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Analyzing the environmental sustainability of an urban vertical hydroponic system

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ABSTRACT

Analyzing the environmental sustainability of an urban vertical hydroponic system
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Food systems are considered one of the most important anthropogenic activities contributing to climate change. On the other hand, climate change influences the conditions for growth with more frequent droughts and heatwaves. This contradiction poses a significant challenge to future food systems, which need not only become more sustainable, but also increase its production to feed a growing population, as stated in both the United Nations Sustainable Development Goals, and the Swedish action plan on food.

This has given rise to alternative ways of producing food, such as urban farming and, in particular vertical hydroponic farming, where food is grown indoors in a controlled environment with artificial lighting and with a minimum use of water and without pesticides. In this study, a vertical hydroponic farm located in Stockholm, Sweden, is examined using life cycle assessment in terms of environmental sustainability. The farm, located in a basement space, works together with the building in a symbiotic network, where the farm provides the building with excess heat from the lighting, and in turn obtains carbon dioxide from an office floor.

The findings from the study show that electricity is a major contributor to the environmental performance of the farm, along with the infrastructure employed. The impacts of water use in the farm, is very low, along with the impacts associated with the delivery of the crops; illustrating the advantages of producing food locally. By substituting the synthetic fertilizers employed to biofertilizers, and by substituting the plastic bag material to renewable material, reductions in greenhouse gases are possible. The symbiotic development between the farm and the building is shown very beneficial to the farm, highlighting the importance of synergies between actors in urban areas.

Keywords: urban farming, vertical farming, hydroponics, urban symbiosis, life cycle assessment (LCA)

REFERAT

Utvärdering av den miljömässiga hållbarheten av en urban vertikal hydroponisk odling
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Livsmedelsindustrin anses vara en av de största antropogena drivkrafterna bakom klimatförändringarna. Å andra sidan så förändrar klimatförändringar i sig förutsättningarna för hållbar odling, med mer frekventa torrperioder, extrem värme och extrem nederbörd. Denna konträra situation ställer stora krav på framtidens livsmedelsindustri, som dessutom måste producera mer mat för att mätta en ökande befolkning; ett åtagande som står angivet både i FN:s globala mål och i den svenska Livsmedelsstrategin.

Många forskare menar att dagens livsmedelsindustri inte kommer klara denna omställning, och att alternativa metoder för att producera mat behövs. Urban odling har föreslagits som en del av lösningen, och i synnerhet vertikal hydroponisk odling där grödor växer inomhus i en kontrollerad miljö med artificiell belysning, låg vattenanvändning och utan bekämpningsmedel. Den här studien undersökte en vertikal hydroponisk odling i Stockholm, och bedömde dess miljömässiga hållbarhet med hjälp av en livscykelanalys. Odlingen, som sker i en källarlokal, samarbetar med den omslutande byggnaden i en urban symbios, där odlingen förser byggnaden med spillvärme från belysningen, och får i sin tur koldioxid från en kontorslokal.

Enligt resultat från studien bidrar elektriciteten till den största miljöpåverkan, men även infrastruktur har stor påverkan. Vattenanvändningen i odlingen är däremot väldigt låg, och miljöpåverkan från leveransen av varorna är mycket låg, vilket belyser fördelarna med att odla mat lokalt. Odlingen kan bland annat minska sin miljöpåverkan genom att byta ut det nuvarande konstgödslet till biogödsel och genom att byta ut plastpåsarnas material till förnybar plast. Symbiosen mellan odlingen och byggnaden visade sig vara väldigt gynnsam, vilket vidare belyser vikten av samspel mellan olika aktörer i den urbana miljön.

Nyckelord: urban odling, vertikal odling, hydroponik, urban symbios, livscykelanalys (LCA)

PREFACE

This master's thesis was conducted in collaboration with IVL Swedish Environmental Research Institute and SweGreen AB. This report corresponds to 30 credits and finalizes the Master's Degree Program in Environmental and Water Engineering at Uppsala University and the Swedish University of Agricultural Sciences, SLU.

I want to extend my gratitude to the people that have contributed to this paper: First, my supervisor Michael Martin at IVL, for help with everything (basically), without your knowledge and inputs, this report would merely be a few words scrawled on a piece of paper. Second, my subject reader Ingrid Strid at SLU for well-needed inputs and interesting talks over Zoom. Last, the people at SweGreen: Sepehr, Yulya, Joakim, Adam, Sixten, and Andreas – thank you for your warm hospitality, for fun days in the farm, and for putting up with my never-ending questions.

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POPULÄRVETENSKAPLIG SAMMANFATTNING

Utvärdering av den miljömässiga hållbarheten av en urban vertikal hydroponisk odling
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År 2050 förväntas den globala befolkningen ha uppnått nästan 10 miljarder, och majoriteten av dessa kommer bo i städer. Det här innebär att livsmedelsindustrin behöver producera mycket mer mat, men samtidigt ställs också höga krav på att maten som produceras är hållbar. Jordbruket och hela livsmedelsindustrin skapar nämligen stora påfrestningar på miljön, genom bland annat användning av bekämpningsmedel och skövling av skog. Jordbruket i sig påverkas också själv av klimatförändringarna, genom mer frekventa torrperioder, extrem värme och extrem nederbörd, vilket äventyrar produktionen.

Den här prognosen skapar stora utmaningar för dagens livsmedelsindustri. Hur ska vi kunna öka produktionen av mat när jordbruksarealerna minskar? Ska vi fortsätta odla på landsbygden eller närmare städer där efterfrågan är högre? Ska vi satsa på ökad import av mat eller ökad självförsörjning? Det här är alla högst aktuella frågor för svensk livsmedelsindustri och för Sverige, som påstås vara det land i Europa med lägst självförsörjningsgrad.

Många forskare menar att dagens livsmedelsindustri måste ändras, för att kunna möta framtidens utmaningar. Urban odling har föreslagits som en del av lösningen, där mat produceras i städer; på hustak, odlingslotter, och till och med inomhus i byggnader. Inomhusodling, eller vertikal hydroponisk odling som det också kallas, har blivit mer populärt de senaste åren, med stor framgång bland annat i Japan. Vertikal hydroponisk odling innebär att grödor, framför allt kryddor och sallad, växer inomhus med LED-belysning och ofta används en vattenlösning istället för jord. Vertikal hydroponisk odling går att kombinera med redan befintlig infrastruktur; många sådana odlingar är nämligen placerade i källare och kan dra nytta av byggnadens existerande värmesystem eller ventilationssystem.

I den här studien undersöktes en vertikal hydroponisk odling i en källarlokal i centrala Stockholm, och olika parametrar analyserades för att se om odlingen är hållbar. Enligt resultaten så bidrar elektriciteten från LED-belysningen med den största miljöpåverkan från odlingen. Vattenanvändningen visade sig däremot vara väldigt låg, och dessutom används inga bekämpningsmedel. Varorna som produceras, främst basilika, koriander och olika sallatsväxter, levereras lokalt till matbutiker och restauranger, och därför är miljöpåverkan från denna transport väldigt låg. Dessutom samarbetar odlingen med resten av byggnaden genom att odlingen förser byggnaden med spillvärme från belysningen, och får i sin tur koldioxid från en kontorslokal. Det här samspelet visade sig vara väldigt fördelaktigt för odlingen.

Vid en jämförelse mellan den vertikala hydroponiska odlingen och ett teoretiskt växthus så visade resultaten att inomhusodlingen hade ett lägre vattenfotavtryck än växthuset, en högre produktion av grönsaker per area, men en högre elektricitetsförbrukning.

ABBREVIATIONS

DCB - dichlorobenzene

GHG - greenhouse gas

ISO - the International Organization for Standardization

LDPE - low-density polyethylene

LED - light-emitting diode

PET - polyethylene terephthalate

PVC - polyvinyl chloride

VHF - vertical hydroponic farming/farm

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1 INTRODUCTION

1.1 REASONS FOR STUDY

By 2050, the world population is estimated to reach 9.7 billion, with up to 70% living in urban areas (United Nations, 2019). This transition will put significant pressure on global food systems, for example, requiring a doubling of food production compared to today (Hunter et al., 2017). Furthermore, over 30% of food is lost or wasted annually. The advancing urbanization threatens food production by replacing former farmland and natural habitats with new buildings and infrastructure. Food systems are recognized in the United Nations Sustainable Development Goals (SDG), SDG 2, where it is stated that a profound change in food and agriculture systems is needed, with added requirements for resilient practices that increase productivity and production (United Nations, n.d.).

Besides our rapidly growing population, global food production is threatened by the consequences of an urgent and inevitable climate change (Intergovernmental Panel on Climate Change, 2014). The world is increasingly faced with global problems, including extreme weather, environmental pollution and shortages of fossil fuel, water and capable arable land, all of which challenges food systems and food security. Climate change is projected to result in farm yield loss and thus, food security is of principal concern (Intergovernmental Panel on Climate Change, 2014).

On the contrary, the agricultural sector itself emits extensive greenhouse gases (GHGs), further contributing to climate change. Agricultural activities, such as deforestation to create more space for agriculture and the production of fertilizer, release substantial amounts of carbon dioxide and other GHGs to the atmosphere. Therefore, agriculture is one of the most important anthropogenic activities contributing to climate change (see e.g., Ivanova et al., 2016 and Tukker et al., 2016), and has been suggested to account for over 25% of anthropogenic GHGs (Gordon et al., 2017). Agriculture also affects biogeochemical flows, biodiversity, land system changes, water and pollution levels. In Europe, emissions from agriculture account for 10% of the GHGs, making it the third largest emitter by sector, after fuel combustion and transport (European Environment Agency, 2019). In Sweden, the corresponding number is 13% (Statistiska Centralbyrån, 2019c).

Furthermore, the food system has become increasingly globalized. Much of the produce consumed in many European countries is not produced within these countries, relying heavily on trade (Zhang et al., 2017). This leads to a distancing of producers and consumers with many consumers not knowing where their food originates. As Martin & Brandão (2017) show in their study on the environmental consequences of food consumption, a large share of the impacts from Swedish food consumption originate abroad; with fruits and vegetables accounting for a significant amount (Statistiska Centralbyrån, 2019b). Another reaction to globalized food systems is an increase in demand for locally produced food (Hempel & Hamm, 2016, Pinstrup-Andersen, 2018).

Several researchers state that traditional farming systems cannot cover these immense challenges and the consequences that come alongside (see e.g. Despommier, 2011, Gashgari et al., 2018, Singh et al., 2020). A paradigm shift is needed in both urban development and global food systems, to meet the future challenges with urbanization, population growth, and climate change. There are a number of studies presenting different approaches to address sustainable food systems. These include primarily changes in diets, a reduction of food loss and food waste, and improved food production practices (EAT-Lancet Commission, n.d., Garnett, 2014, Lindgren et al., 2018).

One possible approach to reach these objectives is with urban farming, where crops are grown in urban areas, in close proximity to their markets (as opposed to conventional farming that often takes place in rural areas). According to some authors, urban land needs to be flexible if it is to meet socio-economic and sustainability objectives (van Leeuwen et al., 2010), and offer dual purposes as with producing food and providing housing. Urban farming could be a way of rewiring and interconnecting producer and consumer in ways that enhance transparency, and create better resilience to flaws in the production chain, thus improving food security (Llorach-Massana et al., 2017).

One approach within urban farming is the concept of vertical farming and hydroponics, where crops are grown indoors using artificial light, protected against rising pollution levels and oscillation in climate (Kozai, 2013). Furthermore, vertical farming may circumvent the obstacle of finding land to cultivate in cities if vertical farming is conducted in unoccupied buildings and residual spaces (Dorr et al., 2017). However, vertical farming has been shown to have high initial installation costs and require large amounts of energy for lighting (Banerjee & Adenaeuer, 2014; Wang et al., 2016).

Urban symbiosis, where two or more facilities share energy, water, materials or by-products in urban environments, has been suggested by some authors to integrate with vertical farming as a way to reduce costs and impacts (Gentry, 2019; Martin et al., 2019; Sanjuan-Delmás et al., 2018). While these systems are often suggested to improve the sustainability of food production, few analyses of the environmental implications these urban farming techniques have been performed. Several studies suggest that these systems may have a smaller water footprint compared to conventional farming but are large consumers of energy (Kozai et al., 2016; Martin & Molin, 2019). Only a few life cycle assessments have been done on an existing system to explore the symbiosis with indoor vertical farming systems within (or below) buildings (see e.g. Chance et al., 2018, Martin et al., 2019). It is therefore of great importance to examine the strengths as well as its drawbacks to determine the plausibility and improvement potential and whether it is a prospective cultivation method for the future.

1.2 AIM AND OBJECTIVES

This thesis aims to assess and improve the environmental performance of the vertical hydroponic system at the Stockholm-based urban farming company, SweGreen. This is done by identifying and evaluating important processes that can be improved to promote a more sustainable production system. The main objective of this project is to perform a life cycle assessment (LCA), in order to answer the research questions (RQs) as follows,

RQ1 Where in the life cycle do important sustainability impacts occur (hotspots)?
RQ2 How can these impacts be reduced?

1.3 SCOPE

The time-span of this project was 20 weeks. With the purpose of performing an LCA, compromises were made due to available data. Some data was collected from SweGreen firsthand, while some data was developed through assumptions with experts and from available literature. The LCA model did not include the impacts associated with the use of the product or waste from retail and households, since the focus was on analyzing and improving the system at SweGreen, and not the full life cycle.

The literature review occurred continuously throughout the project, but with a primary focus during the initial three weeks. The review circled around the concepts of urban farming, urban symbiosis and life cycle assessment, but also reviewed agriculture and food production in general, with a focus on European and Swedish conditions. Since both urban farming and urban symbiosis are modern concepts, recent publications (2015 and later) were prioritized. Information was collected from a variety of sources, such as journal articles, reports, books, videos, as well as podcasts.

This project may provide a basis for future studies and comparisons with other vertical hydroponic systems. However, such a comparison lies outside the scope of this particular study. The focus of this study instead is on improving the sustainability performance of the system used at SweGreen.

2 BACKGROUND

This chapter provides detailed descriptions of relevant concepts revolving around food production, urban farming and urban symbiosis. It starts by describing how food production is addressed in the Swedish environmental objectives and continues with a section about conventional farming to provide insights on how the majority of food is produced today. It is later focused on urban farming, including vertical farming and hydroponics, in addition to urban symbiosis.

2.1 FOOD PRODUCTION IN A SWEDISH CONTEXT

Sweden has 16 environmental objectives, but not one is solely dedicated to food production (Naturvårdsverket, n.d.). The objective "Begränsad klimatpåverkan," states that drivers of climate change should be stabilized to ensure a robust food production system, and the goal "Ett rikt odlingslandskap" says that agriculture should be run in a rational and competitive way. Moreover, Sweden has an action plan regarding food called "Livsmedelsstrategin" (Regeringskansliet, 2017). According to this plan, Swedish food production should increase and competitively contribute to the global food supply chain, increase export and favor innovation. According to several researchers, trading among countries is crucial, but should not replace domestic production (Rydberg et al., 2019). Increasing food production while also limiting climate change may pose a major challenge to the Swedish food system, especially since Swedish food production is already being affected by climate change. One of the most recent indications of this is the summer drought of 2018 that led to a decrease in food production and increased food prices (Regeringskansliet, 2018). Further, Sweden also has a national action plan on how to reduce food loss and food waste[1] (Livsmedelsverket, 2018), though some researchers argue that further actions are needed (Strid, 2019).

2.2 CONVENTIONAL FARMING

As cities grow and urbanization expands, agriculture tends to move further away from urban areas and their consumers. As a result, more focus is placed on rural farming, which refers to farming that takes place outside towns and cities, often in small settlements with low population densities (National Geographic, 2011). Due to the majority of food being produced in rural areas while the majority of food consumption takes place in urban areas, agriculture products need to be transported from rural to urban areas each day (Gordon et al., 2017). Agricultural land, consisting of arable land and pasture, amount to roughly 8% of Sweden's total land use (Statistiska Centralbyrån, 2019a).

The cultivation method in rural areas can vary. Two of the most common methods include conventional farming and greenhouse growing. Greenhouses can be located both in rural areas

[1] Food loss is defined as the food lost post-harvest up to, but excluding, the retail level, and food waste as the food lost at retail and consumer level (FAO, 2019).

as in urban areas, but because large-scale greenhouses are primarily placed in rural areas, they will be discussed in this section rather than the next section of urban farming.

Conventional farming refers to the method where crops are grown in conventional soil, employing direct sunlight and irrigation and dependent on local weather (Barbosa et al., 2015). Crops in open fields can be grown conventionally, dependent on monoculture and fertilizers, employing both conventional or organic practices.

Large-scale greenhouses are often located in rural areas (Gentry, 2019) as they require a large amount of space, which may be difficult to find in urban areas; partly because urban areas are already very dense, and partly because urban land is often more expensive than rural land (Jordbruksverket, 2012). The growing method in greenhouses may vary, from growing with soil to hydroponic systems (as discussed in further detail in section 2.3.2). The large glass walls enable the plants to use the sun as their primary source for photosynthesis (even though additional lighting is installed in Swedish greenhouses to compensate for darker months (Graamans et al., 2018)), but have a significant drawback in releasing a lot of heat. Therefore, a majority of energy in a greenhouse is used for heating purposes (Nilsson et al., 2015). In 2017, energy originating from fossil fuels made up 18% of the total energy consumption in Swedish greenhouses (Persson, 2018).

2.3 URBAN FARMING

Urban farming is the practice of growing and distributing food in urban areas (Sanjuan-Delmás et al., 2018). As opposed to rural farming, crops grown in urban areas are already close to their primary markets. Urban farming includes small scale farming, such as allotment gardens where the main outcome may not always be food production, and large scale farming, such as rooftop gardening and indoor farming (FAO, 2011, Kozai et al., 2016). Rooftop and indoor farming are sometimes referred to as vertical farming, simply meaning the production of food in buildings by optimizing for space by vertically 'stacking' the cultivation area. Vertical farming in relation to indoor farming will be described in further detail below.

Several studies suggest that urban farming may have social advantages, such as local employment and development of local economies (Sanjuan-Delmás et al., 2018). When producing its own food, urban areas can become more independent and thus more resilient to changes in the global political climate. Urban farming may also be a way to interconnect urban people with nature and allow the rural (often exhausted) land to "heal itself" (Despommier, 2011, p. 11). The same argument applies for biodiversity as urban farming (when placed outdoors) may be a way to protect biodiversity in urban areas with more green areas for pollinating animals (Eigenbrod & Gruda, 2015).

2.3.1 Vertical farming

Vertical farming has gained momentum as an alternative growing method where crops are grown indoors in stacked layers and thus increasing the volume produced within a limited area

(Kozai et al., 2016). Despite its name, vertical farming may grow crops horizontally or vertically, “vertical” rather refers to the fact that crops are grown in vertical layers, see Figure 1 for different versions of vertical farming. The systems can vary in size and configuration, from two-level or wall-mounted systems to large warehouses, and tapping into urban infrastructure, either existing or newly constructed. Some researchers have suggested vertical farms be implemented in unutilized space such as idle multistory car parks and unused factories (see e.g. Oda, 2020).

Vertical farming enables fresh produce all year round by using artificial light and heat (Xydis et al., 2017). As it is placed indoors, it is not dependent on weather conditions, which also allows for lower use of fertilizers and pesticides compared to conventional farming (Chance et al., 2018). Many vertical farms don’t use pesticides at all. Factors such as temperature and photo-intensity are held at optimal levels to maximize crop yield, and production can be adapted to the exact conditions needed by various crops. The enclosed system of vertical farms also enables efficient use of water, as irrigation and evaporation losses are reduced (Chance et al., 2018).

Figure 1 Two types of vertical farming systems. Vertically grown crops (left) and horizontally grown and stacked crops (right). Own picture, SweGreen farm.

In urban areas, vertical farming may be one possible factor in mitigating climate change (Dorr et al., 2017). First and foremost, it may lead to a higher consumption of plant products, since the main crop in vertical farms are leafy greens and herbs, and buying from a nearby indoor farm might spark interest in these vegetables and a desire to buy. It is well known that plant-based diets have a smaller carbon footprint than animal-based diets (see for example EAT-

Lancet Commission, n.d., Martin & Brandão, 2017, Sandström et al., 2018). Moreover, the production can take place in buildings and basements, in close proximity to consumers. As such, the reduced transportation distances may increase the nutritional value of the produce, as the produce are available for consumers right after harvesting, without the large supply chains seen in conventional systems (Avgoustaki & Xydis, 2020, Pinstrup-Andersen, 2018).

Vertical farming is advancing at a fast rate in Japan, particularly after the earthquake and subsequent tsunami in Tohoku of 2011 (Cornely, 2015). The disaster destroyed farmland, and as a consequence, the country had to import large amounts of food. This gave rise to more faith in indoor farming as a way to become more self-sufficient, even when the outside environment is changing. Similarly, in Sweden, where food production is limited by the harsh climate and limited available light (especially during the winter months), vertical farming could be an opportunity to increase the self-sufficiency of the produced fruit and vegetables. This might be desirable since Sweden's self-sufficiency, which was found to be only 45% of its food requirements, was found to be the lowest in Europe (Rydberg et al., 2019).

Qualified crops for indoor farming are those where most of its biomass is consumed, including salads and herbs. Compared to tomatoes, where we only consume the fruit, herbs and salads are in that way more energy efficient since the production of stems and leaves in tomatoes are wasted from a human food perspective (Hamm, 2015). Moreover, leafy greens and herbs usually don't grow taller than 30-40 cm, and are therefore suited for cultivating in stacks (Kozai et al., 2016). Crops should also be chosen based on their yield, where high yielding crops have low environmental impacts in comparison to low yielding (Dorr et al., 2017). A Swedish study that interviewed wholesalers reported an increase in sales and demand for different kinds of kale and leafy vegetables (Fernqvist & Göransson, 2017), all of which are suitable for indoor farming (Kozai et al., 2016). Staple food crops, such as potatoes, rice and wheat, are, however, not suitable for indoor farming (Kozai, 2013)

Significant drawbacks of vertical farming include high energy consumption for lighting and heating and the cost requirements of water, which is available freely in nature (Banerjee & Adenaeuer, 2014). The reduction in food miles may be challenged by the fact that in many cases, companies starting out with the purpose of local food production, move to larger facilities outside urban areas as a result of upscaling (Gentry, 2019). Some argue that indoor crops could supply only a small proportion of the urban population's food needs, and should, therefore, be seen as complementary to more conventional production (Pinstrup-Andersen, 2018). Moreover, indoor farming doesn't employ biodiversity in the way that outdoor farming can. Vertical farming is in a controlled indoor environment without pollination and aims to limit the growth of organisms, which may be viewed as pathogenic in such controlled, sterile environments.

2.3.2 Hydroponics

The methods of growing in vertical farming can vary. Specifically, in this study, hydroponics is explored. The term hydroponics was derived from Greek words "hydro" (water) and ponos (labor) (Hussain et al., 2014) and the method is a way of growing plants in nutrient baths, see

Figure 2. The plants are often grown indoors with artificial lighting and without soil, but this is not required for it to be defined as hydroponic. The water in a hydroponic system is usually circulated throughout the system and recycled in a so-called closed system, hence greatly reducing the water use of the plants (Kozai et al., 2016). The system needs to be closely monitored and treated in a sterile manner to prevent contamination of water.

Figure 2 Hydroponic system in a greenhouse. Plants are suspended in a nutrient bath (inside the white cover). Retrieved from www.pixabay.com.

There are various kinds of hydroponics, ranging from systems that are easily built-up at home, to full-scale systems that can be used in greenhouses or indoor vertical farms (Kozai et al., 2016). The two main types for growing leafy vegetables are (1) deep flow technique and (2) nutrient film technique, see Figure 3. In the deep flow technique system, nutrient-rich water is supplied from a reservoir to the roots of plants whenever the water level in the growing bed becomes lower than a set value. The water is then recirculated back into the tank. The nutrient film system works in a similar way, but with the growing bed at a slight slope (Kozai et al., 2016). A third hydroponic technique is the drip irrigation system, where water is drip-fed down vertically through a growing wall (Gentry, 2019).

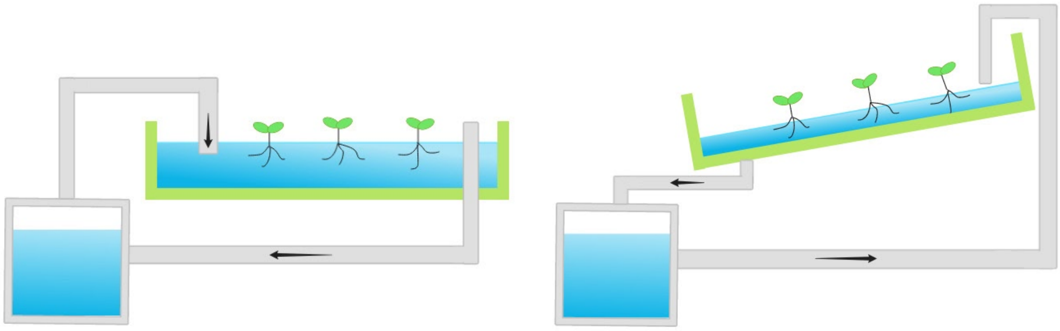

Figure 3 Schematic pictures of deep flow technique (left) and nutrient film technique (right) hydroponic systems.

Some benefits of hydroponics compared to conventional growing techniques include the reduction in water use and increased yields. A study in Arizona found that hydroponic farming reduced water usage by a factor of 13, and yield was increased 11 times, compared to conventional farming per area (Barbosa et al., 2015). Almost all the nutrients applied are captured by the plants in hydroponic farming, reducing the cost and environmental impacts associated with the production of fertilizers, and also reducing the runoff, which consequently reduces eutrophication of streams and lakes (Pinstrup-Andersen, 2018).

In Sweden, vertical hydroponic farming (VHF) has seen rising popularity as a growing method that could challenge conventional farming and greenhouses (Banerjee & Adenaeuer, 2014). Some elements of VHF are required even in greenhouses, such as artificial lighting, but greenhouses have an added disadvantage of not being able to take advantage of urban systems (e.g. district heating systems) or reduce transportation since most greenhouses are located outside urban areas (Gentry, 2019). A study showed that most of Sweden (from Stockholm northwards) had an advantage in VHFs compared to greenhouses with reference to the light and water resource demands, due to the greenhouses already requiring a lot of external lighting (Graamans et al., 2018).

As with most new innovations and technologies, the initial costs of installations and the risk of failure are high (Pinstrup-Andersen, 2018). However, real estate costs for VHF may be relatively low if occupying an existing building with residual space, for example, offices. The major running costs in a hydroponic farm are those for electricity, which can be subdivided into lighting, cooling, airflow and water pump costs (Gentry, 2019). The amount of purchased energy is therefore much higher for VHF compared to conventional farming. One alternative is to incorporate renewable energy into the system, for example by installing solar panels, thus reducing its dependence on fossil fuels (Al-Chalabi, 2015). This brings up trade-off issues and questions of whether this renewable energy could better be used for other purposes, considering there is already a renewable resource in the sun for food production (Hamm, 2015).

2.3.3 Light

As described above, energy use, and therefore what kind of lighting used, is of great importance when designing an indoor farm. The radiation that plants require for photosynthesis, photosynthetically active radiation (PAR), lies in the spectrum of visible light of 400 to 700 nm (Kozai et al., 2016). When light energy (photons) is captured by plants, less than 10% of captured photons are converted into chemical energy, and the rest is converted into heat (Kozai et al., 2016).

Plants mainly need red and blue radiation for growth (Park & Runkle, 2018). Red radiation (600-700 nm) is considered the most efficient in photosynthesis based on quantum yield, whereas blue (400-500 nm) is added for normal photosynthetic functioning and to obtain desired phenotypes. One limitation of using red and blue colored lights is that plants appear purple to the human eye and making it hard to detect defects, such as nutritional deficiencies and disease symptoms. One possible solution would be to add green or white light, but since these are not as efficiently used in plants, red and blue lights are considered the best option (Park & Runkle, 2018).

Light-emitting diodes (LEDs) are increasingly being used as the light source in VHFs (Park & Runkle, 2018). LEDs have seen a steady price decline with increased improvements in technology over the last few years, they are also robust and long-lived, making them a favorable choice nowadays. LEDs have a high luminous efficacy, meaning that they efficiently convert electric energy to light energy. The spectral distribution of emitted light can also be controlled easily. In vertical farming, this can be used to improve and optimize plant production by using a light source with several types of LEDs with different peak wavelengths. A drawback of LEDs is their high initial costs (Park & Runkle, 2018). See Figure 4 for a depiction of LEDs in a vertical farm.

Figure 4 Vertical grown basil with a vertical LED panel. Own picture, SweGreen farm.

2.3.4 Growing media

In soilless plant culture, plant roots sit within a porous rooting medium known as a ‘growing medium’ or ‘substrate’ (Barrett et al., 2016). Effective soilless growing media must have a physical structure that enables an appropriate balance of air and water for healthy root development and a biological and chemical environment in which roots have access to nutrients. A growing medium often consists of different substrates, inorganic or organic, with peat being the most commonly used in horticulture. Other constituents include rockwool, coir pith (a waste product of the coconut industry), wood fiber and composted materials (Barrett et al., 2016, Gruda, 2019). Peat, the most widely used substrate, is a well-suited substrate in hydroponics as it is relatively cheap and low in plant nutrients but able to absorb and release them when added as fertilizer (Barrett et al., 2016). Drawbacks include the extraction of peat and the consequent release of stable, sequestered carbon into the active carbon cycle, thereby aggravating the impact of climate change (Schonning, 2015).

Another important growing medium in hydroponic systems, especially those for tomato production, is rockwool. Rockwool is made by melting basalt rock with limestone and other amendments and extruding the molten material into fibers (Komosa et al., 2011). It is, therefore, an inorganic growing media, hence it is neither biodegradable nor renewable. The advantages of rockwool include its lightweight, sanitary qualities, substrate uniformity and ease of handling (Gruda, 2019). See Figure 5 for an example of a rockwool plug used extensively in the industry.

Figure 5 Rockwool plug as a growing medium with seeds on top. Dimensions roughly 3x1 cm. Own picture, SweGreen farm.

2.3.5 Nutrients and fertilizers

Plants need various elements (nutrients) for growth, with 17 nutrients being essential for higher plants (Kozai et al., 2016). The elements that are required in relatively large amounts are called macronutrients, and include carbon, oxygen, hydrogen, nitrogen, potassium, calcium, magnesium and sulfur. Micronutrients are nutrients required in smaller amounts, and include among others, iron, zinc, copper and chlorine. The nutrients are applied to plants through fertilizers, a mix between different nutrients, and are absorbed by the roots. Carbon, hydrogen and oxygen, however, are applied by way of carbon dioxide (air) and water, respectively, and not mainly through fertilizers. Fertilizers may also include so-called beneficial elements, which are nutrients with a growth-promoting effect, including sodium and silica. In hydroponics, all nutrients are supplied to the plants by a nutrient solution, i.e. a liquid fertilizer. The liquid fertilizer should have a pH of around 5.5 to 6.5, but may fluctuate due to the unbalanced absorption of cations and anions by the plant (Kozai et al., 2016).

Nitrogen, potassium and calcium (N, P, K, respectively) are often referred to being the most essential nutrients for plant growth (Kozai et al., 2016). Nitrogen is particularly responsible for foliage development. Nitrate, which is the dominant form of nitrogen in fertilizers, is an essential component for producing proteins and chlorophyll. When nitrate is absorbed by plants, it is reduced to ammonium and further assimilated into amino acids. However, ammonium added directly as fertilizer is also important for plant growth, especially under low-light intensity. Potassium is responsible for the regulation of internal pH and the osmotic potential of the plant. Calcium is a constituent of the plant's cell wall and is involved in the construction and function of the cell membrane, among other functions (Kozai et al., 2016).

The production of fertilizers may have large environmental impacts. In fact, the production of mineral nitrogen is one of the largest consumers of fossil energy in Swedish agriculture (Nordberg, 2019). Today the dominant method of producing mineral nitrogen is by the energy-intensive Haber-Bosch process, where hydrogen (mainly from methane from natural gas) and dinitrogen produce ammonia. Furthermore, Sweden is heavily dependent on the import of fertilizers, and some argue that this poses a larger threat to Sweden's insufficient self-reliance than the import of food (Eriksson, 2018).

Some authors have suggested implementing biofertilizers from biogas digestate to hydroponic farms as a way to reduce impacts from fertilizers (Martin et al., 2019). This readjustment could also benefit the biogas industry by providing a new market for the biogas digestate, which has been recognized as a bottleneck in the production system (by e.g. Martin, 2015 and Olsson & Fallde, 2015). Other researchers have suggested recycling nutrients from wastewater for use in agriculture, to promote local industries and circularity, increase in self-sufficiency, and decrease in emissions related to the agricultural industry (see e.g. Jönsson et al., 2020). However, the possibilities of using fertilizers from sewage sludge are still very limited in Sweden (Jordbruksverket, 2017).

2.4 URBAN FARMING IN FUTURE FOOD PRODUCTION

Urban farming has been suggested as a key factor in future food production. Retailers and wholesalers request better flavors, sustainable packages, stable deliveries, and consistent quality in future food production, along with an increase in Swedish products throughout a longer season (Fernqvist & Göransson, 2017). Below are some suggested reasons for how urban farming can contribute to some of these factors, with a primary focus on vertical hydroponic farming.

Various media have reported a decrease in people working in the agricultural sector (see for example BBC, n.d., Sveriges Radio, 2016). More and more young people are choosing an urban lifestyle instead of maintaining family farms in rural areas, and fewer young people are educating themselves in traditional agricultural practices. Farming is seen as an uncertain business where it is hard to see what the future might hold, with challenges such as climate change and its consequences for farmers. Here, urban farming may be a way to reinvent what it means to be a farmer and provide an attractive workplace for young prospective farmers. Urban farming, in the sense of VHF, is often automated and leverages technology, which could be seen as attractive for young people (FAO, 2016). Furthermore, working in an urban indoor farm may circumvent some of the "negative" aspects of working in a rural farm. These include irregular working hours and difficult workloads, and allow proximity to urban amenities and lifestyle; inspiring young people to a future career as a rural farmer.

The importance of local food is highlighted in a study by Hempel & Hamm (2016), where they discovered that German consumers generally valued local food over organic food. This speaks in favor for VHF, which is indeed local, but are not allowed to be called organic since not grown in soil[2] (which is a prerequisite for the organic label (European Commission, 2019)).

As previously mentioned, many authors state that urban farming cannot replace rural farming, but should be seen as complementary. According to O´Hara (2016) there is a role for every part of the landscape for food production. Rural areas should be dedicated to growing crops that can be easily stored and transported, while urban areas should grow perishable crops that run the risk of being spoiled easily, providing fresh and high quality produce.

2.5 SUSTAINABILITY OF VERTICAL FARMING SYSTEMS

In order to review the environmental performance of indoor growing systems, LCA is typically employed. Nonetheless, in the literature, there are few life cycle assessments of urban farming systems, specifically, VHF. The subsequent text summarizes the methodology and key findings from some of these LCA's.

Martin & Molin (2019) performed an LCA on a vertical farm located in a basement of a building in Stockholm, with a closed hydroponic system. The aim of the study was to assess the environmental impacts of a VHF in Stockholm, and to suggest improvements that would contribute to a more sustainable production system. The scope was a cradle-to-gate perspective, with waste management excluded, and the functional unit was set to one pot of basil. The chosen impact categories were greenhouse gas emissions, acidification, eutrophication, abiotic resource depletion and human toxicity. The result showed that the factor contributing most to the greenhouse gas emissions was the growing medium (soil, which contains large shares of peat), and by substituting the growing medium from soil to coir, the emissions significantly reduced. Electricity, transport, and pots did also contribute significantly to greenhouse gas emissions. The pot and packaging were the factors contributing most in the acidification impact category, and by substituting the plastic pot to a paper pot, the impacts reduced significantly. Furthermore, it was shown that the GHGs would increase by 260% if a greenhouse structure

[2] This matter is widely debated, see e.g. Highland, 2017.

had to be produced instead of growing in an already existing building, thus showing the importance of VHFs to utilize existing space.

Martin et al. (2019) performed another LCA on the same vertical farm as in the previous paper, with the addition of exploring the benefits of a potential urban symbiosis with other urban residual material streams. Conventional gardening soil as the growing media was replaced by paper, compost and brewers' spent grains, and conventional fertilizer by biofertilizer from biogas digestate. The results showed that by changing the growing media, greenhouse gas emissions could be significantly reduced, illustrating a decrease of over 60% if changing from conventional soil to a blend of compost and paper. Replacing conventional fertilizer with biofertilizer also reduced greenhouse gas emissions, though not as substantial compared to the replacement of growing media. Electricity was found to have a major impact, primarily a result of the LED lighting, which accounted for over 80% of greenhouse gas emissions from energy use.

Graamans et al. (2018) analyzed the environmental performance of a VHF compared to greenhouses, in terms of energy, water, carbon dioxide and land. A theoretical VHF was compared to three theoretical greenhouses located in Sweden (Kiruna), the Netherlands and the United Arab Emirates. In terms of energy efficiency, the results showed that the VHF outperformed all greenhouses (the most efficient one being in Sweden). In terms of purchased energy, however, greenhouses are more efficient as they use solar energy for photosynthesis (247 kWh for the VHF compared to 182 kWh for a greenhouse in Sweden with artificial illumination). The calculated load of artificial lighting in the VHF exceeds all other loads, e.g., heating and dehumidification, for each greenhouse at each location. In terms of water, the water use efficiency was higher in the VHF than in the greenhouses. Furthermore, the production per area was higher in the VHF than in the greenhouses in all three locations. The authors conclude that VHFs may be more suitable than greenhouses for lettuce production at higher latitudes, like in the northern parts of Sweden, and this is based on the fact that the energetic performance of the Swedish greenhouse with artificial lighting, considerably improves with artificial lighting. At even higher latitudes, heating will require more electricity than lighting.

Sanjuan-Delmás et al. (2018) conducted an LCA of an integrated rooftop greenhouse[3] in Barcelona. The aim of the study was to quantify the environmental impacts of the life cycle (cradle-to-grave) of 1 kg tomatoes, and also to compare these impacts to a conventional greenhouse with similar theoretical conditions. The greenhouse shares resources with the existing building, including using the rainwater collected in the building to water plants. The crop sits in perlite bags and has an open hydroponic system, meaning that the leachates are disposed of. The selected impact categories were climate change, ecotoxicity, terrestrial acidification, freshwater eutrophication, marine eutrophication and fossil fuel depletion. The yield result showed that the use of fertilizers had the largest environmental impacts for all

[3] An integrated rooftop greenhouse is a vertical farm in a rooftop greenhouse connected to a building (Sanjuan-Delmás et al., 2018).

impact categories, however, infrastructure (construction of the greenhouse, rainwater harvesting, auxiliary equipment) had a larger impact on fossil fuel depletion. The leachates from the crop sent to the sewer contributed between 40-85% of the environmental impacts of eutrophication and were found to be primarily caused by the nitrates and phosphates contained in the leachates. It was found that the integrated rooftop greenhouse had lower environmental impacts in five of the six impact categories (all but marine eutrophication) compared to the conventional greenhouse.

Chance et al. (2018) reviewed the material flows and social impacts of an urban symbiotic network in a facility in Chicago accommodating numerous industries, including a VHF, an anaerobic digester, a coffee roastery and a brewery. The majority of the material flows between industries are through waste, e.g. spent grains from the brewery to the indoor farm and food waste from the facility as a whole to a flower farm. The authors argue that the urban symbiosis enables the tenants to be more aware of their residual flows, and encourages collaboration. The facility may also help to provide knowledge to urban residents about the origins and environmental impacts of the food they consume.

2.6 URBAN SYMBIOSIS

Urban symbiosis involves two or more facilities in geographic proximity in an urban area that share energy, water, materials, or by-products (Ashton, 2009). The idea is derived from biology in which symbiosis represents the association of different species in a relationship where the different species mutually benefit (Chertow, 2000, Martin, 2020, Neves et al., 2020). The definition has been transplanted from the research field of industrial symbiosis where industries are engaged in coordinated efforts for their resource management activities to achieve collective economic, social and environmental benefits. Thanks to its geographical propinquity, cities have the potential to provide services for their residents much more efficiently than rural areas can: the density of different entities is higher, and distances for transport are smaller (Mulder, 2017).

Researchers and professionals alike have proposed a symbiotic relationship between VHF and district heating (Gentry, 2019, Martin et al., 2019, SweGreen, n.d.). According to them, the high installation and implementation costs associated with urban farming can benefit from synergies with existing urban infrastructure such as waste heat, carbon dioxide, and many urban residual material streams. One way of integrating these two entities would be to use the excess heat from the vertical farming (LEDs often produce heat in excess of the required temperature, thus requiring additional costs for LED cooling), and share heat back into the district system or to neighboring buildings (Gentry, 2019). Another idea is to utilize carbon dioxide emissions from power plants or existing buildings, to improve plant growth.

The advantages of urban symbiosis include resource use reductions, waste reductions, the creation of local circular economies and social capital (Chance et al., 2018). By employing waste-to-energy strategies, food production and water-recovery systems, a city can become a natural ecosystem counterpart, with an efficient use of residual flows (Despommier, 2011).

However, urban symbiosis projects are often not the core business for the involved partners which can lead to obstacles in implementation and investments in the symbiosis, and potential benefits from the symbiosis might fall unevenly on the participating partners (Chertow & Lombardi, 2005, Gentry, 2019). The symbiosis leads to a transition from an independent company to multiple interdependent ones, and this might create a risk to the partners (Vernay & Mulder, 2016). Furthermore, collaboration through symbiosis does not necessarily lead to expected environmental performance goals, e.g. where there is ambiguity regarding responsibilities of partners, thus industrial symbiosis requires careful selection of the partners and a clear assignment of responsibilities and goals (Ashton, 2011).

3 SWEGREEN

SweGreen is a Stockholm based urban farming company producing roughly 11 tonnes of plants annually under the brand *Stadsbondens*. In the future, there are plans to increase production to roughly 25 tonnes per year. They focus mainly on leafy greens and herbs, such as pak choi, green kale, basil and cilantro, with basil being the most commonly cultivated. The crops are either packed in bags or put in recirculating trays and delivered to retailers and restaurants, and their products are also available to purchase online. The hydroponic system is located in the basement space in an existing building on Kungsholmen, within Stockholm, providing their customer segment (population of Stockholm) with locally produced food all year round.

3.1 GERMINATION

Growing is divided into two main processes: germination and cultivation. For germination, seeds are put in rockwool plugs (the growing medium, hereinafter referred to as only "plugs"), soaked in water and are put in a germination chamber on steel trays to germinate and grow for a week. The pre-germinated seeds in the plugs are moved into a nursery; a small room with racks where the crops grow in horizontal layers with LED lights with the addition of water and nutrients until they are approximately 10 cm tall, which takes another week. See Figure 6 for a depiction of the germination process.

Figure 6 Seeds in rockwool plugs in the germination chamber (left). Seedlings on racks with LED lights in the nursery (right). Own picture, SweGreen farm.

3.2 CULTIVATION PROCESS

From the germination process, the seedlings remain in the plugs and are moved to the main growing room, a large growing space with growing walls and vertical LED panels facing the walls, see Figure 7. The growing walls use ZipGrow technology, a patented technology of white plastic panels and a matrix media out of recycled plastics, which serves as a plant anchoring material (Zaleta, 2013, ZipGrow, n.d.). The technology enables the seedlings to be “zipped” in place by the matrix media when planting. Alongside the matrix media runs a wicking strip made out of polyester, which captures and delivers water to the plugs with seedlings (Storey, 2014), see Figure 8. Water enriched with a nutrient solution drips from pipes at the top of the growing walls, down through the wicking strip[4], see Figure 9 for a depiction of the process. The runoff at the bottom of the tower is collected and cleaned via filters[5] to later re-enter the growing walls.

The time of cultivation varies from crop to crop, but for basil, the estimated time from seed to full-grown plant is roughly 5 weeks. Some of the herbs are re-grown a few times, meaning that after harvest the root and stems together with the plug are not removed, but used again for the next harvest. For the salads and kale, the roots and stems in the plugs are removed after each harvest.

Instead of the organic waste going to an incineration plant, which is the default organic waste handling method for the area, SweGreen pays for the pickup and delivery of their organic waste to a composting facility to promote more sustainable waste handling.

[4] The hydroponic system employed is the so-called drip irrigation system.
[5] Water filters and UV filters.

Figure 7 Main growing room with growing towers standing on carts. In the middle of the two carts are ventilation pipes and LED panels. Own picture, SweGreen farm.

Figure 8 Close-up of a growing wall with basil with the matrix media visible (left). Wicking strip and matrix media on display for presentation purposes (right). Own picture, SweGreen farm.

Figure 9 Schematic overview of the irrigation process. Water drips from a pipe at the top of the growing wall, down through the wicking strip and plugs with crops. Water is collected at the bottom (not showing). Retrieved from www.ZipGrow.com.

3.3 RECIRCULATING SYSTEMS AND SYMBIOSIS

The building and the hydroponic system work together in a partial symbiotic relationship where SweGreen provides the building with residual heat (from LED lighting) and where SweGreen obtains carbon dioxide from an office floor in the building. The system requires no additional heating as the LED lights themselves generate sufficient heat to the vertical farm. Furthermore, a share of the heat that the LED lights generate is captured by a water circulation system that runs alongside the light panels to cool and improve the efficiency of the LEDs, in a process called LED cooling. The heat is then transferred via a passive heat exchanger to geothermal facilities and is utilized by the building.

The ventilation and water from irrigation and evapotranspiration are recirculated within the farm (closed-loop system), thus reducing the water consumption. Warm, moist air that leaves the farm enters a dehumidification unit (connected to a fan, heat pump and geothermal facilities) where the warm air cools and condenses into a water tank, and is used again for the irrigation system. The cool air circulates back into the farm; this process is referred to as the dehumidification process.

4 LIFE CYCLE ASSESSMENT - THEORY

4.1 INTRODUCTION TO LCA

Life Cycle Assessment (LCA) is an international and comprehensive tool for quantifying emissions associated with any goods or services (European Commission, 2010). The initial step of an LCA is to study a specific product (goods or service) and map out all of the activities that are associated with its life cycle, including its construction, use and disposal (Finnveden & Moberg, 2005). The next step is to take the life-cycle activities and transform them into environmental impacts. These impacts are obtained from the inputs and outputs to the natural world that are caused by anthropogenic activities.

LCA is a tool that can be used to support decisions (Finnveden et al., 2009). To contribute to effective decision-making, standards of practice have been developing, with the most broadly used and recognized being part of the International Organization for Standardization (ISO) standards: 14040 and 14044. According to these standards, every LCA study should consist of four phases: (1) Goal and scope, (2) Inventory analysis, (3) Impact assessment, and (4) Interpretation (ISO, 2006), see Figure 10. These are described in detail in the sections below.

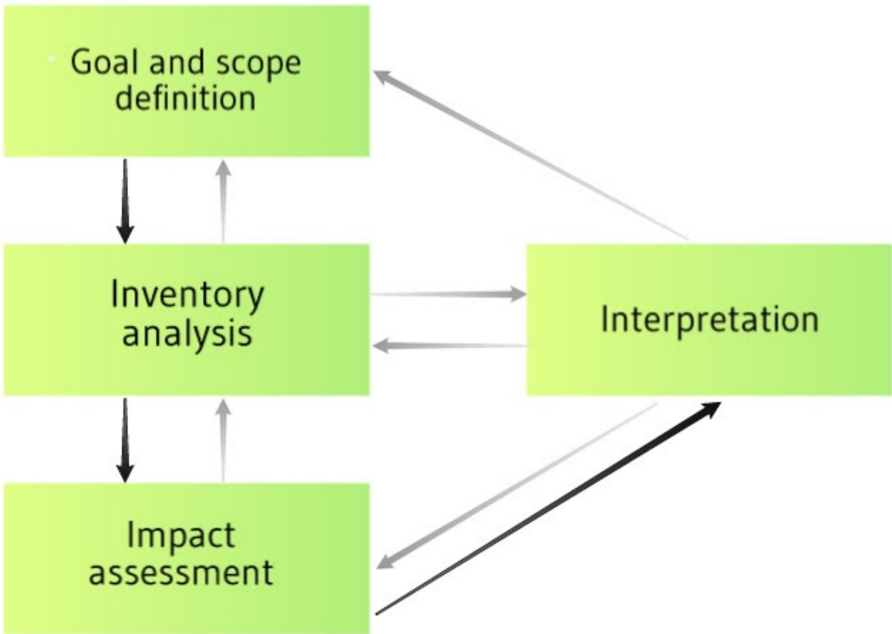

Figure 10 Overview of the ISO Life Cycle Assessment framework. Black arrows denote the standard linear procedure and grey arrows denote where adjustments and iterations are made.

4.2 GOAL AND SCOPE DEFINITION

The goal and scope definition phase includes defining the aim of the study and its scope. First and foremost, it should be clearly stated why the LCA is being done, and for what purpose it will be used, e.g. for increased knowledge, marketing, or to identify hotspots (ISO, 2006). One of the main reasons that analysts seek to use LCA is to make comparative assertions, alas compare multiple products or systems. However, comparisons between studies are only possible if the assumptions and scope of each study are equivalent (ISO, 2006).

The scope definition is often more extensive and presents what is included or excluded in the study (ISO, 2006). The scope involves an introduction to the functional unit, which is defined as a quantified performance of a product system, and is used as a reference unit. The functional unit should explicitly state units, as the results of the LCA will be normalized by the functional unit.

The scope definition further includes stating the system boundary, i.e. what processes of the product's life cycle should be included in the study (Finnveden et al., 2009). The LCA performed when considering the full life-cycle of a product (i.e. manufacturing to disposal) is called a "cradle-to-grave" assessment (ISO, 2006), see Figure 11. However, one can choose to only look at certain segments of a product's life cycle, for instance when data are difficult to obtain or when time is scarce. To illustrate the system boundary, one can include a diagram, also called a process flow diagram, of the key components of the product's life cycle stages.

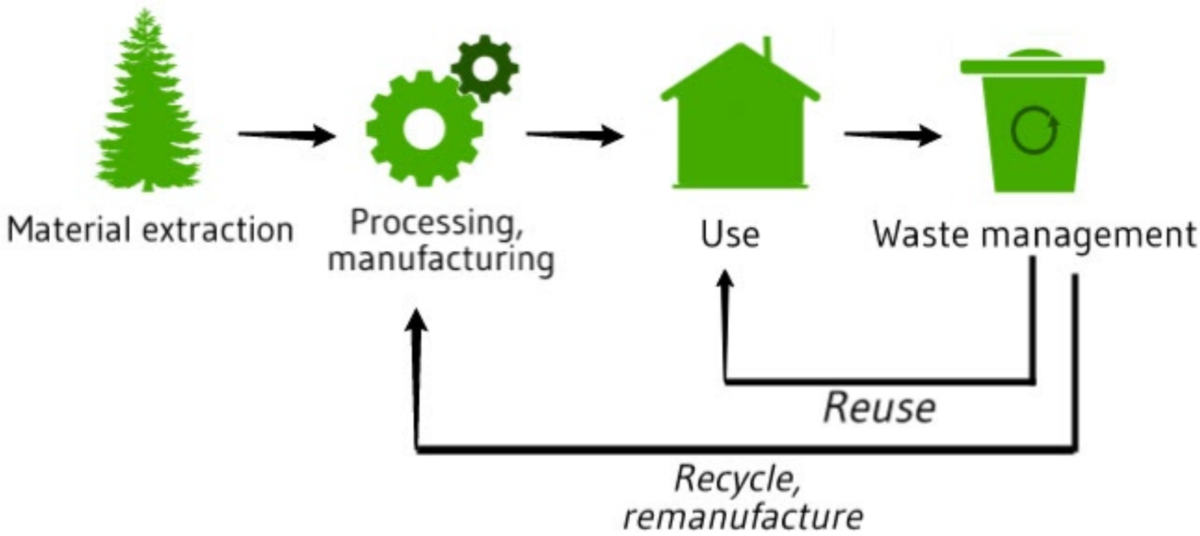

Figure 11 Overview of a product's life cycle from cradle-to-grave.

Allocation problems may occur when a single process yields many products, and when it is not clear to which product the environmental impacts should be allocated (Finnveden et al., 2009). The LCA analyst must then decide how the inputs associated with the system are distributed among the various output products. There are different ways of conducting this partitioning: physical allocation (e.g. allocation based on mass), economic allocation (i.e., allocation based on the monetary value of a product), or system expansion. System expansion is used when considering not only the processes in the actual scope, but also the impacts of by-products such as e.g. waste handling. Allocation should be avoided to the greatest extent, but if an allocation is still needed, it should be clearly stated in the goal and scope definition phase (Brandão et al., 2017, ISO, 2006).

Lastly, the goal and scope definition phase should state the impact categories selected. The selection of impact categories must cover all relevant environmental issues related to the analyzed system (European Commission, 2010). More details about the impact categories are given in section 4.4.

4.3 LIFE CYCLE INVENTORY ANALYSIS

The life cycle inventory analysis (LCI) phase includes an inventory of input and output data to the system (European Commission, 2010). Depending on the defined scope, the inventory analysis will require more or less data collection. The LCI and LCA study is often an iterative process and during the LCI, it becomes clear of what data is available. Data might be hard to obtain, and because of this, the initial scope will typically need to be reconsidered and revised (European Commission, 2010). If necessary, data can be obtained from various databases, such as Ecoinvent.

The LCI phase should, in addition to data collection, include data validation, data allocation (if relevant), relating data to the functional unit, and a data aggregation, where all unit process data in the product system are combined into a single result (ISO, 2006). This could, for example, mean summarizing all different energy uses (in Joule) in all life cycle stages.

4.4 LIFE CYCLE IMPACT ASSESSMENT

The life cycle impact assessment (LCIA) is the third phase of the LCA and consists of a translation from data from the LCI to the corresponding environmental impacts (Finnveden et al., 2009). There are two kinds of impact assessments, 1) Midpoint, which calculates single environmental problems, for example, climate change, and 2) Endpoint, which show the environmental impact on its aggregated effect on either human health, biodiversity, and resource scarcity, say for example the effect on climate change on the biodiversity (Bare et al., 2000). For the midpoint method, the environmental impacts are arranged in different categories and which categories to be considered can vary a lot depending on the goal of a particular LCA. The ReCiPe method is one example of an LCIA method, which includes and this calculates 18 impact categories, which are presented in Table 1.

Table 1 ReCiPe 2016 Midpoint (H) impact categories. Bolded impact categories are focused on in this study and will be described in detail in chapter 5.

Impact category	Unit
Climate change	**kg CO_2 eq**
Ozone depletion	kg CFC-11 eq to air
Ionizing radiation	kBq Co-60 eq to air
Fine particulate matter formation	kg PM2.5 eq to air
Ozone formation, terrestrial ecosystems	kg NOx eq to air
Ozone formation, human health	kg NOx eq to air

Terrestrial acidification	**kg SO_2 eq to air**
Freshwater eutrophication	**kg P eq to freshwater**
Marine eutrophication	kg N eq to marine water
Human carcinogenic toxicity	kg 1,4-DCB to urban air
Human non-carcinogenic toxicity	**kg 1,4-DCB to urban air**
Terrestrial ecotoxicity	kg 1,4-DCB to industrial soil
Freshwater ecotoxicity	kg 1,4-DCB to freshwater
Marine ecotoxicity	kg 1,4-DCB to marine water
Land use	**m^2a crop eq**
Water use	**m^3 water consumed**
Mineral resource scarcity	kg Cu eq
Fossil resource scarcity	**kg oil eq**

The impact categories are often denoted as climate change (or global warming potential), stratospheric ozone depletion, human toxicity, respiratory inorganics, ionizing radiation, ground-level photochemical ozone formation, acidification, eutrophication, ecotoxicity, land use and resource depletion (European Commission, 2010). However, variations of denotations of impact categories can be found in literature and in practice (see for example Environmental Protection Agency, 2006).

4.5 INTERPRETATION

Life cycle interpretation is the final phase of the LCA, and aims to summarize and discuss the results of the LCI and LCIA, in order to answer the questions posed in the goal definition (ISO, 2006). Depending on the goal of the study, the results can be used as a basis for recommendations and decision-making, and it is, therefore, crucial for the result to be presented in an understandable way to help the user of the study to understand the conclusions as well as the eventual limitations to the study. The interpretation phase may include a sensitivity analysis where the reliability of the final results is checked (ISO, 2006). The impact assessment and interpretation part of the LCA can sometimes be stated simply as results and discussion, to follow the structure of a general scientific report[6].

[6] This study will be structured like this.

5 LCA OF SWEGREEN VERTICAL FARMING SYSTEM

5.1 GOAL AND SCOPE

The goal of the LCA was to evaluate the environmental impacts of producing crops at the vertical hydroponic farm of SweGreen, and to identify hotspots, as well as to test the sensitivity of the results to the assumptions made. As SweGreen is experiencing an ongoing production growth, the environmental impacts of two different production scenarios were chosen to evaluate: **Scenario A** is the current production, which utilizes approximately 40% of the total farm capacity, i.e. growing walls, and **Scenario B** is the maximum production scenario, with 100% of the farm capacity utilized.

The target groups of the LCA are fellow students at the master's degree program in environmental and water engineering, and also the company SweGreen who can use the results to understand their system better from an environmental perspective and make changes to improve their environmental performance. The LCA is also a part of a larger project at IVL, which aims to assess and improve the sustainability of urban vertical farming systems. The results can also be used in comparative purposes with other vertical hydroponic farms, as well as other cultivation methods. Even if the LCA is performed based on Swedish conditions, the results can still be employed in other contexts, though specific contextual differences may occur (e.g. the energy systems employed).

5.1.1 Functional unit and system boundary

The functional unit was chosen to be **1 kg of basil**, where basil was chosen as it is the most common crop cultivated at SweGreen. Basil has also been a functional unit in other LCA's on indoor farms (see e.g. Martin & Molin, 2019), and suits well for indoor growing. The quantity of 1 kg was chosen due to it being a common unit when comparing different foods and has been used as a quantity in other similar assessments which makes an eventual comparison easier (see e.g. Al-Chalabi, 2015, Dorr et al., 2017, Sanjuan-Delmás et al., 2018).

The study included a "cradle-to-gate" perspective, which in this case meant it included all processes from the manufacturing of raw materials used in the farm, up to the transport to supermarkets where the products are sold; see Figure 12 for a depiction of the system boundaries. As such, it included all the upstream activities associated with the cultivation, such as the extraction of materials, production of seeds, fertilizers and packaging materials. The impacts associated with the use of the products, for example, transport from retail stores to households, energy for refrigeration in households, and waste originating in the households, were not considered. Potential waste that occur during the delivery quality control at the retailers upon delivery, were not included, but since all produce are distributed locally this amount is thought to be small[7]. However, waste originating from the farm itself was considered,

[7] In a study by Eriksson et al., 2012 this waste was found to be 3% of the total delivered quantity of fresh fruits and vegetables.

including organic and plastic wastes. Furthermore, transport of the incoming materials was included as well as the delivery of the crops to retail stores. To assess the impacts and potential advantages on the symbiosis between SweGreen and the building[8], the material associated with the symbiosis was also included, i.e. the utility infrastructure (pipe material) for carrying carbon dioxide from the office to the farm, and for providing the building with heat from the LEDs in the farm.

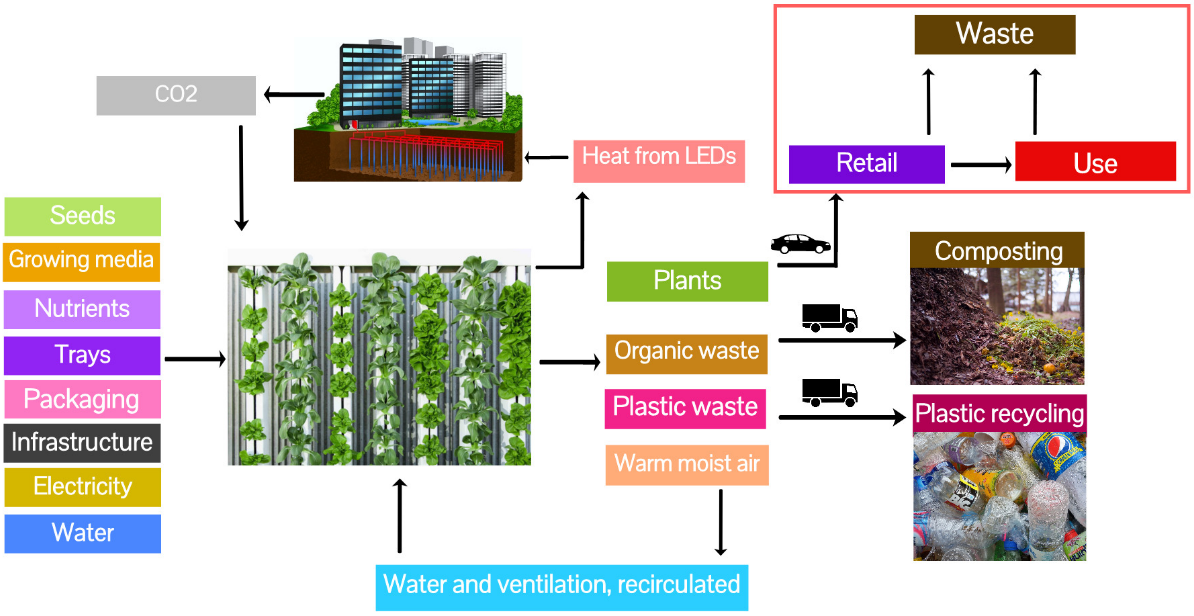

Figure 12 Simplified flowchart of the production system and what was included in the study. Red line represents outside the system boundary.

5.1.2 Impact assessment method and categories

The ReCiPe 2016 Midpoint (H; Hierarchist) impact assessment method was chosen for this study due to it having many different impacts, including water consumption that some methods lack, and due to its prominence in other LCA's on urban farming (see e.g. Dorr et al., 2017, Sanjuan-Delmás et al., 2018). Seven impact categories were chosen to identify the consequences of the input and output flows of the system: 1) Climate change, 2) Water consumption, 3) Land use, 4) Terrestrial acidification, 5) Freshwater eutrophication, 6) Fossil resource scarcity, and 7) Human non-carcinogenic toxicity. They were chosen based on expert opinion (M. Martin, personal communication, March, 2020) along with literature review (see e.g. Brentrup et al., 2004). **Climate change** (kg CO_2 eq) is an immense global challenge which leads to an increase of the global average temperature and consequently effects on precipitation and wind (Brentrup et al., 2004), and was therefore included in this study. Agriculture is considered one of the most important anthropogenic activities contributing to climate change (Campbell et al., 2017). From this impact, a carbon footprint can be produced for a product or process, and efficiently compared to carbon footprints of similar products or processes.

[8] Note that this was not part of the scope but added in the analysis.

Water consumption (m^3) and **Land use** (m^2a crop eq) are two impact categories often discussed in agriculture contexts. In terms of planetary boundaries, land-system change and freshwater use are at an increased risk of transgression (Campbell et al., 2017). Water scarcity is thought to be increasingly pressing in the future and globally 70% of freshwater is used for agriculture (FAO, 2017). The impact category, Land use, describes the exploitation of natural land, and can be used as an indication of the decrease of biodiversity. (Brentrup et al., 2004).

Terrestrial acidification (kg SO_2 eq) has negative impacts on ecosystems and was considered relevant for this study because the farm uses synthetic fertilizers that presumably result in emissions of nitrate which leads to acid deposition (Brentrup et al., 2004). Agriculture practices also contribute heavily to **Freshwater eutrophication** (kg P eq) through nutrients containing e.g. nitrogen and potassium (Campbell et al., 2017). The impact category of eutrophication is also important due to the fact that VHFs are generally thought to have better recirculation of nutrients, thus less in the effluent. **Fossil resource scarcity** (kg oil eq) gives a reference to how fossil dependent the system is, and shows a decreased availability of fossil resources for future generations (Brentrup et al., 2004).

Lastly, **Human toxicity non-carcinogenic** (kg 1,4-DCB), hereafter referred as to Human toxicity, was chosen because it is vital for our food production to be safe for human health. Organic air emissions (e.g. ammonia) during crop production may be toxic to humans due to their contribution to smog (Brentrup et al., 2004).

5.1.3 Allocation

Economic allocation was used to calculate the environmental impact per functional unit. It was used prior to mass allocation since the various crops at SweGreen have quite different economic values for the same mass. The factors in Table 2 were used to allocate the total impacts to the functional unit, i.e. 1 kg of basil. See Appendix 1 for full details on the calculations on the allocation factor.

Table 2 Allocation factor for the functional unit of 1 kg (edible) basil, based on economic allocation.

Crop	Production %	Price SEK per kg	Allocation factor	
			Scenario A	*Scenario B*
Basil (25 g in bags)	12.4	760	$1.47 \cdot 10^{-4}$	$6.36 \cdot 10^{-5}$
Other herbs* (25 g in bags)	25.1	760		
Leafy greens (90 g in bags)	12.5	544		
Leafy greens (in SRS)	50	250		

*Other herbs consist of cilantro, mint, thyme, dill, and parsley.

5.2 INVENTORY ANALYSIS

The data and assumptions on infrastructure, materials, water and nutrients usage and electricity were collected in collaboration with SweGreen through on-site visits and email enquiries. The on-site visits also contributed to in-depth knowledge of the germination and cultivation processes, as the visits also included some labor efforts to understand the process more thoroughly. The data collected is divided into different main categories: infrastructure, germination and cultivation, packaging, electricity, transport and deliveries, and waste. This chapter starts off by presenting a full data inventory for these categories, and will later go into subsections with more details on all categories. Note that some of the data presented below are rounded. The corresponding Ecoinvent datasets for the processes and material and energy inputs presented below are described in further detail in Table 4 and in Appendix 2 Table A9 along with assumptions made.

Table 3 shows the total life cycle inventory for the annual production at SweGreen.

Table 3 Life cycle inventory for the annual production of herbs and leafy greens.

Main category	Process	Unit	Amount	
Infrastructure	Steel	kg	1 500	
	Aluminum	kg	1 400	
	Plastics*	kg	10 200	
	LEDs	kg	10	
	Controllers	kg	130	
	Heat pump	units	1	
	Water pumps	units	32	
	Refrigerator	units	1	
	Dehumidification unit	units	1	
	Packaging machine	kg	150	
	Ventilation duct	m	1 200	
Germination and Cultivation			*Scenario A*	*Scenario B*
	Seeds	units	266 666	617 284
	Growing media	units	133 333	308 642
	Trays	units	889	2 058
	Nutrients	kg	276.6	640.2
	Water	L	26 795	62 025
Packaging	Plastic bags	kg	531	1 229
	Label	kg	177	410
	SRS	units	250	
Electricity	Light	kWh	480 311.20	
	Dehumidification	kWh	38 508.80	
	Heat pump	kWh	45 795.40	
	Water pumps	kWh	49 360.17	
	Other	kWh	32 510.13	
Transport and Deliveries	Ship transport, material	tkm	47 438	
	Lorry transport, material	tkm	577	1 015
	Car deliveries, products	km	520	780
Waste	Organic waste	kg	6 400	8 821
	Plastic waste	kg	181	419

*The plastics include PVC, PET, polyethylene, polypropylene and polyester. The growing walls consist of PVC along with PET for the matrix media, and these two comprise more than 90% of the total weight of plastics.

5.2.1 Infrastructure

The infrastructure denotes all the material and structural components required for the system at SweGreen, for example, the growing walls, material for electrical equipment, irrigation, lighting, and pipes. The infrastructure consists of many different materials. Steel components include racks, cable ladder, and structure for the water tanks. Aluminum components include armature for the LEDs. Plastic components include tubing, trays, various containers, etc., and made of PVC, PET, polyethylene, polypropylene and polyester. PVC and PET are the most common plastic materials used, with PVC being the material of the growing walls, and PET is the material of the matrix media used in the growing walls. Controllers denote various electronic controllers that are used in the farm, including monitors showing pH and EC levels in the water tanks, and LED drivers (devices that enable dimmed lights). Since the infrastructure may last for varying periods, depending on e.g. the material, allocation was performed based on the assumed lifetime of the products and materials, and is presented in Table 4. The impact of the infrastructure was then divided by the assumed lifetime. Table 4 also shows the Ecoinvent datasets used for the infrastructure. For all steel and aluminum parts, metal working processes were added to represent the conversion from metal parts into product components, and the process of injection molding was considered for plastics, see Appendix 2. More information on the lifetimes are given in Appendix 2.

Table 4 Infrastructure materials and objects, with lifetime and modelled Ecoinvent dataset.

Infrastructure	Lifetime (years)	Ecoinvent dataset
Steel	50	steel, low-alloyed
Aluminum	50	aluminum alloy
PVC	25	PVC, bulk polymerisation
PET	3	PET, granulate, recycled
Polyethylene	15	low density polyethylene
Polypropylene	15	polypropylene, granulate
Polyester	1	polyester resin
LEDs	6	light emitting diode
Controllers	10	electronics, for control units
Heat pump	20	heat pump, 4kW
Water pumps	10	pump, 40W
Refrigerator	10	refrigeration machine
Dehumidification unit	20	ventilation control and wiring production
Packaging machine	10	industrial machine
Ventilation duct	50	ventilation duct, steel

5.2.2 Annual Production Figures

Much of the calculations below are based on the figures for annual production. Table 5 shows the annual total production numbers for the current production scenario (A) and the maximal (B). The scale factor (2.35) was used to scale up impacts from Scenario A to B, and was calculated by dividing the production of Scenario B to the production of Scenario A. More information about when this scale factor was used are given in the subsections below.

Table 5 Annual production for Scenario A and B.

	Annual production kg/year
Scenario A	10 800
Scenario B	25 000

Figure 13 explicitly shows the output per plug and is divided into the crops that are regrown and put in plastic bags (herbs) and the crops that are not regrown (leafy greens) which are either put in bags or in re-usable trays (also called SRS). More information about the packaging will be presented in subsection *5.2.4 Packaging*, and more information about the waste produced per plug will be given in subsection *5.2.7 Waste.*

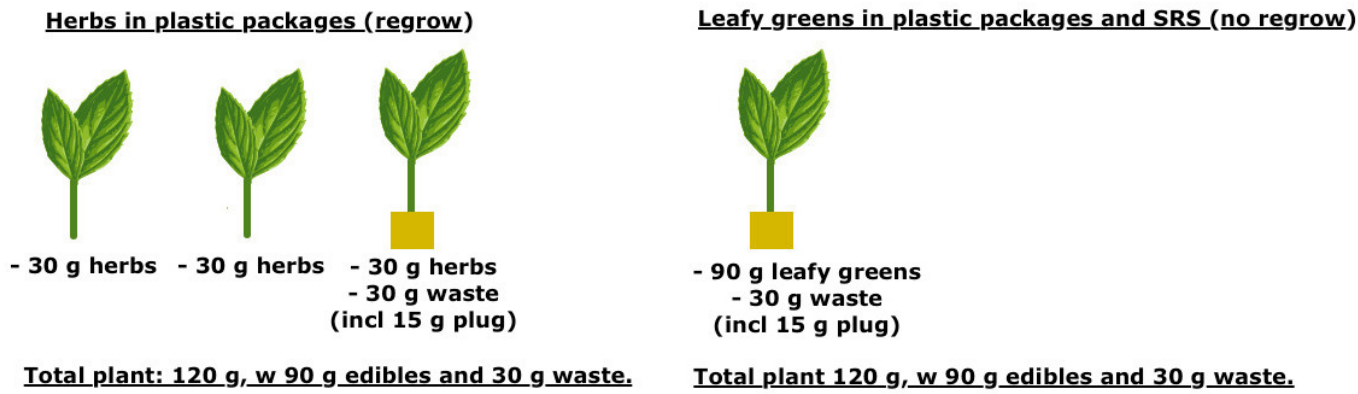

Figure 13 Edible production and organic waste per plug for regrown crops and not regrown. The numbers are based on weighing crops and plugs at the farm, and assuming that those numbers apply for all produce. Note that both crops that are regrown and those who are not contain the same amount of edible per plug.

5.2.3 Germination and cultivation

Raw materials

Germination and cultivation refer to the growing process and the associated raw materials: seeds, plugs, trays, nutrients and water. The seeds, plugs and trays are introduced in the germination process and later transferred to the growing room for cultivation, i.e. the seedlings are still intact in the plugs when they are relocated from germination to cultivation. The modeled Ecoinvent datasets for seeds, plugs and trays are presented in Table 6. As seen in Table 7, there are two different quantities of each material due to the two scenarios producing different amounts. The quantities of seeds, plugs and trays were calculated by assuming that one tray consists of 150 plugs and assuming that each plug contains roughly 2 seeds. The number of plugs in the main growing room was calculated with data from Figure 13, and the number of total plugs were calculated by adding 10% of plugs from the germination process that do not germinate and are therefore thrown away before reaching the growing room[9].

[9] Information retrieved from SweGreen.

Table 6 Ecoinvent datasets for seeds, rockwool plugs (growing medium), and trays.

Input	Ecoinvent dataset
Seeds	grass seed, organic
Rockwool plugs	stone wool
Trays	polystyrene, extruded

Table 7 Amount of rockwool plugs, seeds and trays, annual numbers.

	Plugs in main growing room	Plugs total	Seeds	Trays
Scenario A	120 000	133 333	266 666	889
Scenario B	277 777	308 642	617 284	2 058

Nutrients

SweGreen makes their own nutrient mixes from various nutrients. The annual consumption of nutrients was calculated and estimated from a written protocol where SweGreen keeps track of when they mix new nutrient blends. However, some of the nutrients employed didn't exist as datasets in Ecoinvent, and other datasets had to be used in their stead. Calculation based on molecular weight was used to estimate the proportion of the actual nutrients that constitutes the available dataset nutrients. The impacts for the actual nutrients were then calculated by multiplying the impacts for the available nutrient dataset with the proportion. See Appendix 2 for details on nutrient calculations. Table 8 shows the actual nutrients, the available Ecoinvent datasets, and the calculated annual amount for Scenario A. To obtain the amounts of nutrients for Scenario B, each nutrient amount for Scenario A was scaled up using the scale factor, thus assuming a linear relationship between production numbers and nutrient amounts[10].

Due to the closed-loop water system, it was assumed that there were no nutrient emissions to the environment from the farm.

Table 8 Calculated amounts of nutrients for Scenario A fitted to the available Ecoinvent nutrient datasets.

Nutrient	Available Ecoinvent dataset	Amount kg/year
NO_3 NH_4	N-tot	61.0
P P_2O_5	P_2O_5	1.4 10.6
K K_2O	K_2O	15.8 24.3
Mg MgO	MgO	2.1 5.6
Ca CaO	$Ca(NO_3)_2$	6.5 16.3
S SO_3	SO_3	1.4 8.9

[10] For scaled up amounts for Scenario B, see Appendix 2.

Water

Figures on annual water consumption for Scenario A was obtained by SweGreen. The annual water consumption includes all water activities at the farm, e.g. irrigation. A linear relationship between production numbers and water consumption was assumed, and the scale factor was used for extrapolating the water numbers to Scenario B. The Ecoinvent dataset for water can be found in Appendix 2 Table A9.

5.2.4 Packaging

The harvested herbs are packed in bags with an attached label, with each bag containing roughly 25 g of herbs, see Figure 14 for an example of basil in a finished bag. The leafy greens are either packed in bags with 90 g edible leafy greens, or put in plastic trays (SRS). Both the plastic bags and the SRS are made out of polypropylene, but the SRS are re-used multiple times as they are part of the Svenska Retursystem[11]. Modeled datasets for the polypropylene and label are presented in Table 9.

Figure 14 Basil in its package with plastic bag and label, ready for delivery. Own picture, SweGreen farm.

Table 9 Ecoinvent datasets for plastic bags, SRS, and label.

Input	Ecoinvent dataset
Plastic bags	polypropylene, granulate
SRS	polypropylene, granulate
Label	laminating service, foil

[11] Svenska Retursystem provides producers with reusable trays and takes care of the washing and control after use, and sends them back to the producers (Svenska Retursystem, n.d.).

Table 10 summarizes the data on the plastic bags. The amount of plastic bags that go to retail was calculated by dividing the annual consumption of herbs and leafy greens, respectively, by the crop weight per bag. The numbers for the smaller bags used for herbs were based on weighing bags and labels at the farm and assumed that those numbers apply for all packaging.

Table 10 Details on how many plastic bags that go to retail and weights for the herbs and leafy greens in plastic bags.

	Crop per bag kg	Weight plastic bag Kg	Weight label kg	Plastic bags to retail units	
				Scenario A	*Scenario B*
Herbs in bags	0.025	0.002	0.001	162 000	375 000
Leafy greens in bags	0.09	0.002	0.001	15 000	34 722

5.2.5 Electricity

The figures on total annual electricity for Scenario A was obtained by SweGreen, and was assumed to be the same for Scenario B[12], see Table 11. Note that even though SweGreen buys electricity from renewable sources, the default electricity mix was chosen as the Swedish mix, as is usually done in LCA's on urban farming (see e.g. Romeo et al., 2018), and the results are later compared with an alternative electricity mix.

Table 11 Total annual electricity consumption and dataset.

Annual electricity consumption kWh	Dataset
646 485,70	market for electricity, medium voltage, Swedish mix

5.2.6 Transport and Deliveries

The transport of materials was also included in the assessment. When choosing among different datasets, datasets that already included transport were prioritized, but in cases where these datasets couldn't be found, transportation distances were added manually, see Table 12. The growing walls (PVC) were imported by boat from Canada, assuming a distance of 5 000 km, and the growing media and trays were imported from Poland by lorry, assuming a distance of 1 000 km. The steel was part of many different infrastructure objects employed, and assuming a distance of 100 km on average. Furthermore, data on the transport also included the transport (by lorry) of the plastic waste to an incineration plant and organic waste to a composting facility, each distance assumed to be 20 km[13].

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[12] For more information on the assumption, see Appendix 2.
[13] The datasets for transportation required information on the load distances, see Table A9 in Appendix 2.

Table 12 Details on transport. The processes included are those that did not have transport included in its Ecoinvent dataset.

Type of transport	Material transported	From/To	Distance km
Ship transport	PVC	Canada	5 000
	PET	Canada	5 000
Lorry transport			
	Steel	-	100
	Dehumidification unit	Sweden	100
	Growing media	Poland	1 000
	Trays	Poland	1 000
	Plastic waste	Incineration	20
	Organic waste	Composting facility	20

The products from SweGreen are delivered to supermarkets and restaurants. An average distance of 5 km per delivery was assumed for both Scenario A and B, but Scenario B is assumed to require three delivery days each week instead of two, see Table 13.

Table 13 Details on deliveries of finished products per car.

	Distance per delivery km	Deliveries per week	Distance per year km
Scenario A	5	2	520
Scenario B	5	3	780

Various Ecoinvent datasets were chosen to describe the transport/delivery data by boat, lorry and car. See Appendix 2 Table A9 for details.

5.2.7 Waste

As previously mentioned, SweGreen generates both organic waste and plastic waste. Organic waste is treated by composting, and plastic by recycling, see Table 14 for the modeled Ecoinvent datasets. The organic waste consists of plugs, stems and roots, and emerges during three primary processes in the farm: 1) during germination where 10% of the plugs with seeds are assumed not to germinate, 2) during harvesting of the plants where plugs, stems, and roots are sorted out, and 3) due to crop failure or overproduction. Note that the plugs are not organic, but are sorted as such at the farm, and was therefore part of the organic waste weight[14]. The amount of organic waste due to the three processes are presented in Table 15. The organic waste from germination were calculated by multiplying the plug weight (see Figure 13) by the number of plugs in germination (see Table 7). The organic waste from harvesting was calculated by multiplying the waste per plug (see Figure 13) by the total number of plugs. The organic waste from crop failure and overproduction were assumed to be 50 kg per week for Scenario A, adding up to 2 600 kg per year. For Scenario B, this organic waste was assumed to be much lower due to better communication between producers and the sellers, and was set to be a per mil of what

[14] For more information on the recycling of rockwool plugs, see Appendix 2.

is produced in total (based on expert advice from I. Strid, personal communication, 16 April, 2020). This reduction in organic waste from Scenario A to B is assumed possible through added digitalization in the farm with new systems that enable SweGreen to easier control the production.

Table 14 Ecoinvent datasets for the waste handling of organic and plastic waste.

Process	Ecoinvent dataset
Organic waste, composting	biowaste, industrial composting
Plastic waste, plastic recycling	waste plastic, municipal incineration

Table 15 The annual amount of organic waste ("org waste" in table) generated in the farm for Scenario A and B. Note that the organic waste due to crop failure and overproduction is denoted as "production" in the table.

	Org waste germination kg	Org waste harvesting kg	Org waste production kg	Org waste total kg
Scenario A	200	3 600	2 600	6 400
Scenario B	463	8 333	25	8 821

The plastic waste consists of faulty bags from the packaging process, and trays used in the germination process. The faulty bags occur when the bags get stuck in the packaging machine, and the number was assumed to be 20% of the total bags, see Table 16 for the total weight of plastic bags wasted. All trays that are used in the farm are later thrown away, see Table 16 for the total weight. Note that the plastic waste for Scenario B is assumed a linear relationship with the production numbers.

Table 16 The annual amount of plastic waste generated in the farm for Scenario A and B. The numbers were based on weighing one bag and one tray and assuming that those numbers were applicable for all bags and trays.

	Weight plastic bags waste kg	Weight trays waste kg	Plastic waste total kg
Scenario A	89	92	181
Scenario B	205	214	419

6 RESULTS

This chapter presents the impact assessment from the LCA of the vertical hydroponic farm at SweGreen. First, the results are presented in aggregated numbers for Scenario A, to illustrate what processes contribute most to the environmental impacts (i.e. hotspots), and to answer RQ1. Focus will be on Scenario A, since this shows the current production system. Lastly, the results are presented in more detail, to get an insight on what specific inputs that contribute to the impacts.

6.1 RESULTS IMPACT CATEGORIES

6.1.1 Overview

Figure 15 shows the results for Scenario A, scaled up to 100% to show the contribution of each process to the total environmental impact. Electricity is a hotspot, being a major contributor in 6 out of 7 impact categories, and completely dominates in land use and water consumption, with 99 and 96%, respectively. Infrastructure dominates in human toxicity, and has contributions of 10-20% in the other impact categories (disregarding water consumption and land use). The process related to packaging has a notable high impact in fossil resource scarcity. Other noteworthy contributions are those of transport and deliveries along with waste handling on terrestrial acidification.

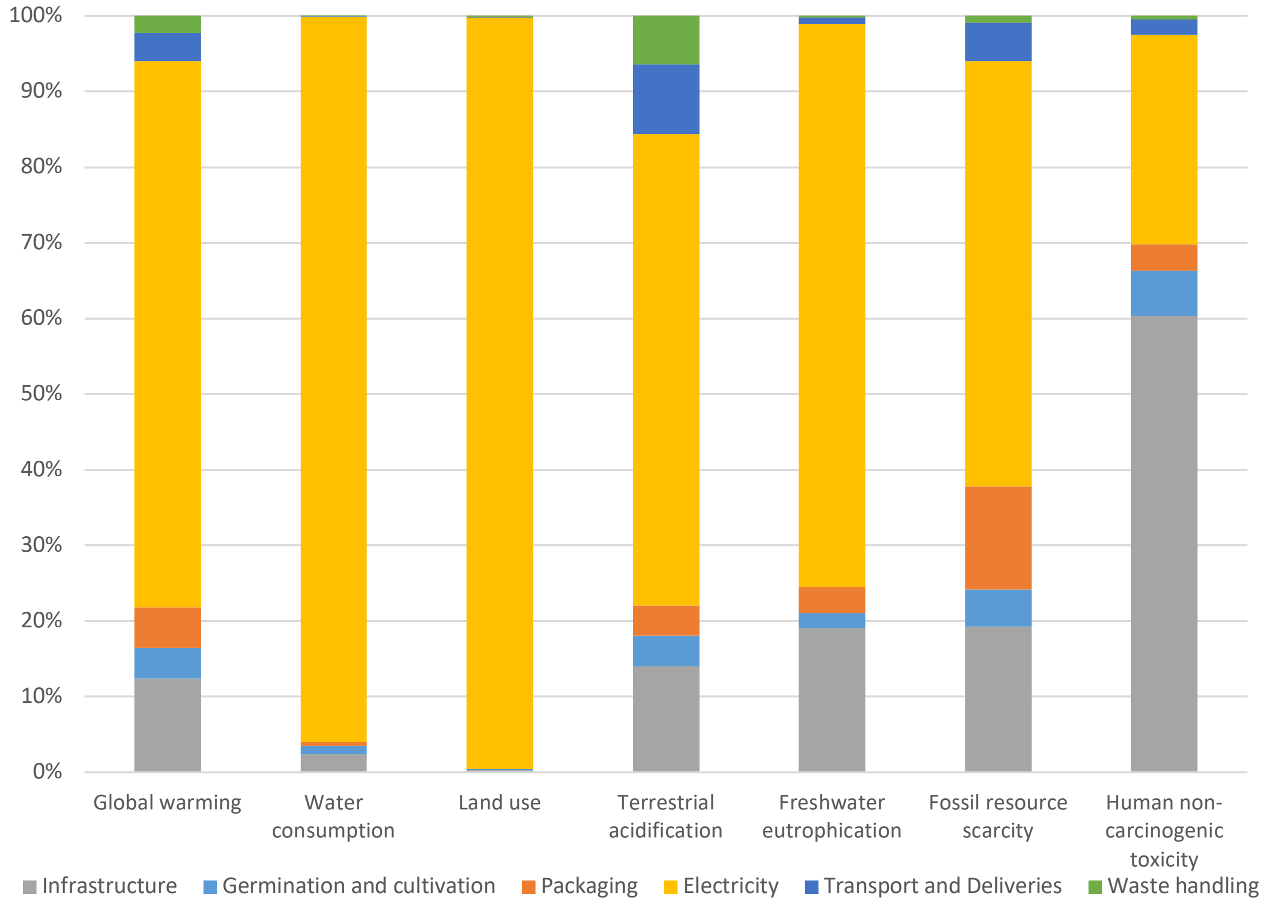

Figure 15 Environmental impacts for Scenario A, presented in the processes of infrastructure, germination and cultivation, packaging, electricity, transport and deliveries, and waste handling. For all impact categories, see Appendix 3.

6.1.2 Electricity

When looking more into detail of the source of electricity impacts, it is shown that the growing lights, LEDs, are the single most dominating input at the farm, contributing to roughly 54% of all greenhouse gas emissions for the life cycle assessment. Further, the LEDs contribute to roughly 75% of the overall electricity impacts, and water pumps, heat pump, fan, and 'other' (which mainly consists of electricity for the refrigerator and UV filters) each contribute to roughly 5-7%, see Figure 16. The water pumps are naturally important for irrigation, but also in the LED cooling processes and the recirculating of the water after condensation. The heat pump and fan enable the dehumidification process, thus decreasing the water use and the need for external ventilation.

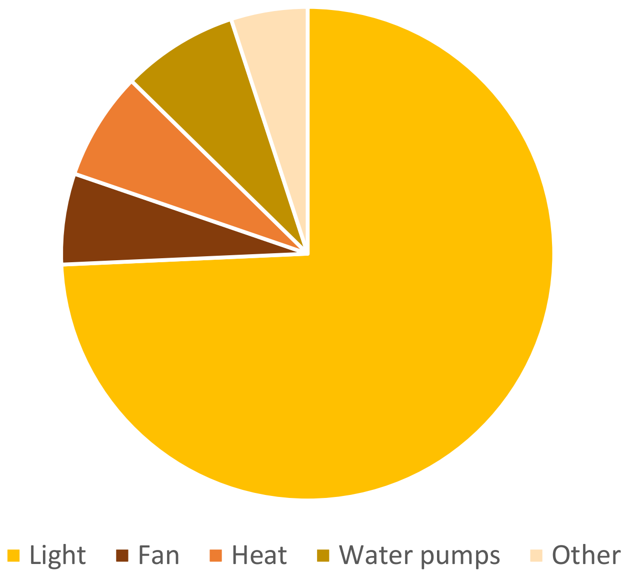

Figure 16 Electricity constituents for the annual electricity usage expressed as percentages, and is the same for all impact categories. Note that the figures are valid for both Scenario A and B.

6.1.3 Infrastructure

As for the other large impacting process, infrastructure, it can be seen that the growing walls comprise the largest share of the inputs for the annual GHGs associated with the farm, see Figure 17. The growing walls also contribute to the single largest material weight of the material employed for infrastructure, see Table 3. The refrigerator and steel and aluminum employed are also notable contributors, along with various plastic material, material for the LEDs, and controllers. See Appendix 3 for the contribution of infrastructure on all impact categories; for example, do controllers dominate in human toxicity.

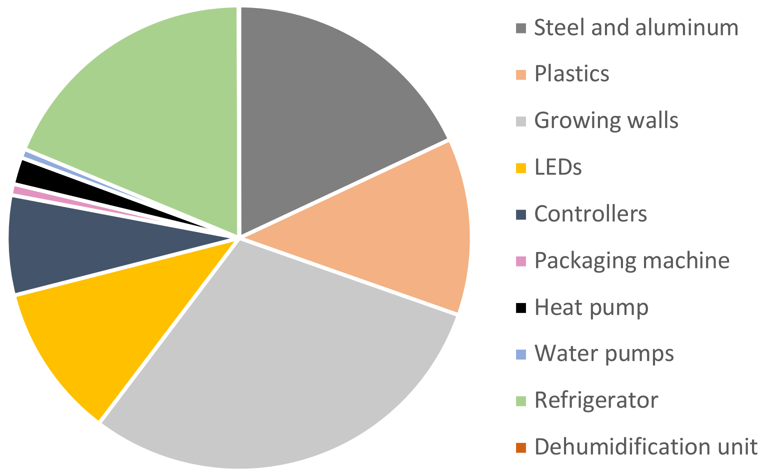

Figure 17 Infrastructure constituents for the annual greenhouse gases expressed as percentages. Note that the figures are valid for both Scenario A and B. Further note that the impacts of the dehumidification unit are too small to be displayed.

6.1.4 Details on figures

Figure 18 shows again the impacts but now showing the disaggregated inputs. Electricity and infrastructure are not subdivided to facilitate an interpretation of the graph. The third largest contributor to GHGs, after electricity and infrastructure is the plastic bags with 4% of the total impacts, thus large reductions in GHGs can potentially be made by changing the material of the plastic bag. The effect of plastic bags is also notable in fossil resource scarcity, where it contributes to more than 11%. The SRS has a low impact compared to the plastic bags. The fourth largest overall contributor is the transport of materials, with roughly 9% of the terrestrial acidification and almost 5% of fossil resource scarcity, with the absolute majority of the transport derive from the impacts of importing the growing walls from Canada. Impacts from the delivery of products, however, are overall very low and do not account for more than 0.5% at most. Composting has a notable contribution in terrestrial acidification, but not as significant in the other impact categories. Plastic recycling, however, has no significant impact overall. The impacts of nutrients are largest in human toxicity (roughly 4% of the impacts) and are noteworthy in climate change, terrestrial acidification, freshwater eutrophication, and fossil resource scarcity, with roughly 2% of the impacts, respectively. The contributions of the growing media are overall very small in all impact categories, and also for the trays that carry the growing media. Water impacts are also very low[15], contributing less than 0.7% at most, which indicates that water overall has a very low impact on the environmental performance of the farm.

[15] Note the difference between "water inputs" which is the direct water use at the farm, and the impact category of "water consumption", which includes water for the full life cycle (e.g. water for generating electricity and manufacturing).

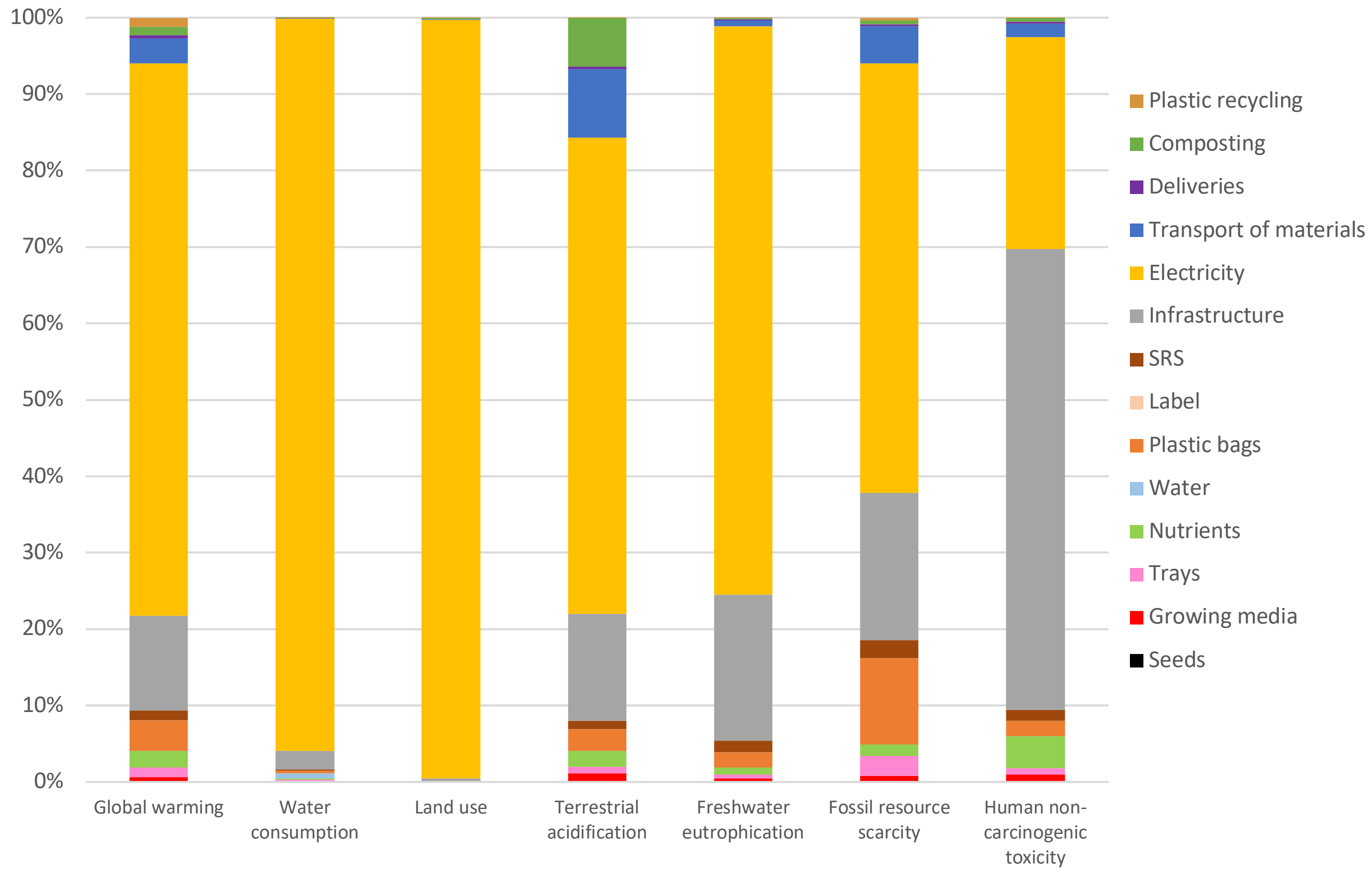

Figure 18 Contribution to the environmental impacts for different processes for Scenario A. Electricity and infrastructure have been aggregated respectively.

6.2 ENVIRONMENTAL FOOTPRINTS

Table 17 summarizes the total environmental impacts per functional unit grown at the farm for Scenario A and B; once again 1 kg of basil. The carbon footprint is 5.3 kg CO_2 eq per functional unit for Scenario A. The water footprint is 0.6 m^3 for Scenario A and includes all water related processes, e.g. the water requirements in the production of energy and raw material. The impacts per functional unit in Scenario B are halved in most of the impact categories, compared to Scenario A. Again, it is important to note that the full system in regards to electricity is run in Scenario A but only about 40% of the capacity for the growing walls is used; in Scenario B the same amount of electricity is used but with all growing walls operating.

Table 17 Total environmental impacts per kg of basil for Scenario A and B.

		Scenario A	*Scenario B*
Climate change	kg CO_2 eq	5.3	2.6
Water use	m^3	0.6	0.3
Land use	m^2a crop eq	1.8	0.8
Terrestrial acidification	kg SO2 eq	0.02	0.01
Freshwater eutrophication	kg P eq	0.003	0.001
Fossil resource scarcity	kg oil eq	1.1	0.6
Human toxicity	kg 1,4 DCB eq	2.6	1.2

7 ANALYSIS

This chapter starts off by analyzing the environmental footprints. It continues by presenting an analysis of substituting the fertilizers and the default bag type used in the farm, to be able to answer the RQ2 on how the environmental performance of the farm can improve. Next, an analysis of the symbiotic development between the farm and the building; the benefits will be presented as a decrease or increase in greenhouse gases[16]. Lastly, a sensitivity analysis is presented to test the overall results in the study in regard to the functional unit choice, electricity, and the allocation procedure.

7.1 ANALYZING THE RESOURCE CONSUMPTION

As illustrated in Table 17, the water footprint for total water consumption is 0.6 m^3 for Scenario A. However, when considering solely the direct water use in the farm, the water footprint becomes remarkably lower with roughly 4 L (or 0.004 m^3) per functional unit, and 2.5 L (or 0.0025 m^3) per kg generic crop fresh weight.

The farm produces roughly 29 kg fresh weight (edible) per m^2 for Scenario A, and more than 67 kg/m^2 for Scenario B[17].

The electricity consumption (purchased) per functional unit is roughly 95 kWh for Scenario A, and 41 kWh for Scenario B (for calculations, see Appendix 2). For generic crop, the electricity consumption is roughly 60 kWh and 26 kWh per kg.

7.2 BIOFERTILIZERS

An analysis was carried out to examine the potential benefits of substituting the synthetic fertilizers to biofertilizer[18]. The biofertilizer was assumed to be produced from biogas digestate and prepared through water removal, see Appendix 4 for a full depiction of the analysis. The GHGs associated with fertilizers were shown to decrease by 97% annually if converting to biofertilizers, however, if comparing to the total GHGs, the emissions would decrease by roughly 2.2%, see Figure 19.

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[16] As well as water consumption, in the analysis of the symbiotic development.

[17] Note that these numbers do not account for the crops that are produced and thrown away, but only consider the crops that are sold.

[18] The analysis followed the same structure as proposed by Martin et al. (2019) with information on nutrient content in biogas digestate from Ljung et al. (2013).

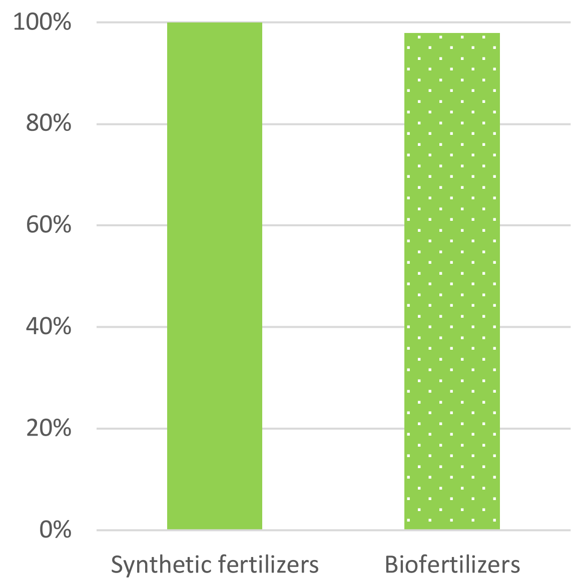
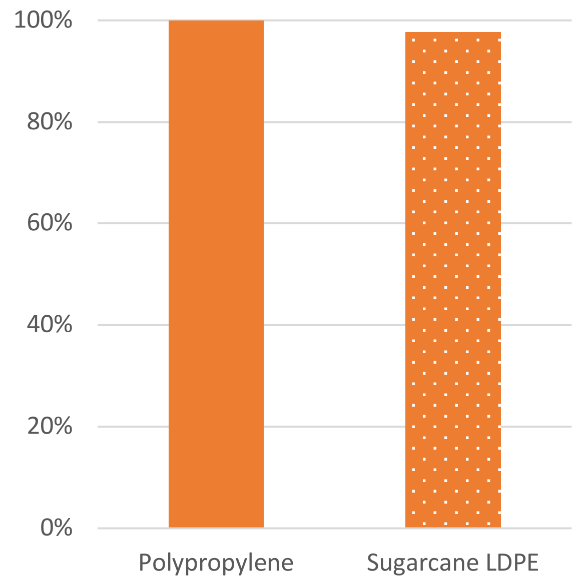


Figure 19 Total annual greenhouse gases for the farm, expressed as percentages, if employing biofertilizers compared to synthetic fertilizers.

7.3 BIO-BASED PLASTIC BAGS

The polypropylene plastic bags resulted in noteworthy contributions in both fossil resource scarcity and climate change, hence a possible scenario with plastic bags made out of sugarcane low-density polyethylene (LDPE) was analyzed. This so-called "green polyethylene" is a popular alternative to all-fossil-based bags and is widely used in the industry (for example through the bag trademark "I'm Green" employed in numerous Swedish supermarkets[19]). The annual GHGs associated by plastic bags were shown to decrease by 58% by the transition to the renewable bag material, and the total GHGs by 2.3%, see Figure 20.



[19] For example ICA, which employs both carrier bags and fruit and vegetable bags of sugarcane LDPE (ICA, n.d.).

Figure 20 Total annual greenhouse gases for the farm, expressed as percentages, if substituting the bag material from polypropylene to sugarcane LDPE.

7.4 BENEFITS OF SYMBIOTIC DEVELOPMENT

As previously specified, SweGreen has symbiotic exchanges with the building. In order to show the potential benefits of the synergies with the surrounding building, a reference scenario was constructed and compared to Scenario A. The reference scenario illustrates a hypothetical system without the symbiosis employed, i.e. without the LED cooling process, the dehumidification process, and the carbon dioxide from the office floor. Without the symbiotic relationship with the building, it is assumed that 1) a building structure is needed[20], 2) the efficiency of LEDs decreases without the LED cooling, thus more electricity is needed, 3) cooling is needed because the LED would give off more heat, 4) more water is needed as it is not recirculated from the dehumidification process, and 5) external carbon dioxide in cylinders are needed, since not obtaining it from the office floor. Further details on the reference system and assumptions are provided in Appendix 4.

The results, as illustrated in Table 18, suggest that the potential GHG emissions would increase significantly by roughly 470%, with the majority corresponding to the building structure. Water consumption would increase by 40%, mainly due to the building structure but also due to the extra water requirement without the dehumidification process, as well as the added electricity. Likewise, the impact categories land use, acidification, eutrophication, fossil resource scarcity and human toxicity, all showed significant increases with the symbiosis, see Appendix 4 Table A16.

Table 18 Increase in greenhouse gases and water consumption, expressed as percentages, in a theoretical scenario without the symbiosis, based on annual figures.

Impact category	Increase w/o symbiosis
Climate change	470%
Water consumption	40%

7.5 SENSITIVITY ANALYSES

7.5.1 Functional unit choice

A sensitivity analysis was carried out to review the impacts of the choice of functional units. This was done in comparison purposes, since various studies use a variety of functional units to describe the environmental performance of vertical hydroponic farms[21]. Table 19 shows the sensitivity for greenhouse gas emissions for Scenario A, with two alternative functional units. As shown in the table, the results can vary considerably with different functional units. The

[20] Without the symbiosis, the farm is assumed not to occupy the basement, thus another structure is needed.
[21] For example did Martin & Molin (2019) use one pot of basil as their functional unit, and Romeo et al. (2018) used 1 kg of leafy greens.

lowest impact is associated with the functional unit of 1 bag of basil, due to this one containing only 25 g of crop.

Table 19 Sensitivity of the greenhouse gas emissions to the choice of functional unit. Note that all impacts consider edible amounts of crops.

Impact per kg basil kg CO_2 eq/kg	Impact per bag of basil kg CO_2 eq/bag	Impact per bag of leafy greens kg CO_2 eq/bag
5.3	0.13	0.34

7.5.2 Electricity dataset

In regard to electricity being the major dominating process, the sensitivity to the choice of electricity mix was evaluated. SweGreen buys renewable energy from wind and solar power, in which it was assumed that the majority originates from wind, thus the default electricity (Swedish mix) was compared to electricity provided solely from wind power. The Swedish electricity mix consists mainly of nuclear energy and hydropower, with a smaller share of renewable sources (Ecoinvent, 2020).

As illustrated in Figure 21, a large reduction in total GHGs is possible when replacing the Swedish mix to electricity from wind power, with decreased emissions by roughly 50%. The carbon footprint for Scenario A decreases from 5.3 kg CO_2 eq to 2.9 kg CO_2 eq, accordingly, see Table 20. The choice of electricity mix has an even larger effect on the water consumption, where the water consumption per functional unit decreases from 600 L to 40 L, see Table 20.

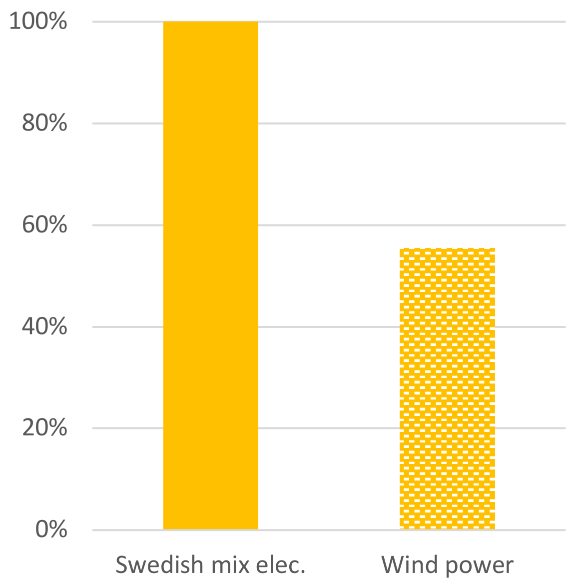


Figure 21 Difference in total annual greenhouse gas emissions, expressed as percentages, with the Swedish electricity mix and electricity from wind power.

Table 20 Sensitivity of the greenhouse gas emissions and water consumption to the choice of electricity dataset, expressed per functional unit. See Appendix 4 Table A17 for all impact categories.

Electricity dataset	Climate change kg CO_2 eq	Water consumption L
Swedish mix elec.	5.3	600
Wind power	2.9	40

7.5.3 Allocation method

This study employed an economic allocation based on the monetary value of the different crops. However, some studies have instead used a physical allocation approach, where the impacts are allocated based on mass (see e.g. Dorr et al., 2017, Martin et al., 2019). Since this choice of methodology could have an effect on the overall results, a sensitivity analysis was performed accordingly. Figure 22 shows that the allocation method has a major impact on the results of climate change, with physical allocation contributing to a smaller carbon footprint than economic allocation: 3.3 kg CO_2 eq compared to 5.3 kg CO_2 eq (Scenario A). This is important to consider if comparing to other studies.

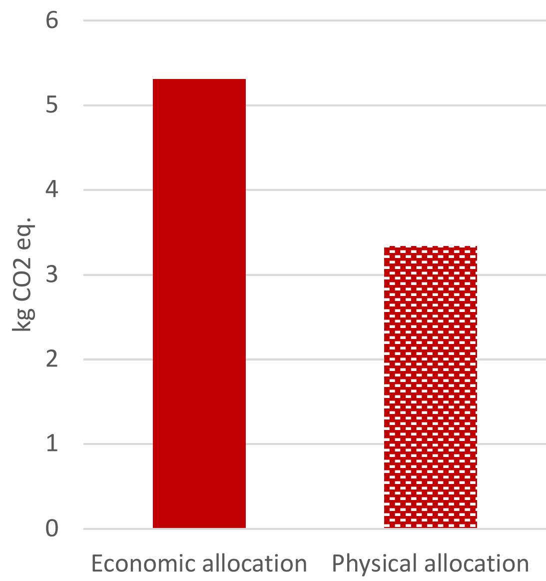


Figure 22 Sensitivity of the greenhouse gas emissions to the choice of allocation method.

8 DISCUSSION

The chapter starts with a discussion on the case study results with a focus on the hotspots and results from the analysis. Next, a discussion on the benefits of the symbiosis, followed by a comparison of vertical hydroponic farms and rural farming. This is followed by a short discussion on the sensitivity analyses. Lastly, a section on the future aspect of vertical hydroponic farms, together with a discussion on the limitations of the study.

8.1 CASE STUDY RESULTS

8.1.1 Electricity

The result showed that electricity was a major hotspot with LEDs being a major contributing process overall in the farm, which concurs with previous research on vertical hydroponic systems (see Martin et al. 2019[22], Romeo et al. 2018, Graamans et al., 2018). Electricity is a prerequisite for the farm to maximize the production of crops, and also to employ the circulating systems that enable the farm to have a comparably low water use. The environmental performance of the farm is thus very dependent on the development and increase in efficiency of the LEDs. It may be rather difficult to lower the electricity consumption since most electrical equipment are already optimized, e.g. some of the water pumps, which are not activated until the water level is above a set level, along with the LED panels and associated light-reflectors that hang vertically parallel to the crops and enable an efficient light distribution to the leaves. Local and renewable energy sources, such as solar panels on the roof, could be installed to reduce the electricity impacts (Al-Chalabi, 2015), but since the building is not the property of SweGreen, this measure may be difficult to implement.

Electricity completely dominated in water use and land use. The electricity impact on land use is mainly due to the mineral extraction (e.g. uranium ore). The impact in water use can partly be explained by the predominance of nuclear energy in the Swedish mix dataset; namely, the water-cooling process in the production of nuclear energy, which has a high water requirement (Ecoinvent, 2020, Romeo et al., 2018). Furthermore, electricity contributes to climate change e.g. through the decomposition process of organic material in hydropower dams in which carbon dioxide and methane are generated (Berga et al., 2006). The emissions of sulfur dioxide and nitrogen oxides from electricity-related transportation, and from waste incineration, contribute to terrestrial acidification (European Environment Agency, n.d.). The effects on freshwater eutrophication may derive partly from the production of nuclear energy where warm water promotes primary production, and partly from hydropower dams, where the long hydraulic residence time and high particle trapping efficiency also promotes primary production (Hydropower Reform Coalition, n.d.). Lastly, electricity affects fossil resource

[22] Martin et al. (2019) did, however, see the largest contributor in the growing medium (soil), which is not consistent with the results in this study, where the growing medium only had minor impacts. Also, in the study by Martin et al., the product was delivered with the medium, which is not the case in this study where only the edible parts are packaged.

scarcity through coal burning and human toxicity through, for instance, zinc emissions (Ecoinvent, 2020, Naturvårdsverket, 2020).

8.1.2 Infrastructure

Infrastructure was shown to be another hotspot, and consistent with other studies on urban farming (Sanjuan-Delmás et al., 2018). However, it is noteworthy that not all LCA's on urban farming include infrastructure which complicates an eventual comparison (see e.g. Dorr et al., 2017). Infrastructure dominates the potential human toxicity impacts due to the electronics employed (impacts from electronics are further recognized in e.g. Biganzoli et al., 2015 and Kiddee et al., 2013). Furthermore, infrastructure contributes largely to the greenhouse gas emissions through emissions in the manufacturing phase of the growing walls and steel and aluminum; and the refrigerator has a large impact on the GHGs due to the refrigerant (Fortems-Cheiney et al., 2015). The environmental impacts from infrastructure are influenced by the waste handling of the materials at end-of-life. If not recycled accordingly, these materials may have a much larger environmental footprint than presented in this study.

8.1.3 Plastic bags

The plastic bags had large impacts on fossil resource scarcity which is due to the fossil oil requirement of producing the polypropylene, which also generates large GHGs. SRS showed significantly lower impacts than plastic bags, but since bags and SRS offer two different purposes, the SRS cannot directly substitute for the bags. By changing the material from fossil dependent-polypropylene to sugarcane LDPE the total annual GHGs increased by 2.3%. However, it is important to consider that despite that the alternative plastic bag is made out of sugarcane, it is not biodegradable, thus needs to be recycled just like the default bag type (Liptow & Tillman, 2012). The easiest thing as to overcome the impacts of the plastic bag could potentially be to simply reduce the crops that are packed and sold in bags, and increase the crops that are sold in bulk with SRS. However, it may be difficult to pack and deliver perishable crops like herbs in bulk, without damaging the crop, and this "solution" could also lead to more waste, since the crops are not as protected as they are enclosed in a bag (Verghese et al., 2015).

The importance of packaging was highlighted in Fernqvist & Göransson (2017), where retailers believe that sustainable packaging will be more important for customers in the future. The article also emphasizes the importance to mediate the origin of the food through the packaging, e.g. by a picture of the producer or the farm. This could be a valid idea for products from vertical farms, since most people might not have a reference as to how the farm looks like.

8.1.4 Nutrients

The impacts of nutrients have in other studies on urban farming shown a large impact (Sanjuan-Delmás et al., 2018) but findings in this study show that the impacts are minor, and remarkably smaller than those of electricity and infrastructure, and is consistent with studies from another VHF (Martin & Molin, 2019). Despite being less significant, reductions in GHGs are still feasible if changing from synthetic fertilizers to biofertilizers. The analysis showed that the total annual GHGs could decrease by 2.2% annually, which, despite its small appearance, is a significant reduction in gases in a comparably easy process. This changeover could also benefit the biogas industry, as proposed by Martin et al., 2019. Additionally, biofertilizers that derive from local sources (not only from digestate, but also from e.g. wastewater) could make for a greater independence in low input farming systems, thus increasing the self-sufficiency in urban farming. This could become even more important in the future where a strong self-sufficiency is crucial to tackle challenges such as climate change, political instability, and pandemics (Baky et al., 2013, Eriksson, 2018).

8.1.5 Water

The direct water use in the farm, i.e. water for irrigation and other operations, was found to have a very low impact in all different categories, which concur with the aim of hydroponic farming, and with previous studies on vertical hydroponic systems (Graamans et al., 2018, Martin & Molin, 2019). The efficient use of water is possible due to the dehumidification process, which on the other hand consumes large amount of electricity. However, when looking at the water consumption of the full life-cycle, the water footprint becomes significantly larger due to the electricity consumption, showing the importance of stating what water footprint one is talking about when promoting a certain product.

8.1.6 Transport and deliveries

One of the advantages of producing food locally is the low impact on deliveries/trade, which is illustrated in the results of this thesis. The vicinity of the farm to the consumers allow for a shortening of the supply chain and the reduction of losses during distribution, as also observed by Romeo et al., 2018. Transport of materials had a notable high impact in terrestrial acidification which is related to the emissions of mainly sulfur dioxide and nitrogen oxides, in the combustion engine.

8.1.7 Waste handling

Composting had a notable impact in terrestrial acidification which may be due to the nitrification process that occurs in composting, where nitrifying bacteria convert ammonia to nitrate (Cáceres et al., 2018). This process could also explain why composting has a contribution in climate change, even if quite small, when nitrous oxide is released through volatilization. This result is difficult to compare to similar studies since no other study on hydroponic farming has examined the organic waste handling of the waste originating in the farm. Nonetheless, it was found in a study of an integrated rooftop greenhouse that the composting of biomass did contribute significantly to both terrestrial acidification and climate change (Sanjuan-Delmás et al., 2018).

8.1.8 Scenario B

By scaling up the production system from 43% to 100% farm utilization, the impacts per functional unit were halved in most of the impact categories, indicating that utilizing the full capacity at SweGreen is the most environmentally beneficial. Water use and land use were the impact categories that were least affected by the upscaling of production system, presumably due to them being dominated by electricity that was assumed being the same in Scenario A to B. The proportion of fossil resource scarcity, however, increased the most, which is due to the plastic bags that need not only increase by the production but also for the extra bags that go to waste in the packaging process.

8.1.9 Recommendations

Based on the findings and discussions, some associated recommendations regarding the environmental performance of the farm are summarized and presented in Table 21.

Table 21 Recommendations to increase the environmental sustainability of the farm.

Electricity	Keep the production at a maximum to reduce the electricity burden per produce. Ensure the purchase of renewable electricity. Examine the possibilities of installing solar panels on the roof.
Fertilizers	Substitute the synthetic fertilizers to biofertilizers, to reduce greenhouse gases and to promote local collaboration with industries (e.g. biogas plants).
Packaging	Change the material to a biodegradable plastic, to reduce greenhouse gases. Increase public perception of VHFs by adding a picture on the farm on the packaging.
Waste	Better communication between farmers, sellers and retailers to hinder overproduction and reduce food loss.

8.2 BENEFITS OF SYMBIOTIC DEVELOPMENT

Table 18 demonstrated the importance of the current symbiotic development between the farm and the building, showing that without the symbiosis the impacts on climate change and water consumption would increase remarkably; similar results are illustrated for the other impact categories, see Appendix 4. This illustrated the value of the farm to employ an already existing building, which is a big opportunity for farming in urban areas as also observed by Kozai et al., 2016, Sanjuan-Delmás et al., 2018 and Martin & Molin, 2019. Moreover, the symbiosis is also crucial to maintain a low water use which is made feasible through the dehumidification process.

It is important to note that this reference scenario does not take into account the additional excess heat that is generated through the LED cooling process and sold to the building. Implementing this through a system expansion would show a decrease in the default impacts, rather than in this reference scenario where it shows what the increased impacts would be.

8.3 SENSITIVITY OF THE RESULTS

As illustrated in the sensitivity analyses, the results are sensitive to the choice of functional unit; the analysis showed a wide range of different impacts depending on the functional unit, which is also highlighted in previous studies, see e.g. Martin & Molin, 2019. When comparing the environmental impacts of different food products, the functional unit of 1 kg produce is, however, the most common (Muthu, 2014), and should therefore obtain the most attention in this study. Furthermore, the choice of electricity dataset has a significant influence on the overall impacts, which has also been tested and confirmed in studies by Martin et al. (2019) and Romeo et al. (2018). The carbon footprint was found to reduce by almost half, and the water consumption per functional unit decreased by more than 90%. This is important to keep in mind when evaluating the sustainability since SweGreen is, in fact, buying electricity from renewable sources such as wind, and not from a default electricity mix.

Lastly, a sensitivity analysis was performed to study the overall environmental performance to the allocation method. In this study, an economic allocation was chosen due to the different monetary value of the crops. It was shown, however, that a physical allocation approach, generates less impacts per kg crop. Basil has the highest monetary value out of all products, yet constitutes the smallest share of the total weight of the products, which is why the economic allocation generates a larger footprint compared to the physical allocation. Both these analyses demonstrate the magnitude of distinctly communicating the chosen methods in the ”Goal and scope definition” phase of the LCA. If mediating results to consumers, it should also be clearly stated on what the units are, e.g. 1 kg basil or 1 bag of lettuce.

8.4 COMPARISON TO RURAL FARMING

As previously specified, vertical hydroponic farming is often seen as a complement to conventional farming methods, rather than replacing them. Although, it can still be helpful to compare vertical hydroponic farming with conventional systems, to understand its strength and weaknesses in order to further develop the system.

When comparing the vertical hydroponic farm in this study, to a Swedish theoretical greenhouse with artificial lighting in a study by Graamans et al. (2018)[23,24], it can initially be said that the vertical hydroponic farm have a much lower water footprint; 2.5 L (or 4 L when looking at only basil) and 16 L per kg fresh weight, respectively. Production per area was also higher for the vertical hydroponic farm; 2.9 and 6.7 kg dry weight per m^2 (Scenario A and B respectively, if assuming a dry weight of 10%) compared to the greenhouse with 2.8 kg dry weight/m^2; it is, however, once again clear that for the VHF to have a full advantage, it is important that the full production system is operating. Lastly, looking at electricity use, the shortcomings of the VHF become evident. Electricity use for the VHF was higher for both Scenario A and B (410 and 950 kWh/kg dry weight) compared to the greenhouse (180 kWh/kg dry weight). This demonstrates the importance of incorporating urban symbiosis into VHFs that could decrease the electricity burden (as also highlighted by Gentry, 2019). It is, however, important to note that there are very few studies of greenhouses in Sweden, making a comparison between VHFs and greenhouses difficult, thus the comparison presented above should only be seen as an implication.

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[23] Note that this comparison does not show a representative picture on all greenhouses compared to all VHFs, but can rather help illustrate some of the advantages and disadvantages for the two different growing systems.
[24] Graamans et al. (2018) used a dry weight of 7% in their study, and this study used 10%.

More general differences between VHF and conventional farming include the wastewater and its effect on eutrophication. In this study, it was assumed that there were no nutrients in the effluent due to the closed-loop system. In reality, however, some nutrients discharge into the sewer network and are treated in a wastewater treatment plant (SweGreen, n.d.). In open field cultivation, the residual nutrients are instead filtered through the soil horizon before reaching streams (Environmental Protection Agency, 2005, Kozai et al., 2016). Another aspect is that indoor farms cannot contribute to the sequestration of carbon from the air, as open-field cultivation may. VHFs are isolated from the natural carbon cycle and do often need an external carbon dioxide source, but this, on the other hand, allows for an increase in growth efficiency (Kozai, 2013), as illustrated in this study by the high production per area. The efficiency of VHFs compared to greenhouses and conventional farming is indeed dependent on geographical locations and light conditions. At low light conditions and cold climate, the relative efficiency of VHFs to greenhouses is high (Gentry, 2019).

Additionally, it is important to differentiate between what type of water is used in VHFs compared to conventional farming. Since the VHFs are usually located in urban areas, they use water from municipal water supply systems, whereas conventional farming use mainly direct rainwater but also surface water. These two types of water have different qualities; the energy and resource requirements of the production of municipal water are e.g. higher compared to the requirements of irrigation water. This complicates a comparison of the water footprints of the different food systems (Rundgren, 2020).

8.5 IMPROVEMENT POTENTIAL

The outcome of VHFs fulfills many of the desires from retailers and consumers, such as local food throughout a longer season, an increase in the production of products like kale and pak choi, consistent quality and better flavors. This could potentially mean that without proving or disproving VHF as a sustainable food system, we could still see an increase in the farms in the near future.

The action plan “Livsmedelsstrategin” calls for an increase in Swedish food production (Regeringskansliet, 2017). This may sound straightforward and feasible, but is in reality a big challenge in times where agricultural land keeps diminish and fewer people choose to work in the agricultural sector. In this aspect, urban farming and VHF could be one part of the solution, offering underutilized space for growing, less food loss through the transportation chain, and an interconnection with the farmer and the consumer. Emissions from agriculture also need to decrease and for this not to counteract the goal of producing more food, it is important for urban farming to develop symbiotic networks with industries and buildings; a possibility which rural farming often lacks. This certainly holds true for VHFs where the lighting electricity demand is high. VHFs should take advantage of the urban surroundings and local resources for the promotion of circularity and self-sufficiency (Gentry, 2019, Martin et al., 2019). Furthermore, VHF could contribute to the resilience of cities and communities by increasing the diversity of how food is produced, which is crucial in a future of inevitable climate change (FAO, n.d., The URBES Project, n.d.).

8.6 LIMITATIONS OF THE STUDY

Considering this study is based on the LCA methodology, it is important to stress that the results are based on assumptions and models. The obtained environmental impacts are, consequently, only implications of the true impacts of the farm at SweGreen.

8.6.1 Scope

Due to the study being constrained by both time and data, the scope was chosen to follow a cradle-to-gate perspective, thus not considering the full life-cycle of the product. By doing so, significant impacts derived from the use of product, and the waste disposal of the product, could be missed. As discussed in this study, organic food waste is a widely debated matter that can influence the sustainability of food systems (see e.g. Garnett, 2014 and Eriksson et al., 2012), and if feasible, it should be added in the scope of future studies. Additionally, the organic waste handling method of composting employed by the farm is analyzed in this study, however, not the benefits of using this compost in a later stage as soil amendment. This would require using a system expansion, in which the impacts allocated to the waste handling process would decrease, as illustrated by Dorr et al. (2017).

When analyzing the symbiotic development, a reference scenario was constructed to get implications on the potential benefits of employing such a development. However, by this method, the avoided impacts from SweGreen selling excess heat to the building, couldn't be assessed, which would have had to be done by a system expansion. SweGreen is selling approximately 95% of their purchased electricity back into the building as heat, and by taking this into further account, the resulting impacts would probably decrease. It is, however, unclear on how much, since the impacts for electricity and heat are very different (i.e. the impacts for electricity are generally much higher). Due to lack of time, the reference scenario-method was used instead as to analyze the avoided burden, rather than the benefits.

It should be noted that the environmental performance of the farm is dependent on all 18 impact categories, but due to the limited time frame, only seven were chosen to analyze in greater depth. Ecotoxicity has been analyzed in other studies of urban farming (Sanjuan-Delmás et al., 2018), but wasn't included here. To understand the full potential environmental performance of the farm, all 18 categories should be analyzed, accordingly. In addition to this, the social and economic aspects are crucial for determining the overall sustainability of the farm, hence a multidisciplinary approach on the LCA would provide a more holistic view on the performance of the farm as a future food system. In future studies, these aspects should be analyzed alongside the environmental performance.

8.6.2 Uncertainties in data

The results of the study include uncertainties in both calculated and modeled data. Uncertainties in calculated data contain, among others, the estimations on material weight, material amount, and material kind, and will affect the results on e.g. infrastructure, growing media, organic and plastic waste, and transportation. The infrastructure employed was found to contribute significantly to the impacts, and are in turn dependent on the authors own estimations from the farm, as well as the datasets. Furthermore, it was for instance assumed that each plug generates the same amount of organic waste, and the consequences of this assumption propagate not only to the impacts of the organic waste and waste handling, but to the impacts of the growing media, trays, and seeds. The water use, nutrient use, and waste, was assumed to be linearly related to the production numbers when scaling up from the current production system of Scenario A to the maximal of Scenario B. Since the farm doesn't operate at maximum capacity at present, this assumption couldn't be tested, however, this simplification and assumption was necessary for the analysis on Scenario B. Electricity data was assumed to be the same for both scenarios, but in reality, the electricity consumption will probably be higher for Scenario B, with longer running times for e.g. the water pumps and the dehumidifier, which would have contributed to higher footprints for Scenario B.

The on-site collected data on the infrastructure and raw material was translated into Ecoinvent datasets. The Ecoinvent database is a dependable and widely used asset when performing an LCA, but becomes limiting when a certain product or process is not available and has to be estimated by another dataset (Dorr et al., 2017). This issue arose on multiple occasions throughout the assessment where an exact counterpart in Ecoinvent was lacking, and was tackled by trying to find a dataset that, despite its difference from the real product/process, described it sufficiently. Now, what is considered being "sufficient" is of course a subjective matter as to what level of accuracy a study wants to achieve. It is also worth pointing out that all datasets have internal uncertainties that were not presented in this study, due to a limited time frame. This study is, however, made with full transparency on what datasets are used and what they are aiming to describe. No datasets were in any way altered, thus contained the original data on e.g. local electricity and water consumption. Hence, some datasets may show larger impacts than would if all data were based on Swedish conditions, especially with Swedish electricity that contain a larger share of renewables than e.g. the European mix.

Some datasets that are worth some extra attention are those of metals, *controllers* and *building*. The datasets on steel and aluminum don't include the mining process, which, if included, would perhaps contribute more in the impacts categories of e.g. land use, terrestrial acidification and climate change. *Controllers* contributed to a large share in the infrastructure employed, and was applied to a wide variety of different controllers used at SweGreen, and had high impacts per kg. It may be that the dataset overestimates the total impacts deriving from controllers, since the controllers are mostly small monitors. A more accurate dataset on the controllers would presumably result in lower total impacts. The dataset *building* described the building that had to be built in the theoretical scenario without the symbiosis development, and lead to significant contributions in greenhouse gas emissions. This dataset includes a default building with steel structure; if building a structure for a vertical hydroponic farm, one could choose a wood structure in lieu of steel, which would reduce the impacts, thus the overall benefits on the symbiotic development.

With these presented uncertainties, along with the uncertainties further explained in Table A9 in Appendix 2 and the sensitivity analyses, it is once again important to note that the results of this study can be seen as indications for the total environmental sustainability on the SweGreen farm. Further studies on the farm are encouraged, as SweGreen is rapidly evolving and employing new techniques and products, as well as the industry of vertical hydroponic farms as a whole.

9 CONCLUSIONS

This study analyzed the environmental performance of the vertical hydroponic farm of SweGreen, located in Stockholm using life cycle assessment. The objectives were to identify where in the life cycle significant impacts occur and analyze how these could be improved.

The largest contributor to the impacts was electricity, and more specifically the lighting employed which contributed to more than half of the greenhouse gas emissions associated with the farm. Even so, the impacts deriving from electricity was considered difficult to mitigate since the farm is dependent on the electricity to maintain a low water use, and since the farm already employs many energy efficient techniques.

Infrastructure was found to be another environmental hotspot. The impacts of growing media, water use, nutrients, and packaging had much lower impacts; despite this, it was feasible to reduce the annual greenhouse gases by roughly 2.2% if substituting synthetic fertilizers to biofertilizers, which could also benefit local industries and contribute to larger self-sufficiency in low input farming systems. If changing the plastic bags from polypropylene to sugarcane LDPE, the annual greenhouse gases could be reduced by roughly 2.3%.

The symbiotic development between the farm and the building was proven beneficial to the farm, and highlighted the importance of synergies between industries, as a way to reduce impacts, foster partnership and circularity. It was further showed that the farm should run on maximal production to minimize the impacts per kg of produce. However, all employed results were shown to be very sensitive to the chosen electricity mix, choice of functional unit, and the allocation method.

Further studies on the farm and in particular the symbiotic relationship, are encouraged to further assess additional use of residual materials and circular development options.

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APPENDIX 1 – ALLOCATION

Economic allocation was chosen as the allocation method. Table A1 and A2 show the contribution of each crop to the annual production. The allocation factors were calculated by the yearly monetary contribution of basil (in %) divided by the annual production of basil (in kg).

Table A1 Allocation factor for the functional unit of 1 kg (edible) basil, Scenario A.

Crop	Production kg/year	Price SEK per kg	Income from basil %	Allocation factor
Basil (25 g in bags)	1 336.5	760	20	1.47E-04
Other herbs* (25 g in bags)	2 713.5	760		
Leafy greens (90 g in bags)	1 350	544		
Leafy greens (in SRS)	5 400	250		
Total	**10 800**			

Table A2 Allocation factor for the functional unit of 1 kg (edible) basil, Scenario B.

Crop	Production kg/year	Price SEK per kg	Income from basil %	Allocation factor
Basil (25 g in bags)	3 093.75	760	20	6.36E-04
Other herbs* (25 g in bags)	6 281.25	760		
Leafy greens (90 g in bags)	3 125	544		
Leafy greens (in SRS)	12 500	250		
Total	**25 000**			

*Other herbs consist of cilantro, mint, thyme, dill, and parsley.

APPENDIX 2 – INVENTORY DATA

The sections below include detailed descriptions of the inventory data, divided into sections of Infrastructure, Numbers on production, Germination and Cultivation, Packaging, Energy, Transport and Deliveries, and Waste. If an input differs a lot from its equivalent dataset, it will be explicitly stated in the text below. For the other inputs, see the datasets in Table A9.

Infrastructure

The infrastructure employed in the farm includes all structures and infrastructural components for the germination chamber, nursery, main growing room, hallway, and the machine room. All these rooms consist of various metal structures, some are known to be either made out of steel or aluminum, while other's materials are assumed. Most electricity objects are described by a dataset for the manufacturing of a certain electricity object, and not by a general dataset for the raw materials. More info on this will be given in the sections below.

Germination chamber and nursery
The germination chamber includes an aluminum chamber with racks where the seeds in rockwool plugs germinate, which is assumed to weigh 100 kg, and a water basin with an assumed weight of 3 kg and assumed material of polypropylene. The nursery consists of 8 steel racks (5 being in the actual nursery room and 3 being placed in the main growing room) with 6 shelves each (4 is used for growing, 1 for holding a water tank, and 1 for the top roof), each rack assumed to weigh 10 kg. There is 1 large black tray per growing shelf, assumed to be made of polyethylene and weighing roughly 2 kg per piece. The 8 water tanks are each known to weigh 2.97 kg of polypropylene, based on information from the seller (AUER Packaging, n.d.). The nursery consists of 8 water pumps. Each rack has 4 LED armature, each assumed weight of 2 kg of aluminum, and 1 controller, assumed weight 0.3 kg. Each LED armature consists of 60 LEDs, assumed weight of 0.3 g per piece based on assumptions from Martin and Molin (2019). Each rack also has 4 LED drivers (a device that enable dimmed lights), with an assumed weight of 0.3 kg per piece, which is described by the dataset "Controller".

Main growing room
The main growing room consists of 72 carts, which itself is made up of 2 walls, one per each side. Each wall consists of either 15 separate ZipGrow towers (assuming 67% of the walls) or 8 (assuming 33% of the walls). 15 towers are used when the crops don't need much space on each side to grow (e.g. herbs), while 8 towers are used when it is a bigger crop (e.g. kale), that require space on both sides. Each cart stands on 4 small wheels which were neglected in the LCA. Each ZipGrow tower has a known weight of 4 kg and is made of PVC. Each wall has a top chute that distributes the water to the towers, and a bottom chute which collects the water that is not taken up by the plants; each chute is assumed to weigh 4 kg (PVC). Each tower contains 2 pieces of PET-matrix media (known weight of 0.285 kg per piece) and 2 pieces of polyester wicking strip (weight based on weighing, 0.0205 kg per piece). See Figure A1 on depictions of the growing walls used at SweGreen.

There are 244 LED armatures in total (assumed material aluminum and weight 5 kg per piece), 131 of which only have LEDs on one side (80 LEDs) and 113 of which have LEDs on both sides (160 LEDs). Each single-sided armature has 1 LED driver, and each double-sided 2 LED drivers, each with an assumed weight of 0.3 kg, described by the dataset “Controller”. Just below the ceiling, a cable ladder, to carry various tubes and pipes, with an assumed material of steel and weight of 150 kg. Furthermore, 4 aluminum ladders (assumed weight 3 kg per piece) are used during cultivation as well as 2 aluminum trolleys (assumed weight of 10 kg). There are 4 big water tanks (IBC containers) each with a known weight of 60 kg and mix of polyethylene and steel (assuming 40 kg polyethylene and 20 kg steel structure). The water tanks sit on top of a steel structure, assumed weight of 200 kg. 10 white containers (containing the nutrient mixes) are connected to the water tanks, each known weight of 0.62 kg polypropylene. Each water tank has 1 water pump, 1 monitor (same assumptions as for controller in nursery), 2 water filters (assumed 1 kg polyethylene), and 1 UV filter. Each UV filter is described by 1 kg of the dataset “Controller”. In the growing room, there are 8 plastic containers that function as a protection for the water pumps for irrigation, these are excluded in the LCA. Water hoses and growing tools (e.g. pulling hooks), are also excluded.

Figure A1 A wall with 15 towers with basil growing. The height of the towers is 244 cm. Opposite the wall is two LED panels and a ventilation duct. Own picture, SweGreen farm.

Packaging and working space

In the hallway and the conjoined storage room are steel racks with a total assumed weight of 800 kg. The packaging machine is described by the dataset ”Industrial machine” and is assumed to weigh 150 kg. The refrigerator is described by the dataset ”Refrigeration machine”. The vacuum cleaners are each described by 1 kg of the dataset ”Controller”, since no other equivalent dataset could be found to describe vacuum cleaners. The dishwasher, which is only used approximately once every 3 months, is neglected in the LCA.

Machine room

The machine room employs the dehumidification unit and heat pump, together with other electricity items. The dehumidification unit is described by the dataset ”Ventilation central unit”. The heat pump is connected to 3 storage tanks, the first one assuming 90 kg steel and 20 kg polyethylene, and the second and third slightly smaller assuming each 55 kg steel and 16 kg polyethylene**.** One water pump is connected to the storage tanks, one to a vacuum degasser, and a third one is connected to the LED cooling process. The vacuum degasser is described by the dataset for water pumps, since no equivalent dataset for a vacuum degasser could be found in Ecoinvent. The immersion heater (which only works as a spare for the heat pump) is neglected in the LCA.

Pipes

Pipes employed in all rooms (including ventilation steel pipes) are made of steel, polyethylene, and polypropylene. Most of the steel pipes are used for ventilation and have various diameters. All steel pipes are assumed to be ventilation ducts with dimensions 100x50 mm and a total length of 1 207 m, based on visual estimations. A dataset explicitly for the ventilation ducts were used (see Table A9). Extension cords, assuming polyethylene, are used in all rooms, assuming a total distance of 770 m and ∅10mm, with 0.07 kg/m (estimations from Bauhaus, n.d.-b). The other polyethylene pipes include: pipes to/from the water buckets and water tanks assuming length 60 m and 0.195 kg/m (estimations from Bauhaus, n.d.-c), pipes for LED cooling with assumed length 50 m with ∅100 mm and 2.2 kg/m (estimations from Wavin, n.d.), various pipes with total length 540 m with ∅30 mm and 0.2 kg/m (PipeLife, 2010), and lastly assuming 10 m ∅70 mm with 2.16 kg/m (estimations from (Wavin, n.d.-a). The polypropylene pipes assuming a total length of 85 m with ∅30 mm and 0.02 kg/m (estimations from Thomas, n.d.).

References on the assumed lifetimes of the infrastructure are given in Table A3.

Table A3 Reference on lifetime on infrastructure materials.

Infrastructure	Lifetime (years)	Reference
Steel	50	(Romeo et al., 2018)
Aluminum	50	(Romeo et al., 2018)
PVC	25	SweGreen
PET	6	(Michael, 2014)
Polyethylene	15	(Romeo et al., 2018)
Polypropylene	15	Own assumption
Polyester	1	Own assumption
LEDs	6	(PARUS, n.d.)
Controllers	15	Own assumption
Packaging machine	10	Own assumption
Heat pump	20	(Greening & Azapagic, 2012)

Water pumps	10	(Martin et al., 2019; Romeo et al., 2018)
Refrigerator	10	(Xiao et al., 2015)
Dehumidification unit	20	Own assumption
Ventilation duct	50	Own assumption

Numbers on production

The numbers on production are based on information from SweGreen. Scenario A represents the production during 2019 with the assumed annual production of 10 800 kg. Currently, roughly 40% of the growing walls are actively employed. Scenario B represents a theoretical maximal production that could be accomplished if all the growing walls were utilized, with 25 000 kg annual production based on calculations from SweGreen.

Germination and Cultivation

Raw materials

The raw materials for the growing process are seeds, rockwool plugs (growing media), trays, nutrients, and water. See Figure A2 on a depiction on a tray with rockwool plugs. The total annual consumption of rockwool plugs are assumed to be 133 333 for Scenario A. This was calculated based on the information on total production and that each plug generates 0.09 kg edible, and that 10% of plugs are wasted before reaching the main growing room. The total annual consumption of rockwool plugs for Scenario B, 308 642, was calculated by scaling up from Scenario A using the scale factor. One wet plug weighs 15 g, based on weighing, and is assumed to carry 2 seeds on average (seed amount ranges from 1 to 10 per plug but with 2 seed per plug being most common). The plugs used for leafy greens are slightly bigger than those used for herbs, but the default plug weight is based on herb plugs in the LCA. The rockwool plugs are delivered to SweGreen in the same package as the small black trays (only referred to as ”trays”), with each tray containing 150 plugs. Each tray weighs 104 g (based on weighing), with known material of polystyrene. The impacts of the sticky fly paper employed in the main growing room for pest control, were neglected in the LCA.

Figure A2 Close-up on a tray with rockwool plugs with seeds on top. Own picture, SweGreen farm.

Nutrients

The demand for nutrients were calculated for Scenario A, and then scaled up for Scenario B (assuming a linear relationship with production numbers and nutrient usage). Each water tank is connected to a controller and a sensor that doses the nutrients automatically whenever the levels are below a set value (the set values are both set for nutrient levels, and pH levels). With information from the protocol that SweGreen is keeping on when they refill the nutrient mixes, and by observing how much nutrient mixes were left in the buckets connected to the water tanks, a total nutrient use of 1.21 kg per day in the main growing room was estimated. This is assumed to be representative for a full year. The amounts of nutrients used for the germination process was set to be 1% of the nutrient usage in the main growing room, based on estimations from SweGreen. The fertilizers used during the germination process are slightly different from those used in the main growing room, but are assumed to have the same content as for the main growing room. With information from the different fertilizer packages and their exact nutrient composition, the amount of each nutrient was calculated, see Table A4. Because all these nutrients weren't available as datasets in Ecoinvent, the datasets for the various nutrients were obtained from corresponding and relevant available dataset, based on molecular weight, from Ecoinvent. For example, for phosphor, the available dataset was P_2O_5, but the nutrient mixes contained both P and P_2O_5; it was therefore calculated how much P ions were included in the P_2O_5 compound. Molecular weights for calculations on the nutrients are given in Table A5, and information on proportion actual nutrient in the Ecoinvent nutrient, are given in Table A6. Lastly, the calculated amounts of nutrients for Scenario B is presented in Table A7[25].

Table A4 Inventory of the actual nutrients in the fertilizers, annual consumption.

Nutrient	**Amount kg/year**	
	Scenario A	*Scenario B*
NO_3	53.5	123.8
NH_4	7.5	17.5
P	9.9	22.9
P_2O_5	10.6	24.6
K	44.7	103.4
K2O	24.3	56.2
Mg	4.8	11.0
MgO	5.6	12.9
Ca	42.3	98.0
CaO	59.0	136.7
S	5.5	12.6
SO_3	8.9	20.6

Table A5 Molecular weights for relevant molecules.

Molecule	**Molecular weight g/mol**	**Reference**
P	30,973	(National Library of Medicine, n.d.)

[25] See the written report for Scenario A.

O	31,999	(National Library of Medicine, n.d.)
K	39,098	(National Library of Medicine, n.d.)
Mg	24,305	(National Library of Medicine, n.d.)
Ca	40,08	(National Library of Medicine, n.d.)
S	32,07	(National Library of Medicine, n.d.)
N	14,007	(National Library of Medicine, n.d.)

Table A6 Proportion of the content of the actual nutrient in the Ecoinvent available nutrient.

Nutrient	Available Ecoinvent nutrients	Proportion nutrient in Ecoinvent nutrients %
NO_3 NH_4	N-tot	-*
P P_2O_5	P_2O_5	14 100
K K_2O	K_2O	35 100
Mg MgO	MgO	43 100
Ca CaO	$Ca(NO_3)_2$	15 28
S SO_3	SO_3	25 100

*Not relevant since N-tot was calculated by simply adding NO_3 and NH_4.

Table A7 Calculated amounts of nutrients for Scenario B, fitted to the available Ecoinvent nutrient datasets.

Nutrient	Available Ecoinvent nutrients	Amount kg/year
NO_3 NH_4	N-tot	141.2
P P_2O_5	P_2O_5	3.2 24.6
K K_2O	K_2O	36.7 56.2
Mg MgO	MgO	4.8 12.9
Ca CaO	$Ca(NO_3)_2$	15.1 37.9
S SO_3	SO_3	3.2 20.6

SweGreen also uses pH adjustment solutions (a basic solution to increase, and acidic solution to decrease the pH solution) for each water tank. However, the impacts of these adjustments were neglected in the LCA.

Water
The total annual water consumption was obtained by SweGreen for Scenario A, and scaled up with the scale factor for Scenario B (assuming a linear relationship with production numbers and water consumption).

Packaging

All herbs except of basil and thyme are wrapped with a small rubber band before packaging. The impact of this rubber band was neglected in the LCA. The leafy greens that are delivered to restaurants are put in SRS trays (without any further packaging), see Figure A3. Each tray has a known weight of 1.53 kg polypropylene (Svenska Retursystem, n.d.). These trays are brought back to SweGreen after each delivery and are re-used multiple times.

Figure A3 SRS (Svenska Retursystem) trays. Retrieved from www.retursystem.se.

The plastic bags are made of polypropylene. SweGreen initially intended to use biodegradable plastic bags, but due to requests from retailers, they are currently using polypropylene.

SweGreen has varied the delivered weight in the herb packages between 20 g and 30 g during the last year, and an herb weight of 25 g herbs per bag was assumed in the LCA. The leafy greens have varied from 160 g to 90 g, with 90 g being the most prevailing weight, thus 90 g of leafy greens per bag was assumed.

Electricity

Electricity figures were obtained from SweGreen and were divided into differing consuming processes: light, dehumidification, heat pump and 'other'. However, in Table 3 in the report, the electricity is also divided into electricity consumption for the water pumps. These electricity numbers were calculated by multiplying the electricity demand of each water pump by the time of hours in use. This was done for all different kinds of water pumps (i.e. water pumps in nursery, water pumps for the large water tanks in the main growing room, water pumps for irrigation growing walls, water pump for the degasser, water pump for the storage tanks and heat pump, and water pump for the LED cooling process).

The energy consumption for Scenario A and B are assumed to be the same. This is based on the fact that the majority of the LEDs are turned on during Scenario A, even if the walls in question are not active, and that LEDs contribute to over 70% of the total electricity consumption. The potential increase in electricity consumption for the water pumps from Scenario A to B, was not included in the LCA accordingly, as it was assumed to have the capacity to handle the watering for the whole system.

When analyzing the sensitivity of the electricity, renewable energy is used to compare with the default electricity dataset (Swedish mix). Even though SweGreen buys electricity from wind and solar power, the dataset representing renewable energy is assumed to be only electricity from wind power. This assumption is justified by the fact that Sweden's total energy consumption consists of 10% wind and only 0,24% solar (Statistiska Centralbyrån, 2019) and because wind energy is used in the sensitivity analysis of a similar study (Romeo et al., 2018)

Transport and Deliveries

For the datasets that didn't include transportation (i.e. those without "market for" dataset[26]), transportation was added manually. Transportation was not added separately in the "market for" datasets, due to lack of information about these transportations.

The carts (i.e. the growing walls and chutes) were imported from Canada, and transported via boat (D. Ward, ZipGrow Inc., personal communication, April 21, 2020). The transportation distance for these ZipGrow systems (i.e. the PVC material) was assumed to be 5 000 km (based on assumed distance from Quebec to Stockholm). The impacts of all transport require information on the load distance in tonne-km (tkm), which is presented in Table A8.

Information on product deliveries was obtained from SweGreen. An average distance of 5 km by car is estimated per delivery. 2 delivery days are needed for Scenario A, and 3 delivery days are assumed for Scenario B.

Table A8 Load distance in tonne-km for the transportation.

Type of transport	Material transported	Load distance tkm	
Ship transport	PVC	42 240	
	PET	5 198	
Lorry transport		*Scenario A*	*Scenario B*
	Steel	151	151
	Ventilation unit	2	2
	Growing media	200	463
	Trays	92	214
	Plastic waste	4	8
	Organic waste	128	176

[26] See Table A9.

Waste

The organic waste that SweGreen generates is collected in a green plastic waste container (waste container not included in the infrastructure) in the hallway. SweGreen and the building have an agreement with a composting facility that receives and treats their organic waste. The central parts of Stockholm currently does not have its own system for organic waste, and the default treatment of organic waste is through incineration. An important environmental benefit provided by compost is avoiding the impacts of incineration (or in some cases, decomposition in landfills) (Dorr et al., 2017). To circumvent this, a system expansion can be carried out to include the alternative process to composting (i.e. incineration), and subtract this from the impact of compost. Due to the scope of the LCA and the lack of time, this wasn't done.

As stated in the written report, the rockwool plugs are inorganic, thus not biodegradable. However, according to the manufacturer, the plugs can be shredded and reused as a soil amendment, and will eventually dissolve at low pH (Grodan, 2011). Nonetheless, the rockwool plugs contain plastics that could be harmful to the environment during and after composting, thus it is recommended that the rockwool plugs are returned to the factories to be melted and re-spun into new plugs (Grodan, 2011, 2018).

Some of the plastic bags that are wasted due to problems with the packaging machine contain a label, but this was neglected in the LCA, assuming only bags were wasted. The number of plastic bags that are wasted was set to be 20% of the total amount of bags, based on information from SweGreen. The trays are often re-used in the farm for various purposes, but since they come delivered in the same package as the plugs, it was assumed that for each 150 plugs, 1 tray is wasted (after usage). SweGreen has bought a new packaging machine that will be delivered during the summer 2020 to reduce plastic waste; however, this machine and the potential benefits from it are not included in the LCA.

Table A9 Inventory data for the full life-cycle at the farm, including comments on assumptions and estimations made.

	Input	LCI Dataset	Comment
Infrastructure	Steel	market for steel, low-alloyed, hot rolled	Material data based on visual estimations and assumptions.
	Aluminum	market for aluminium alloy, AlLi	Material data based on visual estimations and assumptions.
	PVC	polyvinylchloride production, bulk polymerisation	Material data from ZipGrow Inc.
	PET	polyethylene terephthalate production, granulate, bottle grade, recycled	Material data from ZipGrow Inc.
	Polyethylene	packaging film production, low density polyethylene	Material data based on calculations and assumptions.
	Polypropylene	market for polypropylene, granulate	Material data based on visual estimations and assumptions.
	Polyester	market for orthophthalic acid based unsaturated polyester resin	Material data from ZipGrow Inc.
	LEDs	market for light emitting diode	Material data based on visual estimations and blueprints from SweGreen. Information on mass for one LED from Martin and Molin (2019).
	Controllers	market for electronics, for control units	Data based on visual estimations and assumptions. The dataset describes LED drivers, monitors on pH and EC levels, UV filters, and vacuum cleaners. Dataset includes 46% steel, 32% plastics, 14% printed wiring boards and 8% cables.
	Heat pump	market for heat pump, diffusion absorption, 4kW	Data based on assumptions.

	Water pumps	market for pump, 40W	Dataset describes 31 water pumps and one vacuum degasser (total of 32).
	Refrigerator	market for refrigeration machine, R134a as refrigerant	Dataset assumed to be a good representative for the refrigeration room employed at the farm.
	Dehumidification unit	ventilation control and wiring production, central unit	Dataset is based on ventilation unit for 6 flats. Assumed that the dehumidification unit at SweGreen can be described by this.
	Packaging machine	market for industrial machine, heavy, unspecified	Mass based on visual estimations. No packaging machine was found in Ecoinvent; thus industrial machine was assumed as the best available representative.
	Ventilation duct	market for ventilation duct, steel, 100x50 mm | ventilation duct, steel, 100x50 mm | Cutoff, S	Data based on visual estimations. Assume that all steel pipes can be described by this dataset.
Germination and cultivation	Seeds	market for grass seed, organic, for sowing	Data based on calculations. Grass seeds are assumed to be representative for all seeds.
	Rockwool growing media	stone wool production	Data based on weighing and assumptions. Note that stone wool and rockwool are the same thing.
	Trays	polystyrene production, extruded, CO2 blown	Material data based on weighing and assumptions. Polystyrene is the true material of the trays (based on email inquire from the producer).
	Nutrients N	market for nitrogen fertiliser, as N	Data based on visual estimations and calculations. N-tot are assumed to represent NO_3 and NH_4.
	Nutrients P	market for phosphate fertiliser, as P2O5	Data based on visual estimations and calculations. P_2O_5 are assumed to represent P and P_2O_5.

	Nutrients K	market for potassium fertiliser, as K2O	Data based on visual estimations and calculations. K_2O are assumed to represent K and K_2O.
	Nutrients Mg	market for magnesium oxide	Data based on visual estimations and calculations. MgO are assumed to represent Mg and MgO.
	Nutrients Ca	market for calcium nitrate	Data based on visual estimations and calculations. $Ca(NO_3)_2$ are assumed to represent Ca and CaO.
	Nutrients S	market for sulfur trioxide	Data based on visual estimations and calculations. SO_3 are assumed to represent S and SO_3.
	Water	tap water production, microstrainer treatment	Dataset assumed to be a good representative for Stockholm water treatment which e.g. includes straining.
Packaging	Plastic bags, SRS	market for polypropylene, granulate	Material data based on calculations and assumptions. Mass based on weighing.
	Label	market for laminating service, foil, with acrylic binder	Material data based on calculations and assumptions. Mass based on weighing.
Electricity	Electricity mix	market for electricity, medium voltage, Swedish mix	Swedish mix is assumed to be the default electricity mix. Medium voltage represents 1 kV to 24 kV (suitable for small scale industry).
	Electricity wind	electricity production, wind, <1MW turbine, onshore	Dataset assumed to be a good representative for SweGreen's green electricity fund from wind and solar power. (Wind 10%, solar 0.24% in Swedish mix (Statistiska Centralbyrån, 2019)).
Transport and deliveries	Ship transport	market for transport, freight, sea, transoceanic ship	Data based on assumptions on ship delivery from Quebec to Stockholm.
	Lorry transport	transport, freight, lorry 16-32 metric ton, EURO6	Dataset for the transportation of materials.

	Car deliveries	market for transport, passenger car, EURO 5	Assume medium sized car.
Waste handling	Composting	treatment of biowaste, industrial composting	Dataset assumed to be a good representative for composting of the organic waste from SweGreen.
	Plastic incineration	treatment of waste plastic, mixture, municipal incineration	Dataset assumed to be a good representative for treatment of the plastic waste from SweGreen.
General	Steel work	metal working, average for steel product manufacturing	Applied to all steel and aluminum parts. An explicit dataset for 'aluminum work' wasn't accessible, but 'steel work' is considered representative enough for the study.
	Injection moulding		Applied to all plastics (PVC, PET, polyethylene, polypropylene, polyester, sugarcane LDPE). 1 kg injection molding is required per 0.994 kg plastics (Ecoinvent, 2020).

APPENDIX 3 – RESULTS IMPACT CATEGORIES

Figures A4-A6 present additional information on the results presented in the study. Table A10 present the details on the calculations of the electricity consumption per functional unit.

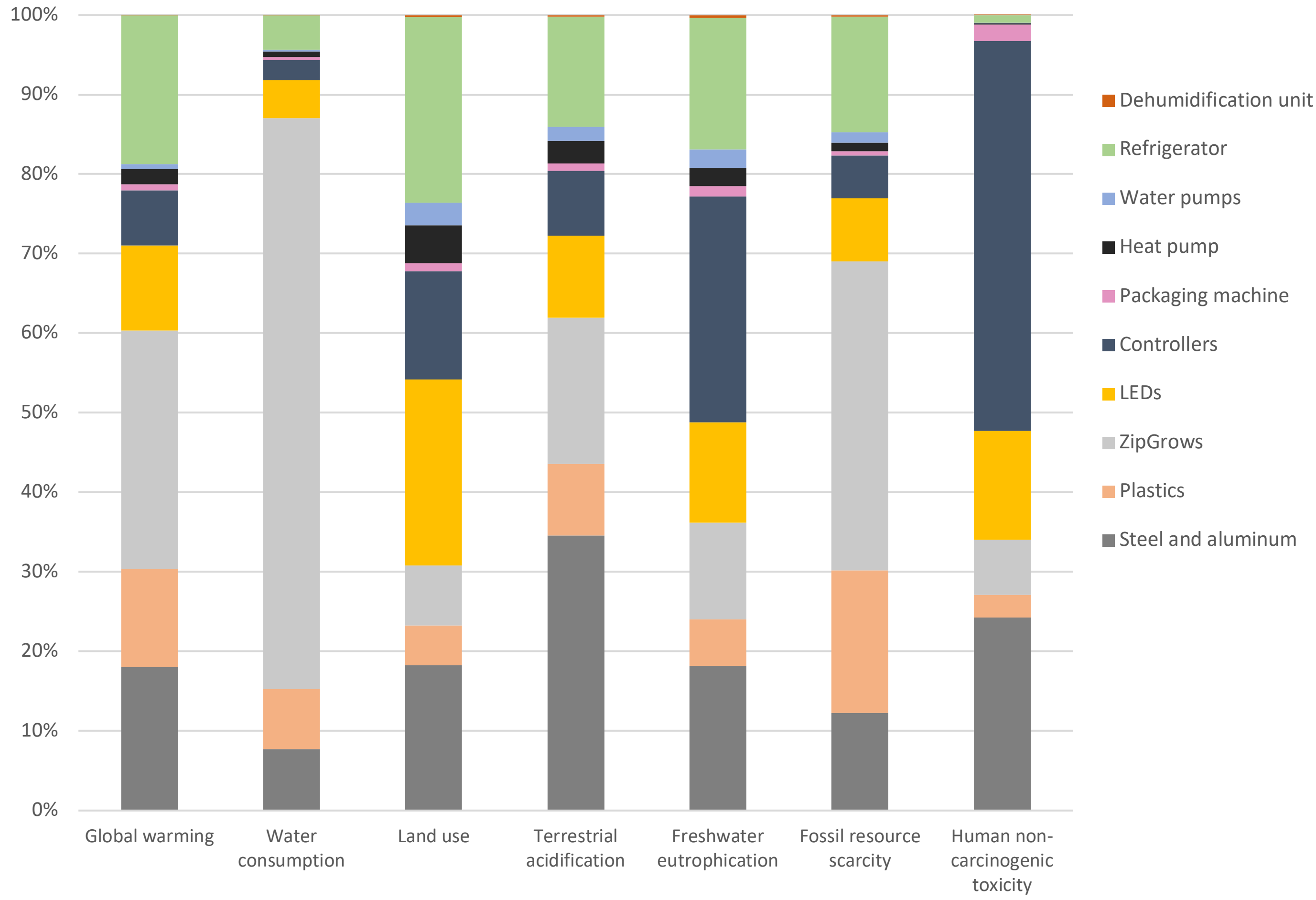


Figure A4 Infrastructure constituents for all impact categories. "Plastics" consist of polyethylene, polypropylene, and polyester. "ZipGrows" consist of PVC and PET (material of the matrix media).

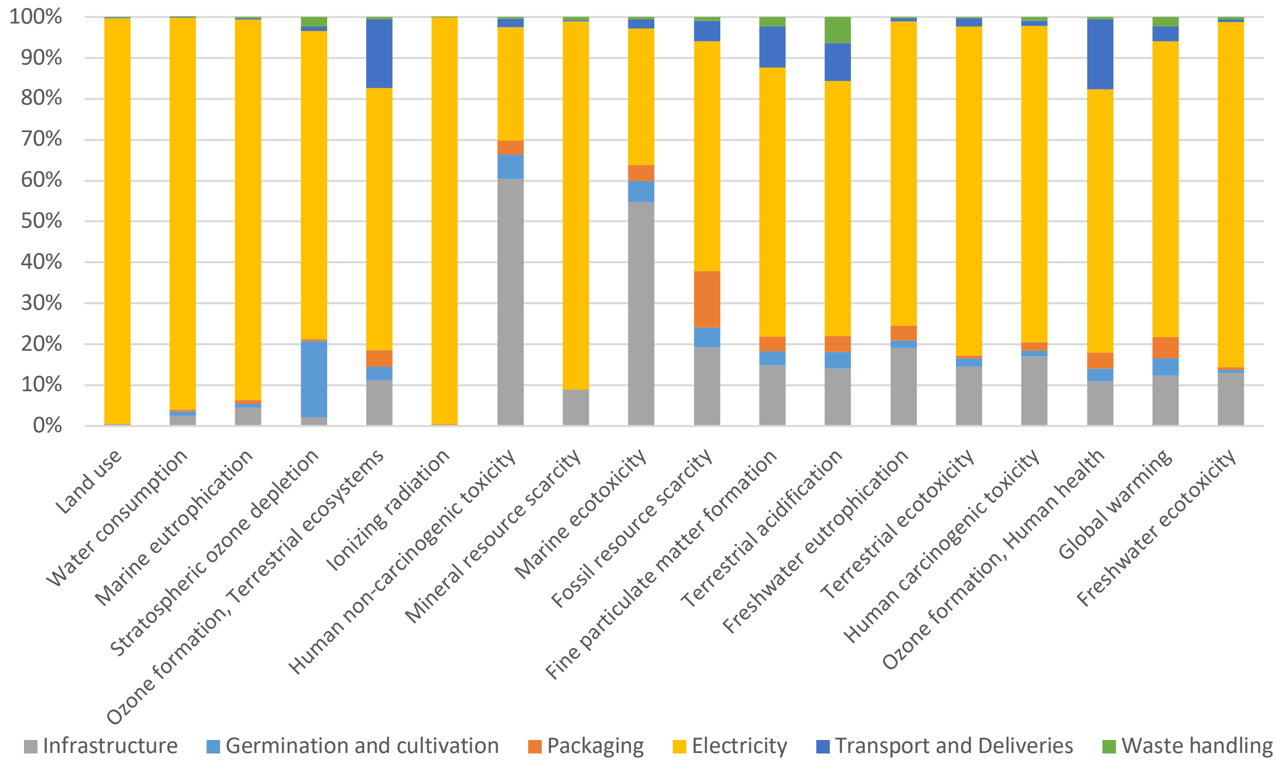


Figure A5 Environmental impacts of the indoor vertical farm at SweGreen for all 18 impact categories in ReCiPe Midpoint (H).

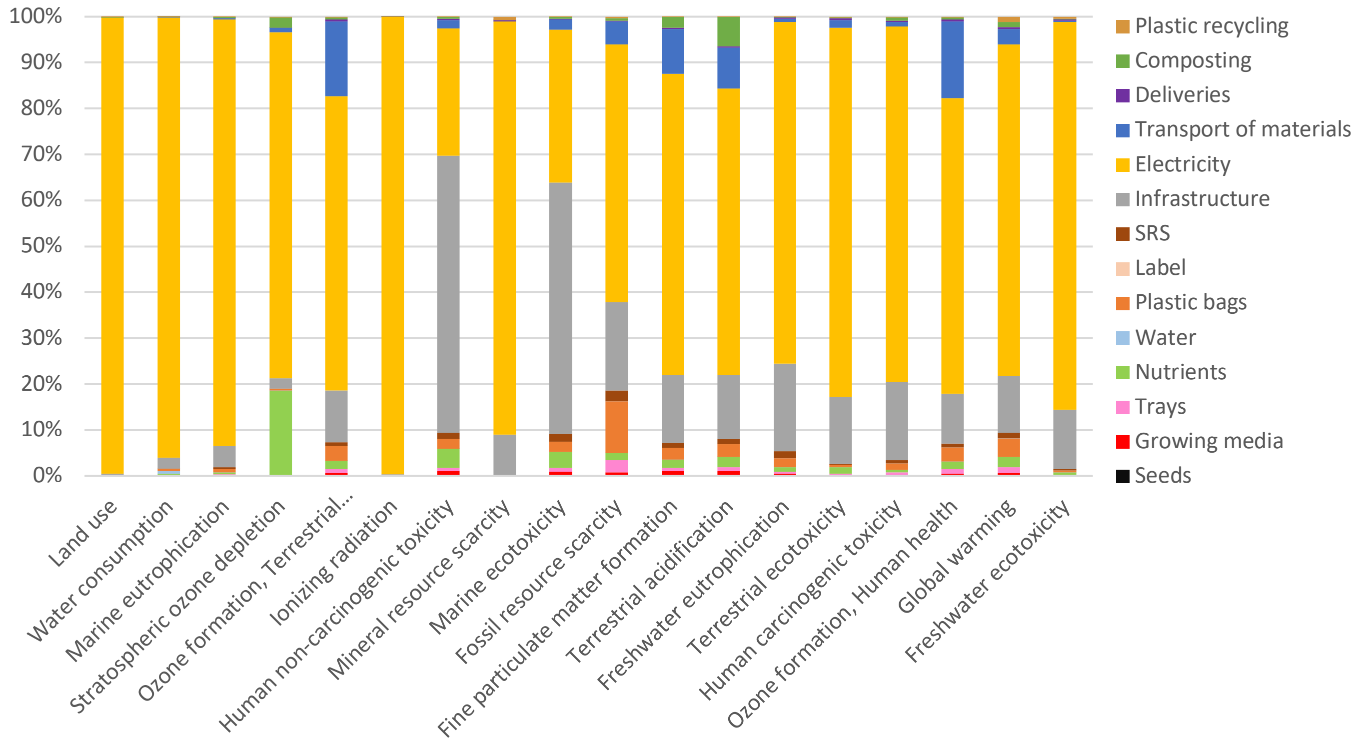


Figure A6 Environmental impacts of the indoor vertical farm at SweGreen for all 18 impact categories in ReCiPe Midpoint (H), showing contribution of each input.

Table A10 Electricity consumption (purchased) per functional unit for Scenario A and B.

	Annual electricity consumption kWh	Electricity consumption per 1 kg basil kWh
Scenario A	646 485.7	95.16
Scenario B	646 485.7	41.11

APPENDIX 4 – ANALYSIS

Biofertilizers

An additional analysis was added in order to show the potential benefits of employing biofertilizer instead of conventional fertilizer[27]. The biofertilizer was assumed to be produced from biogas digestate and prepared through water removal. Further, it was estimated that not all required nutrients could be replaced by biofertilizer, and a small portion of synthetic fertilizers was needed. The biofertilizer from biogas digestate was described by the dataset "drying, sewage sludge" (see Table A9) and had an estimated content ratio of N-tot 178.5 g : P-tot 16.9 g : K-tot 50.2 g, per kg digestate (Ljung et al., 2013). It was only these three nutrients that were accounted for in the biofertilizer analysis; the rest of the nutrients (Mg, MgO, Ca, CaO, S, and SO_3) were assumed to have sufficient amounts in the digestate, but without examining this any further. Table A11 summarizes the data on the synthetic fertilizer, and Table A12 the data on the digestate/biofertilizer.

Table A11 The annual requirement of N-tot, P-tot, and K-tot, retrieved from Table 8 in the report, and the amount of N-tot, P-tot, K-tot in 1 kg of the synthetic fertilizer (calculated from information in Table 8).

Nutrient	Annual requirement kg	Content in fertilizer g/kg
N-tot	61.0	396
P-tot	12.0	78
K-tot	40.1	261
Sum of all nutrients	*153.9*	-

Table A12 The content of nutrients in the biogas digestate, and the factor that N-tot in the digestate needs to be multiplied by to reach the same amount as N-tot in the synthetic fertilizer. Also showing the content in biofertilizer and what needs to be added as extra from synthetic fertilizer.

Nutrient	Content in digestate g/kg	Content in synthetic fertilizer compared to biofertilizer wrt. N	Content in total biofertilizer kg	Extra from synthetic fertilizer* kg
N-tot	178.5	2x	61.0	-
P-tot	16.9	-	5.8	6.2
K-tot	50.2	-	17.2	23.0
Total biofert.	-	-	*341.8*	-

* i.e. what amount of P and K that is missing in the biofertilizer and has to be added as synthetic fertilizer.

As illustrated in Table A12, the annual requirement of biofertilizers is 341.8 kg to cover the needs for N-tot. An addition of 6.2 kg P-tot and 22.9 kg K-tot would need to be added to cover the requirements as outlined in Table A11, and this was assumed to derive from synthetic

[27] The analysis followed the same structure as proposed by Martin et al. (2019) with information on nutrient content in biogas digestate from Ljung et al., 2013.

fertilizers. Table A13 shows the decrease in impacts if substituting synthetic fertilizers to biofertilizers.

Table A13 Decrease in total impacts if employing biofertilizers instead of synthetic fertilizers.

Impact category	Decrease w biofertilizers
Climate change	-2.2%
Water consumption	-0.2%
Land use	-0.1%
Terrestrial acidification	-2.0%
Freshwater eutrophication	-0.9%
Fossil resource scarcity	-1.4%
Human non-carcinogenic toxicity	-4.0%

As specified in the report, the annual greenhouse gases associated with fertilizers decreased by 97% annually if converting to biofertilizers, see Figure A7.

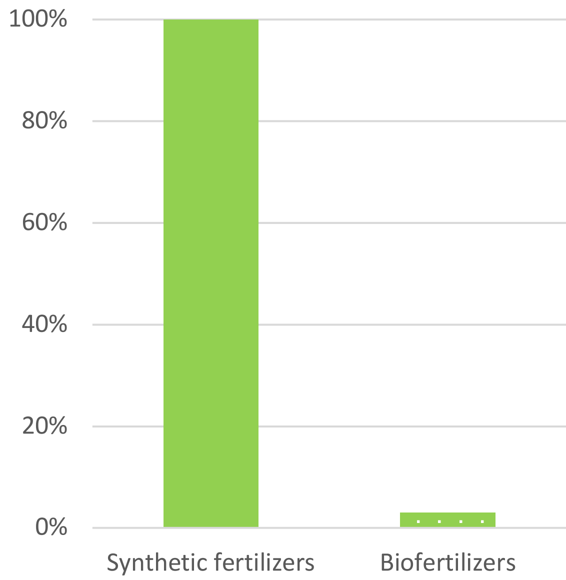


Figure A7 Annual greenhouse gases associated with synthetic fertilizers and biofertilizers, expressed as percentages.

Bio-based plastic bags

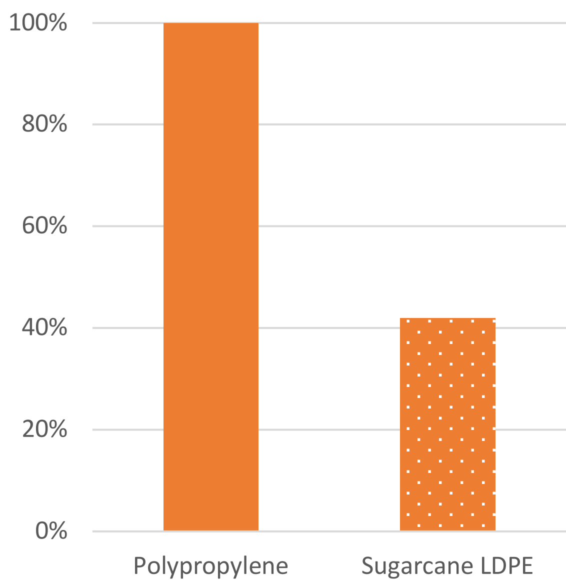
An analysis was performed to investigate the potential benefits of substituting the default plastic bag material of polypropylene to a bag made out of sugarcane and low-density polyethylene (LDPE). Figures on the carbon footprint of 1 kg sugarcane LDPE was retrieved from Liptow & Tillman, 2012. In the study, the authors analyze the carbon footprint of the sugarcane LDPE bag based on two scenarios. The first one is when considering emissions from land use change, i.e. the emissions that originate when changing the land from e.g. forest to crop land for the growth of the sugarcanes (2.6 kg CO_2 eq/kg plastic). The second one is without considering emissions from land use change, i.e. illustrating a "best case scenario" of the carbon footprint of the plastic (0.3 kg CO_2 eq/kg plastic). The study by Liptow & Tillman considered sugarcane produced in Brazil and later disposed of in Europe, with a waste treatment of incineration with electricity recovery. Most of the data was based on Swedish conditions, but with electricity from a European mix.

In the analysis, the "best case scenario" was assumed when choosing the carbon footprint of the sugarcane LDPE. As for all plastic materials in the LCA, the dataset of "injection molding" was added to mimic the production of a bag from the plastic material. The analysis does not take into account on how well the biodegradable plastic is performing compared to the polypropylene material. It is simply assumed that the two materials are equal thus can be compared without any modifications. It is also assumed that the two different kinds of bags weigh the same. Further, it is worth mentioning that various studies on the subject have obtained different carbon footprints of the sugarcane LDPE[28], thus the results can vary substantially. This wasn't analyzed in further detail in the study. See Table A14 for the decrease in impacts by substituting polypropylene to sugarcane LDPE.

Table A14 Decrease in total impacts if employing sugarcane LDPE instead of polypropylene bags.

Impact category	Decrease w biofertilizers
Climate change	-2.2%
Water consumption	-0.2%
Land use	-0.1%
Terrestrial acidification	-2.0%
Freshwater eutrophication	-0.9%
Fossil resource scarcity	-1.4%
Human non-carcinogenic toxicity	-4.0%

As specified in the report, the annual greenhouse gases associated with plastic bags decreased by roughly 58% if converting to sugarcane LDPE bags, see Figure A8.



[28] See e.g. Hischier, 2012.

Figure A8 Annual greenhouse gases associated with polypropylene bags and sugarcane LDPE bags, expressed as percentages.

Symbiotic development

The symbiotic farm-building development was analyzed with a reference scenario illustrating a theoretical scenario without a symbiosis, and compared to Scenario A. The symbiotic relationship is present in both the dehumidification process where water is recirculated, and in the LED cooling process, and these processes had to be altered in the reference scenario accordingly. Thus, in the reference scenario, no electricity for the dehumidification process[29] was needed, nor the material employed for the dehumidification unit or the heat pump. Also, the water pump, with associated electricity, that drives the LED cooling process was assumed not to be needed. The impacts from all these processes were "subtracted" from the total impacts, and are noted as "Subtracted processes" in Table A15, accordingly.

Without the symbiotic relationship, it was assumed that a structure had to be built for the farm, as previously specified in the report. Without the LED cooling process, the LEDs would not be as efficient thus requiring an addition of 20% electricity[30], and the LEDs would give off more heat, thus the need for cooling by an air conditioner. Without the dehumidification process in which the water is recycled back to the farm, extra inputs of water would be needed. Lastly, carbon dioxide was added because without receiving carbon dioxide from the office, SweGreen presumably has to buy extra in cylinders[31]. The impacts from these processes were "added" from the total impacts, and noted as "Added processes" in Table A15.

The building structure is described by the dataset "market for building, hall, steel construction", with unit m^2, which was scaled up to the area of the main growing room (see Table XX). The lifetime for the structure was 50 years, according to the dataset. The electricity requirement for cooling (added processes) was assumed to be the same as the electricity need for the fan in the dehumidifier, and the object for cooling was assumed to be the same as the one modeled for the dehumidification unit. The extra need for CO_2 was described by the dataset "carbon dioxide production, liquid" with unit kg; the required amount for the farm was calculated by the method described in Graamans et al. (2018) with a supplied CO_2 as twice the accumulated dry weight in the farm. This is based on the theory on the weight loss in the transformation from CO_2 to carbohydrates (68%) and the CO_2 fixation efficiency (70%), assuming that no CO_2 exits the farm, and a harvest index of 1. By this method, the required annual amount of CO_2 added up to 2 160 kg. The information on the amount of extra water that would need without the symbiosis was obtained by SweGreen. See Table A15 on the "added" and "subtracted" amounts, together with their datasets. See Table A16 on the resulting benefits of the symbiotic relationship.

Table A15 Data on the subtracted and added processes.

29 As specified in the report, the dehumidification process includes electricity from both a fan and a heat pump.
30 Based on expert advice (M. Martin, personal communication, April, 2020).
31 Carbon dioxide enrichment is extensively being used in greenhouses, see Aldrich & Bartok, 1998.

Subtracted process	Unit	Amount subtracted	Dataset
Electricity, fan	kWh	38 508.80	market for electricity, medium voltage, Swedish mix
Electricity, heat pump	kWh	45 795.40	
Electricity, water pump*	kWh	10 512.00	
Dehumidification unit	units	1	ventilation control and wiring production, central unit
Heat pump	units	1	market for heat pump, diffusion absorption, 4kW
Water pump*	units	1	market for pump, 40W
Added process	**Unit**	**Amount added**	**Dataset**
Building structure	m^2	370	market for building, hall, steel construction
Electricity, LEDs	kWh	96 062.24	market for electricity, medium voltage, Swedish mix
Electricity, cooling	kWh	38 508.80	
Air conditioner	units	1	ventilation control and wiring production, central unit
Water	L	420 480.00	tap water production, microstrainer treatment
Carbon dioxide	kg	2 160.00	carbon dioxide production, liquid

*Water pump connected to the LED cooling process.

Table A16 Increase in impacts for all seven impact categories, expressed as percentages, in a theoretical scenario without the symbiosis, based on annual figures.

Impact category	Increase w/o symbiosis
Climate change	474%
Water consumption	41%
Land use	9%
Terrestrial acidification	691%
Freshwater eutrophication	284%
Fossil resource scarcity	473%
Human non-carcinogenic toxicity	978%

Figure A9 illustrates the constituents of the added inputs to the reference scenario.

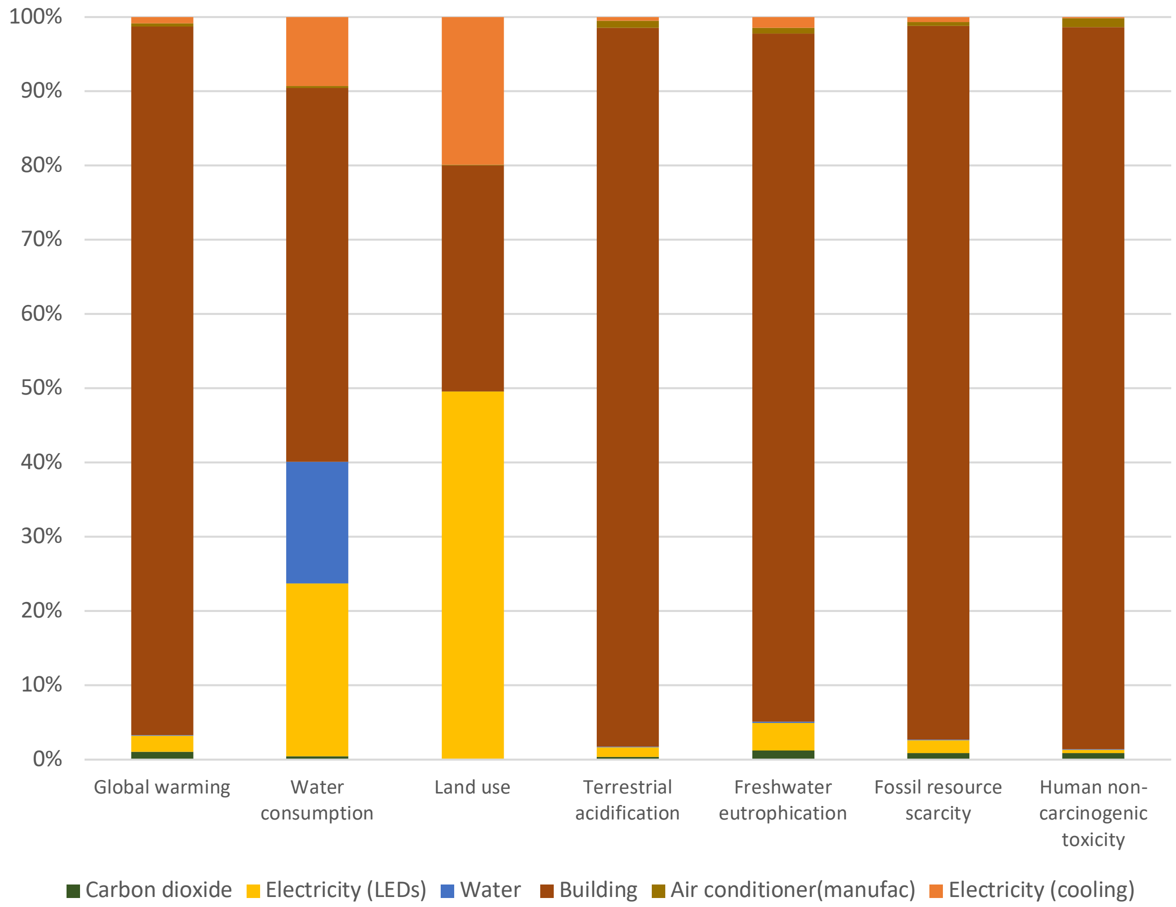


Figure A9 The share of each added input in the reference scenario.

Sensitivity analyses

Table A17 shows the total environmental impacts per kg basil for Scenario A with the dataset of wind power instead of Swedish mix.

Table A17 Total environmental impacts per kg of basil for Scenario A, expressed in both the dataset of Swedish mix and wind power.

		Swedish mix electricity	*Wind power*
Climate change	kg CO_2 eq	5.3	2.9
Water use	L	600	44
Land use	m^2a crop eq	1.80	0.14
Terrestrial acidification	kg SO2 eq	0.020	0.015
Freshwater eutrophication	kg P eq	0.003	0.002
Fossil resource scarcity	kg oil eq	1.1	1.3
Human toxicity	kg 1,4 DCB eq	2.6	2.2

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