Vertical farming: skyscraper sustainability? *Sustain. Cities and Soc.* 18, 74–77.

Arvidsson, R., Tillman, A.-M., Sandén, B. A., Janssen, M., Nordelöf, A., Kushnir, D. and Molander, S. (2018). Environmental assessment of emerging technologies: recommendations for prospective LCA. *J. Ind. Ecol.* 22(6), 1286–1294.

Barge, U. (2020). *Analyzing the Environmental Sustainability of an Urban Vertical Hydroponic System*, UPTEC WUppsala University, Uppsala, p. 89.

Benke, K. and Tomkins, B. (2017). Future food-production systems: vertical farming and controlled-environment agriculture. *Sustain.: Sci., Pract. Policy* 13(1), 13–26.

Brandao, M., Martin, M., Cowie, A., Hamelin, L. and Zamagni, A. (2017). *Consequential Life Cycle Assessment: What, How, and Why?. Reference Module in Earth Systems and Environmental Sciences*. Elsevier, December 2017.

Brander, M., Tipper, R., Hutchison, C. and Davis, G. (2009). *Consequential and Attributional Approaches to LCA: A Guide to Policy Makers with Specific Reference to Greenhouse Gas LCA of Biofuels*. Technical Paper TP-090403-A.

Brander, M., Gillenwater, M. and Ascui, F. (2018). Creative accounting: A critical perspective on the market-based method for reporting purchased electricity (scope 2) emissions. *Energy Policy* 112, 29–33.

Chapman, S., Buttler, A., Francez, A.-J., Laggoun-Défarge, F., Vasander, H., Schloter, M., Combe, J., Grosvernier, P., Harms, H., Epron, D., Gilbert, D. and Mitchell, E. (2003). Exploitation of northern peatlands and biodiversity maintenance: a conflict between economy and ecology. *Front. Ecol. Environ.* 1(10), 525–532.

Cherubini, F. (2010). GHG balances of bioenergy systems – overview of key steps in the production chain and methodological concerns. *Renew. Energy* 35(7), 1565–1573.

Despommier, D. (2011). The vertical farm: controlled environment agriculture carried out in tall buildings would create greater food safety and security for large urban populations. *J.Verbraucherschutz Lebensmittelsicherheit* 6(2), 233–236.

Dorr, E., Koegler, M., Gabrielle, B. and Aubry, C. (2021). Life cycle assessment of a circular, urban mushroom farm. *J. Clean. Prod.* 288, 125668.

Ekvall, T. and Finnveden, G. (2001). Allocation in ISO 14041—a critical review. *J. Clean. Prod.* 9(3), 197–208.

Finnveden, G. (2000). On the limitations of life cycle assessment and environmental systems analysis tools in general. *Int. J. Life Cycle Assess.* 5(4), 229–238.

Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D. and Suh, S. (2009). Recent developments in life cycle assessment. *J. Environ. Manag.* 91, 1–21.

Freidberg, S. (2014). Footprint technopolitics. *Geoforum* 55, 178–189.

Frischknecht, R., Jungbluth, N., Althaus, H. J., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G. and Spielmann, M. (2005). The ecoinvent database: overview and methodological framework (7 pp). *Int. J. Life Cycle Assess.* 10(1), 3–9.

Graamans, L., Baeza, E., van den Dobbelsteen, A., Tsafaras, I. and Stanghellini, C. (2018). Plant factories versus greenhouses: comparison of resource use efficiency. *Agric. Syst.* 160, 31–43.

Guinée, J. B., Heijungs, R. and Huppes, G. (2004). Economic allocation: examples and derived decision tree. *Int. J. Life Cycle Assess.* 9, 23–33.

Heiskanen, E. (1999). Every product casts a shadow: but can we see it, and can we act on it? *Environ. Sci. Policy* 2(1), 61–74.

Hermann, B. G., Kroeze, C. and Jawjit, W. (2007). Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators. *J. Clean. Prod.* 15, 1787–1796.

Hojlund, B. A. (2008). Substitution of peat with garden waste compost in growth media preparation: a comparison from a LCA-modelling (EASEWASTE) perspective. Proceedings of the International Congress CODIS 2008. Solothurn, Switzerland.

Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M. D. M., Hollander, A., Zijp, M. and van Zelm, R. (2016). *ReCiPe 2016: A Harmonized Life Cycle Impact Assessment Method at Midpoint and Endpoint Level*. Report I: Characterization. RIMV Report 2016-0104.

ILCD (2010). *International Reference Life Cycle Data System (ILCD) Handbook—General Guide for Life Cycle Assessment—Detailed Guidance* (1st edn.).

ISO (2006). *ISO 14044:2006 Environmental Management -Life Cycle Assessment -Requirements and Guidelines*. International Standards Organisation (ISO).

Lazarevic, D. (2012). *Life Cycle Thinking and Waste Policy: Between Science and Society*. Royal Institute of Technology (KTH), Industrial Ecology.

Martin, M., Heiska, M. and Björklund, A. (2021). Environmental assessment of a product-service system for renting electric-powered tools. *J. Clean. Prod.* 281, 125245.

Martin, M. and Molin, E. (2019). Environmental assessment of an urban vertical hydroponic farming system in Sweden. *Sustainability* 11(15), 4124.

Martin, M., Poulikidou, S. and Molin, E. (2019). Exploring the environmental performance of urban symbiosis for vertical hydroponic farming. *Sustainability* 11(23), 6724.

Martin, M., Weidner, T. and 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, 849304.

Milestad, R., Carlsson-Kanyama, A. and Schaffer, C. (2020). The Högdalen urban farm: a real case assessment of sustainability attributes. *Food Secur.* 12(6), 1461–1475.

Orsini, F., Pennisi, G., Zulfiqar, F. and Gianquinto, G. (2020). Sustainable use of resources in plant factories with artificial lighting (PFALs). *European J. Hortic. Sci.* 85(5), 297–309.

O'Sullivan, C. A., McIntyre, C. L., Dry, I. B., Hani, S. M., Hochman, Z. and Bonnett, G. D. (2020). Vertical farms bear fruit. *Nat. Biotechnol.* 38, 160–162.

Plevin, R. J., Delucchi, M. A. and Creutzig, F. (2014). Using attributional life cycle assessment to estimate climate-change mitigation benefits misleads policy makers. *J. Ind. Ecol.* 18(1), 73–83.

Pulighe, G. and Lupia, F. (2020). Food first: COVID-19 outbreak and cities lockdown a booster for a wider vision on urban agriculture. *Sustainability* 12, 5012.

Quantis (2012). *Comparative Life Cycle Assessment of Horticultural Growing Media Based on Peat and Other Growing Media Constituents Final Report*. Quantis, Lausanne.

Romeo, D., Vea, E. B. and Thomsen, M. (2018). Environmental impacts of urban hydroponics in Europe: a case study in Lyon. *Procedia CIRP* 69, 540–545.

Rufí-Salís, M., Petit-Boix, A., Villalba, G., Gabarrell Durany, X. and Leipold, S. (2020). Combining LCA and circularity assessments in complex production systems: the case of urban agriculture. *Resour. Conserv. Recycl.* 166, 105359.

Sala, S., Farioli, F. and Zamagni, A. (2013). Progress in sustainability science: lessons learnt from current methodologies for sustainability assessment: Part 1. *Int. J. Life Cycle Assess.* 18(9), 1653–1672.

Salomaa, A., Paloniemi, R. and Ekroos, A. (2018). The case of conflicting Finnish peatland management – skewed representation of nature, participation and policy instruments. *J. Environ. Manage.* 223, 694–702.

Specht, K., Siebert, R., Opitz, I., Freisinger, U., Sawicka, M., Werner, A., Thomaier, S., Henckel, D., Walk, H. and Dierich, A. (2014). Urban agriculture of the future: An overview of sustainability aspects of food production in and on buildings. *Agric. Human Values* 31, 33–51.

Thomaier, S., Specht, K., Henckel, D., Dierich, A., Siebert, R., Freisinger, U. B. and Sawicka, M. (2014). Farming in and on urban buildings: present practice and specific novelties of zero-Acreage Farming (ZFarming). *Renew. Agric. Food Syst.* 30(1), 43–54.

Toboso-Chavero, S., Madrid-López, C., Villalba, G., Gabarrell Durany, X., Hückstädt, A. B., Finkbeiner, M. and Lehmann, A. (2021). Environmental and social life cycle assessment of growing media for urban rooftop farming. *Int. J. Life Cycle Assess.* 26(10), 2085–2102.

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. and Marcelis, L. F. M. (2021). Current status and future challenges in implementing and upscaling vertical farming systems. *Nat. Food* 2(12), 944–956.

van der Voet, E., Lifset, R. J. and Luo, L. (2010). Life-cycle assessment of biofuels, convergence and divergence. *Biofuels* 1(3), 435–449.

Vinci, G. and Rapa, M. (2019). Hydroponic cultivation: life cycle assessment of substrate choice. *Br. Food J.* 121(8), 1801–1812.

Published by Burleigh Dodds Science Publishing Limited, 2023.

Wardenaar, T., Van Ruijven, T., Beltran, A. M., Vad, K., Guinée, J. and Heijungs, R. (2012). Differences between LCA for analysis and LCA for policy: A case study on the consequences of allocation choices in bio-energy policies. *Int. J. Life Cycle Asses* 17, 1059–1067.

Weidema, B. (2001). Avoiding co-product allocation in life-cycle assessment. *J. Ind. Ecol.* 4(3), 11–33.

Weidner, T., Yang, A., Forster, F. and Hamm, M. W. (2022). Regional conditions shape the food–energy–land nexus of low-carbon indoor farming. *Nat. Food* 3(3), 206–216.

Weidner, T., Yang, A. and Hamm, M. W. (2019). Consolidating the current knowledge on urban agriculture in productive urban food systems: learnings, gaps and outlook. *J. Clean. Prod.* 209, 1637–1655.

Weidner, T., Yang, A. and Hamm, M. W. (2021). Energy optimisation of plant factories and greenhouses for different climatic conditions. *Energy Convers. Manage.* 243, 114336.

Zamagni, A., Guinée, J., Heijungs, R., Masoni, P. and Raggi, A. (2012). Lights and shadows in consequential LCA. *Int. J. Life Cycle Assess.* 17(7), 904–918.

Zamagni, A., Pesonen, H.-L. and Swarr, T. (2013). From LCA to life cycle sustainability assessment: concept, practice and future directions. *Int. J. Life Cycle Assess.* 18(9), 1637–1641.