TALLINN UNIVERSITY OF TECHNOLOGY

FACULTY OF ENGINEERING

Tartu College

LIFE CYCLE ASSESSMENT OF HYPERLOCALLY AND CONVENTIONALLY PRODUCED LETTUCE

HÜPERLOKAALSELT JA TRADITSIOONILISELT TOODETUD LEHTSALATI OLELUSRINGI HINDAMINE

MASTER THESIS

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THESIS TASK

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Thesis topic:

Life cycle assessment of hyperlocally and conventionally produced lettuce

Hüperlokaalselt ja traditsiooniliselt toodetud lehtsalati olelusringi hindamine

Main objectives of thesis:

1. Conduct life cycle assessment of hyperlocally produced lettuce
2. Compare environmental impacts of hyperlocal and conventional lettuce
3. Compare impacts when adding food waste and nutritional value to assessment

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Gather data	01.01. 2021
2.	Data analysis	23.04. 2021
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TABLE OF CONTENTS

INTRODUCTION

Food production and consumption are becoming increasingly important in the global debate on sustainability (Sokolow *et al*, 2019; FAO 2015). In the last decade, and even more in the light of the recent COVID pandemic, the problems with food waste, security, availability and nutritional degradation have come under higher public and academic scrutiny. While animal-based products are found to cause the highest environmental impacts, the supply chains of vitamin-rich foods like fruits and vegetables, and especially leafy greens, are found to be most inefficient (Laurentiis *et al*, 2018; Plazzotta et al, 2017). At the same time, malnutrition has been declared a major problem by WHO, even in developed countries where calories are plentiful, but consumption of healthy vitamins is lacking (Ritchie and Roser, 2017).

Evidence of the overly long supply chains and inefficiency of the old business-as-usual fruit and vegetable production and consumption practices are also becoming clearer for the consumer. Some of the fastest growing trends in the food sector point towards organic and locally sourced food. In response to higher sustainability standards and consumer trends, conventional farming methods like open field and greenhouse cultivation are developing cleaner ways of production (Barbosa et al, 2015). Transportation and packaging is becoming more resource-efficient, nutrition preserving technologies are advancing and numerous initiatives and business models that tackle food waste are created (Heller *et al*, 2019).

Some solutions take a different approach to the various problems in our food system. Growing food in urban environments has become a popular way of greening up the cities and providing at least some of the food locally and without the environmental burdens of conventional farming (Mok *et al*, 2014). Hydroponic technologies help to reduce water and pesticide use (Barbosa et al, 2015). A newer hydroponic and local urban farming method, vertical farming, provides land use efficiency and reduces transportation impacts while resulting in higher yield and nutritional quality (Martin and Molin, 2019; Benke and Tomkins, 2017). While being more efficient in some aspects, these methods still fall into the established food supply chains, resulting in excessive packaging, transportation, physical and nutritional food loss.

A whole other method that is not tied to the established supply chain is hyperlocal growing - cultivating and harvesting food right where it is consumed. While backyard gardening is nothing new, devices that allow anyone to grow leafy greens, smaller fruits and vegetables at home, offices, schools, hospitals, or restaurants without farming knowledge are becoming more popular. While different environmental gains and impacts of urban gardening, hydroponic and vertical farming have been researched, no studies on the environmental impacts of using hyperlocal smart indoor gardens exist. The assumed trade-off for the various environmental gains of using these systems is the high electricity consumption of LED grow-lights that the gardens use.

The objective of this thesis is to find out the environmental impacts of growing food with a hyperlocal food growing device at home compared to conventional farming methods and to point out critical aspects of improvement. The comparison will be conducted using life cycle assessment (LCA) methodology with the object of assessment being lettuce production and consumption from cradle to grave.

The research questions are:

1. What are the environmental impacts of different stages of the life cycle of hyper-local food production and consumption?
2. How do the environmental impacts of conventional farming compare to hyper-local farming?
3. How do the environmental impacts of conventional farming compare to hyper-local farming when physical food waste and nutritional value degradation are taken into account?

And hypotheses are:

- More than 90% of the impacts in the hyperlocal method come from electricity use of LED grow-lights
- Conventional farming methods have lower impacts in every category when comparing kilogram to kilogram production and consumption
- When factoring in physical food loss, the impacts between both systems level out and when nutritional value degradation is added, the hyperlocal method becomes less impactful compared to conventional.

Life cycle inventory (LCI) data for conventional farming methods is taken from a previously conducted LCA of food products for which the results have been added to an Ecoinvent database. The compared conventional farming system can be regarded as very resource efficient so the study is not skewed with a comparison of the worst example of conventional method with a promising new method.

The use of hyperlocal indoor gardens is modelled using relevant Ecoinvent database LCI data with OpenLCA software. Life cycle impact assessment results will be expressed through three midpoint impact categories: climate change, agricultural land occupation and water depletion. The results of the study would be beneficial for finding out how hyperlocal growing devices compare to conventional farming methods and other novel farming methods alike, giving a ground for their increased adoption or pinpointing critical aspects that need to be addressed to make them more sustainable.

The following literature review introduces different farming methods relevant to this study, followed by environmental impacts that these different methods bring about or help to avoid. Concerns over food waste, nutritional value of food and malnutrition are also described in the literature review along with a description of the LCA method. Method and materials chapter expands on research questions and hypotheses and describes the data, methods and assumptions used in conducting the LCA. Results chapter reveals the results of life cycle impact assessment (LCIA) and the following discussion and summary chapters add context to these results, suggest further studies and summarise the findings.

Hyperlocal food production, conventional food production, food waste, nutritional degradation, life cycle assessment, master thesis.

1 LITERATURE REVIEW

Studies from the recent decades have demonstrated how food is a major driver of climate change, freshwater depletion, biodiversity loss and land degradation (Foley *et al*, 2011, Mayer 2019, de Vrese *et al*, 2018). Estimates show food production and consumption to be responsible for 20-30% of total environmental impacts of an average person (Tukker and Jansen, 2006). Agriculture causes around 30–35% of greenhouse gas emissions globally, most of it coming from tropical deforestation, methane emissions from rice cultivation and livestock and N_2O emissions from fertilizing (Foley *et al*, 2011).

Vitamin-rich foods like fruits and vegetables are the largest food group consumed worldwide, making up 30% of the total mass of food intake (WHO, 2003). The overall impacts of fruits and vegetables tend to be lower than impacts of animal-based products in developed countries (Tukker and Jansen, 2006). But inefficiencies in the whole production and consumption supply chain are higher, causing a vast amount of avoidable impacts (Gustavsson *et al*, 2011). While on average, globally, a third of food goes to waste, the number for fruits and vegetables is 45% and up to as high as 60% for leafy greens like lettuce (Gustavsson *et al*, 2011; Heller *et al*, 2019; Mattsson *et al*, 2018; Blake, 2015; Strid and Eriksson, 2014; De Laurentiis *et al*, 2018; Beausang *et al*, 2017). The production and consumption of vitamin-rich food will be the main focus in the following literature overview.

1.1 Farming methods

The growing world population demands an equally rapid growth of food production. According to most estimates, by 2050, it needs to rise by 50% to feed 10 billion people (WRI, 2019). At the same time, whole regions are dealing with substantial loss of arable land and are prone to increasing risks from climate change (Foley *et al*, 2011). To make food systems resilient to these changes while also sustainably feeding the growing population, it is ever more important to find ways of reducing its environmental impacts and to develop entirely new methods of production and consumption (Zarei *et al,* 2015; Barbossa *et al,* 2015). Moreover, it is crucial to increase resiliency of food systems in urban areas where the majority of people live (Romeo *et al*, 2018). In Europe, by 2050 more than 80% of people are expected to live in cities (United Nations, 2015) and thus, growing food in or near urban areas needs to be advanced. Meeting the goal of increased food production along with the reduction of environmental impacts has been highlighted as one of the greatest challenges of the 21st century (Foley *et al*, 2011).

1.1.1 Conventional farming

By historical definition, conventional farming or modern industrial farming is the practice of growing crops in soil, usually in open air, using irrigation, fertilizers, pesticides and machinery (Barbosa *et al,* 2015, Le Campion *et al*, 2020). It is also defined by high inputs of these resources, which in turn causes a plethora of environmental impacts (Le Campion, *et al*, 2020; Foley *et al*, 2011). It is further found that conventional methods are not equipped to increase resource efficiency and reduce environmental impacts in a significant manner (Foley *et al*, 2011). A good illustration is the wide use of fertilizers, advanced irrigation and crop planning during previous decades that has only increased global yields by 20% between 1985 and 2005 (*ibid*).

Conventional farming is also positioned as the opposite to organic practices that try to minimize the impacts of farming and deter from the use of synthetic pesticides and fertilizers (Le Campion *et al*, 2020). Contrast to the high input farming methods are low input methods that still fall under the definition of conventional, but, for example, use integrated pesticide management techniques that aim to keep the use of chemicals at minimum levels (*ibid*).

The problem with most conventional farming definitions is that they fail to encompass technical specifications (Le Campion *et al* 2020). For example, a farm can be highly resource-efficient, but not organic in all aspects, or vice versa. In the current study, the definition of conventional farming is further expanded and set to cover the whole production, distribution and consumption of food. A technologically advanced heated greenhouse is used in this LCA for a comparison as the conventional method. It uses the aforementioned integrated techniques and manages to be highly water efficient. But it is still considered conventional in this study because it operates within the boundaries of conventional farming supply chains.

1.1.2 Hydroponic farming

Compared with soil based cultivation, the soil-free method of hydroponics can be more cost-effective (Grafiadellis *et al*, 2000), producing higher yields, enabling a more on-demand production, while requiring less land, water and nutrients (Nejad and Ismaili, 2014; Barrett *et al*, 2016). As a result, global use of this practice and its importance in the food sector is on the increase (Barrett *et al*, 2016).

Hydroponics is used for growing non-root vegetables, often the varieties that can be sold at a more premium price, such as lettuce and herbs (Benke and Tomkins, 2017). But staple vegetables like tomatoes, eggplants and strawberries are grown as well (Barbosa *et al*, 2015). Hydroponics is mostly used in a controlled environment, meaning that runoff from fertilizer use and other contaminants can be avoided effectively and nutrients can be better managed to drive up nutritional value of produce (Brechner and Both, 2014). The majority of systems are designed to support continuous production throughout the year (*ibid*).

Hydroponic systems are versatile, starting from primitive home-made setups to sophisticated commercial enterprises (Barbosa *et al,* 2015). While saving water, opening up non-farmable land for farming and allowing all year round cultivation, the downsides of hydroponics are heavy up-front investment into facilities and equipment, higher cost of labor and high energy consumption for providing sufficient light and optimal year-long growing environment (*ibid*).

Concluding a study of hydroponically grown lettuce, Barbosa *et al* (2015) stated that lettuce farmed this way is indeed water, land, and time efficient, but it cannot be deemed more sustainable than conventional methods when energy for lighting and temperature control is needed.

1.1.3 Local and hyperlocal urban farming

Urban farming has been identified as a promising solution to food security and to reduce pressure on agricultural land and fresh water (Specht *et al*, 2014). There are many examples and methods for urban farming, with approaches such as community and rooftop gardens that are gaining popularity among citizens and vertical and hydroponic farming that are becoming popular commercially (Martin and Molin, 2019; Mok *et al*, 2014).

Vertical farming or urban vertical farming is a technologically advanced version of farming, mostly using either hydroponic, aeroponic or aquaponic methods with the main difference of even smaller land requirement, which is usually achieved by stacking layers of “fields” on top of eachother (Sanjuan-Delmas *et al*, 2018).

These farms can be integrated with a building in many ways, be placed on a rooftops or on facades, they can be fully exposed to the outside, enclosed, or fully closed systems, use various growth media, and they could be built for different purposes, for education, research, or commercial production (Association for Vertical Farming, 2016). Majority of commercial producers mainly use controlled environments and are therefore less affected by climate change or other outside factors that might disturb the production, they typically use LED grow lights and carefully manage nutrients and water (Martin and Molin, 2019).

Significantly smaller land use allows vertical farms to be built as local urban farms, producing food closeby to the majority of consumers living in urban areas (Chance *et al*, 2018). Advocates of vertical farming, most notably Dickson Despommier, microbiology professor emeritus of Columbia University, claim that controlling the growing conditions increase productivity, while closeness to consumers means fewer transportation emissions, reduced food loss and fresher produce, with the downside of 3-4 times higher cost to cover the high land price, technological and working capital investment (Benke and Tomkins, 2017).

While soil-less methods like hydroponic farms have been used for more than five decades (Barrett *et al,* 2016), commercial versions of vertical urban farms are around a decade old practice, but they are growing at a high annual rate of 24% by operating revenue (Statista, 2021). The claims of higher sustainability, however, are not backed by many studies, as urban farming practices are still in their infancy (Martin and Molin, 2019; Romeo *et al*, 2018). Vertical farming still needs to achieve effects of economies of scale. For example, if transportation is considered, studies have shown that supplying retailers with high quantities of produce with lorries, even if shipped thousands of kilometers, can be comparable in terms of greenhouse gas emissions, when the alternative, produce grown close by, is transported by smaller quantities with smaller consumer cars and more frequently (Mok *et al*, 2014).

An even closer-to-consumer method is growing food at home or any other place where food is consumed. While growing food in a home backyard is a thousands of years old practice, today, for the majority of people, modern city life doesn’t enable such methods due to room, time or knowledge constraints.

For the past decade, electronic indoor food growing devices have been gaining popularity. They allow anyone to grow a part of their daily food without any plant cultivation knowledge or significant time effort. Being soilless systems utilizing different growth media, they are mostly using hydroponics on a small scale. Their added benefits include reduction of water use, no transportation of water-heavy produce, less packaging, no need for pesticides, no need for additional heat or land use, as homes are already heated and provide some existing floor space. Trade-offs typically include higher price per plant mass compared to conventionally grown produce and higher electricity consumption since they mostly use LED grow lights. While urban farms are classified as local farms - close to the consumer - these systems are classified as hyperlocal farms - right where the consumption happens (De Chabert-Rios and Deale, 2016).

1.2 Environmental impacts of food production and consumption

Food causes significant impacts on the environment and biodiversity. It has been calculated that the food distributed and consumed in European Union along with its production processes generates 60% of eutrophication, 30% of climate change and 33% of ecotoxicity impacts of the whole region (Romeo *et al*, 2018).

Looking at it with a wider perspective, agriculture generates two types of impacts: the ones caused by expansion of food production and the ones generated by intensification of existing production methods (Foley *et al*, 2011). The authors (Foley *et al*, 2011) explain the first one as expanding agricultural production to at the expense of natural ecosystems and the second one as increasing the productivity of existing production through the heavier use of machinery, irrigation, fertilizers and biocides.

When looking at the environmental impacts of specific food products, it is important to consider the different processes that make up the whole supply chain and consumption. The following processes have been highlighted as the most impactful in fruit and vegetable production, including lettuce (Stoessel *et al*, 2012), which is the focus product in this study.

1.2.1 Energy use

Off-season consumption of fruits and vegetables, especially in colder climates, requires production in heated facilities. Studies have shown that when heat is produced using fossil fuels, its environmental burdens become biggest throughout the whole production and consumption life cycle, notably reaching even higher than long distance transportation (Cellura *et al,* 2012). Concluding a LCA of fruit and vegetable production in Switzerland, Stoessel *et al* (2012) suggested that during off-season it is better to choose vegetables from warm southern countries where additional heating is not required, even if they are transported from thousands of kilometers away, and only during summer and fall, local production is a better option.

In a LCA study focusing on hydroponic lettuce production in Arizona with hot summers and cold winters, it was found that energy used for cooling and heating of the production facility consumed 20.56 ± 1.94 kWh per year per kilogram of lettuce, while supplemental artificial lighting required another 4.17 ± 0.58 kWh per year per kilogram and pumps for water and nutrient distribution contributed 0.18 ± 0.03 kWh per year per kilogram (Barbosa et al, 2015).

For comparison, in the same study, the total energy use for the conventional lettuce production, as opposed to the hydroponic, was calculated to be 0.31 kWh per year per kilogram, split between the energy use related to fuel consumption at 0.09 kWh and pumping of groundwater at 0.21 kWh (Barbosa et al, 2015). In the Switzerland study, it was similarly revealed that comparing heated or non-heated growing methods, the difference in greenhouse gas emission changed by a factor of 10 (Stoessel et al, 2012).

In vertical urban farms, similar problems with high energy consumption and resulting emissions are generated by the need of artificial lighting and controlling of the room temperature (Romeo *et al*, 2018). Advocates of the practices point to LED lighting becoming more efficient and the possibility to use renewables and smart ways of utilising neighbouring buildings' excess heat or cooling capacity (Benke and Tomkins, 2017).

The added bonus of more technologically advanced lights and total control over the growing environment promise to increase productivity and the modification of preferred nutrient content in crops (*ibid*), meaning that more nutritional value is achieved for the higher resource use. Considering hyperlocal growing systems, it can be assumed that lighting is similarly a major source of its life cycle impacts. But as homes, offices or other places where these systems are used are already heated or cooled for living, no extra resources are required for keeping plants at optimal temperatures.

1.2.2 Land use

Arable land for food production is scarce. 38.6% of land which is not covered with ice already serves the purpose of feeding the world (Barbosa *et al*, 2015). Croplands cover 1.53 billion hectares, while pastures take up another 3.38 billion hectares (Foley *et al*, 2011). The World Resources Institute estimates that feeding 10 billion people by 2050 would require additional arable land mass twice the size of India (WRI, 2019). To put it into a historic perspective, by 2050, the size of arable land available to service the food requirement for each person will need to shrink to one third of what it was in 1970 to cope with increased demand (Benke and Tomkins, 2017). Novel solutions are needed to achieve that (*ibid*).

A wide scale study conducted by Foley *et al* (2011) showed that between 1985 and 2005 croplands and pastures throughout the world grew by 154 million hectares, yielding about 3% growth rate. However, to the detriment of the environment, this slow increase brought with it a significant expansion of agriculture in some areas, such as the tropics, but only little changes or even a decrease of agricultural land use in the rest of the world. The outcome is the relocation of agriculture towards the tropics, which in addition to environmental impacts expands food supply chains and makes them vulnerable to food security issues (*ibid*). Comprehensive data showed that by the turn of the 21st century, food production had already converted 70% of grasslands, 50% of the savanna, 45% of the temperate forests, and 27% of the tropical forest biome (Ramankutty *et al*, 2008).

Novel agricultural methods can help to alleviate the strain between land use and the need for higher productivity. Even one-storied hydroponic production has been found to be 10 times more efficient in terms of land use than conventional soil-based production (Barbosa *et al*, 2015). In that study, hydroponic lettuce took up on average one square meter per 24 plants with yearly output of 41 ± 6.1 kg/m^2, which is 11 ± 1.7 times more land-efficient than conventional methods demonstrated (*ibid*).

As vertical farms are in essence stacked fields that use hydroponics or similar methods, the land use reduction becomes even more significant with proponents claiming differences of up to a hundredfold (Specht *et al*, 2014; Benke and Tomkins, 2017). When considering hyperlocal solutions, land use is even less of a concern as the systems only take up a portion of the space that is already in use for living purposes.

1.2.3 Transportation

Long distance transportation, especially air freight, can have a large share in the impact of vegetable and fruit production (Sim *et al,* 2006). Sea freight can reduce this impact, but on the other hand it is limited by storing conditions and longevity of the produce (Stoessel *et al,* 2012). It is important to note that most LCAs conducted about food supply chains and transportation conclude that transportation itself does not have as high of an impact as generally believed (Garnett, 2014).

In an comprehensive LCA conducted over the whole food system in the United States, it was found that transportation of food only contributes 4% of greenhouse gas emissions (Weber and Matthews, 2008). But when accompanying activities are considered and in the case of LCAs, the system is expanded to processes like refrigeration, IT services, packaging and processing that come along with longer transportation choices, the environmental impacts can become significant (Garnett, 2014).

Estimating the emissions from transportation involves much uncertainty. For example, if we would attribute all the emissions of transporting a cargo container to food, the results would be inaccurate as other products might be hauled together with food in that same container (Rama and Lawrence, 2008). This is especially true for fast perishable plants that are transported as belly cargo in passenger airplanes - a transportation method that is mainly meant for and thus accounted for as moving people around, not food (Mok *et al,* 2014).

In addition, emissions calculations and subsequent decisions for food transport must consider economies of scale (McWilliams 2009). A great example is that 2000 apples hauled over 2000 kilometers require the same amount of fuel as 50 apples taken to farmer's market from a local producer and brought home, totaling only 50 kilometers of car ride (*ibid*). Some argue that for this reason, urban agriculture, that would result in more frequent short car rides, compared to long lorry transportation, could increase greenhouse gas emissions (Mok *et al*, 2014).

Studies have demonstrated that during off-season in colder regions such as Northern Europe it is more energy-efficient and economically viable to transport produce from warmer climates where it can be grown without the use of heated greenhouses or artificial lighting to colder regions that would otherwise require these complementary technologies (Romero-Gamez *et al*, 2014).

Thus, the transportation distances become long, as on the practical side, their costs are calculated to be lower than running heating or lights. But as Garnett (2014) brought out, the longer transportation distances that seem more viable at first add to various other environmental impact contributions when upstream processes and accompanying services are considered. Longer transportation also means longer shelf life, and with it, more nutritional value loss and the need to use protective treatments or added packaging.

One of the most effective ways observed for reducing transportation impacts, is to prefer local in-season produce over off-season, if there is a high probability of it being transported via air freight and consume less fruits and vegetables that are exotic and do not naturally grow in the region (Stoessel *et al,* 2012). Another example supporting this is a study focusing on soil-based urban community gardens in the United Kingdom, which argued that the most significant reductions in greenhouse gas emissions from urban farming can be achieved when specific crops are selected, which are fast growing and would otherwise need to be shipped frequently over long distance (Kulak *et al*, 2013). Crops such as leafy greens.

Similar conclusions can be made for hyperlocal growing as well. The largest gains can be achieved with crops that are fast growing, are not locally in-season all the time, but are in high demand and would thus require frequent transportation from long distances.

1.2.4 Water use

Approximately 75% of the earth's surface consists of water, but less than 1% of it is freshwater and in turn, 70% of the 1% is already being used by agriculture (Evans and Sadler, 2008). The last five decades of the 20th century saw the world's irrigated cropland double in size (Gleick, 2003). While animal-based food products such as beef or cheese alone account for higher water use per mass of the end product, fruits and vegetables play an equally or even more important role in the global water use because they are consumed more by total mass (Tukker and Jansen, 2006).

Researchers have arrived to the conclusion that the Earth can safely sustain freshwater use as large as 4000 km^3 yr^{-1} (Sokolow et al, 2019). FAO (United Nations Food and Agriculture Organisation) has estimated that freshwater withdrawals have already been over that boundary for the past decade (*ibid*).

An important aspect is where the water is being drawn from for food production - unfortunately, places under already high water stress tend to be the regions where most of the world's fruits and vegetables are produced (Stoessel *et al*, 2012). But the produce is consumed elsewhere, essentially creating scarcity in one region at the expense of serving others. This contributes to high water stress in most areas, in which almost half of the world's population will live in by the year 2030 (Foley *et al*, 2011).

Hydroponics has been found to use significantly less water than conventional soil-based methods (Benke and Tomkins, 2017). A comparative study of lettuce production in Arizona found that hydroponic systems in the area use 13 ± 2.7 times less water compared to conventionally produced lettuce, 20 ± 3.8 l/kg compared to 250 ± 25 l/kg. The global average water use of lettuce production is 161 liters per kilogram (Sokolow *et al*, 2019).

While mostly similar to the studied hydroponic system, commercial vertical farms can achieve even higher rates of water retention due to closed environment production (Benke and Tomkins, 2017; Sanjuan-Delmás et al, 2018). Similarly low water uptake is advertised for hyperlocal solutions. The hyperlocal growing device in the current study uses an estimated 17 liters of water per 1 kilogram of lettuce, according to numbers provided by the producer.

1.2.5 Fertilizer use

The majority of fertilizers that are used in agriculture are non-renewable mineral fertilizers that need to be extracted from earth and go through various stages of production (Romeo *et al*, 2018). As with other non-renewable resources, their production puts a heavy burden on the environment, but more importantly, their use yields unwanted damage to ecosystems (*ibid*). To feed the world and meet the high demand, excessive amounts of fertilizers are used in conventional agriculture (Le Campion, 2020). Collated data from 1950 to 2000 has shown the global fertilizer use increase by 500% (Foley *et al* 2011).

As said, the majority of impacts from fertilizers come from their excessive use, not production, although conversion of nitrogen from atmosphere and mining of phosphorus all have considerable environmental impacts (Cordell *et al*, 2009; MacDonald *et al*, 2011). Fertilizers that leach to the ground after being applied on fields contribute to the degradation of freshwater and marine ecosystems, and after applying on the field, they release nitrous oxide, a greenhouse gas (*ibid*).

However, fertilizer use is not a problem everywhere, as some regions even have too little of it. Regions like China, Northern India, United States and Western Europe have been identified as places where the fertilizer excess is the largest. At the same time, other regions have too little nutrients for productive farming. Thus, it has been observed that only 10% of all croplands over the world are responsible for 32% of nitrogen and 40% of phosphorous surplus. (Foley *et al*, 2011)

In hydroponics, including in commercial vertical farming and hyperlocal home devices, any nutrients that end up not absorbed by plant roots at first, stay in the system and are recycled within it, unlike traditional soil-based methods where some is lost (Benke and Tomkins, 2017). Therefore, the negative environmental impacts of fertilizer use are avoided, but some of the impacts from production still remain.

1.2.6 Pesticide use

In conventional agricultural practices, pesticides are used to control unwanted bugs, fungi and weeds to maximise yield (Margni *et al,* 2002; Le Campion *et al*, 2020). They are considered to be an integral part of successful traditional agricultural practices, providing many positive effects in terms of productivity (Margni *et al*, 2002). FAO has estimated that 300 grams of pesticide compounds are produced each year per person (Gustavsson *et al*, 2011). Because of their widespread use, pesticides have largely dispersed to unwanted places, to aquatic and terrestrial ecosystems and to human life (Hellweg and Geisler, 2003). It has been noted that the main source of pesticide exposure to humans comes from the consumption of food, a figure that is 5 orders of magnitude higher than from water or inhalation (Juraske *et al*, 2009).

This involuntary consumption of pesticides leads to notable decrease in life expectancy (*ibid)*. But it is important to note that the health benefits from consuming large amounts of vegetables and fruits have been found to far outweigh the negative effects of pesticide residues that come with them (Aktar *et al*, 2009). However, in developing countries and for high risk groups such as children, pregnant women and elderly, the risks of too big exposure to pesticides over time or immediately through uncontrolled use at farms still remains (*ibid*).

Many local urban farms that use controlled environments can operate without the use of pesticides while not decreasing productivity (Marin and Molin, 2019). Hyperlocal growing devices also grow produce without the need of using pesticides, which, in people’s homes would be very uncomfortable.

1.2.7 Infrastructure and packaging

Infrastructure of production facilities are usually not included in food LCAs as their lifetime is expected to be very high. However, Cellura *et al* (2012) studied the environmental impacts of conventional peppers, melons and tomatoes that were grown on protected fields. Their results revealed that the observed crops had high impacts from packaging and greenhouse structures, but mainly because the materials of these structures were not reused much over seasons and thus had a high waste rate.

On the other hand, a LCA performed on a small vertical farm in an office building’s basement showed that infrastructure has a minute share in various impact categories but the plant container used in production and later packaging use is of very high significance (Martin and Molin, 2019). The system also used artificial lighting, although from a comparatively renewable Swedish electricity mix. On the other hand, another case study of growing tomatoes in Spain in a rooftop urban farm proved the infrastructure plays an important role in the life cycle impacts, reaching up to 50% of impacts in fossil fuel depletion and climate change (Sanjuan-Delmás *et al*, 2018). Granted, the latter study did not have artificial lighting and much of the plastic infrastructure was regarded to go to disposal relatively fast (*ibid*).

Heller *et al*, (2019) and Williams and Wikström (2011) have highlighted that although food packaging receives widespread criticism, especially the use of plastics, its environmental impacts are somewhat counterintuitively negated when considering that the alternative is food with fewer protection and thus higher waste rate. Local urban production, and even more so, hyperlocal growing allows the use of less packaging as produce does not need to travel far, doesn’t need to be protected as much and is consumed sooner. Hyperlocal method only requires packaging for the components that are used for growing, such as growth medium, but not for the produce, which has larger volume and requires more protection.

1.3 Food waste and loss

A large volume of produced food is never consumed but is instead discarded, degraded or consumed by pests along the supply chain. A widely cited large scale study by FAO

(Gustavsson *et al*, 2011) suggests that about one-third of food ends up not being consumed. According to data from 2015, this level of inefficiency results in roughly $940 billion in world-wide economic losses each year (FAO, 2015). Furthermore, the food that is produced but never eaten consumes about one-quarter of all fresh water used in agriculture (Kummu *et al*, 2012) and generates 8% of all global greenhouse gas emissions (FAO, 2015).

It is important to differentiate food loss and waste (Gustavsson *et al*, 2011). Food waste indicates food that is suitable for human consumption but is discarded, either by choice or after the food has been left to spoil or expire due to disregard or excess production (FAO, 2017). While food waste is related to the distribution, retail and consumer stages, food loss refers to the unintentional decrease at the production stage (Mattsson *et al,* 2018). Food loss and waste together are defined as a decrease throughout the whole system from production to consumption, regardless of the cause, signifying both mass and quality of food that was grown for human consumption (FAO, 2017).

In the developing countries, food loss is more prevalent where, by some estimates 40% of food is lost post-harvest because of processing, storage and transport conditions (Gustavsson *et al*, 2011). When food production inefficiencies are added to the equation, countries in South Asia and Southeast Asia average 87% food loss while in Sub-Saharan Africa it can reach up to 95% (Lipiński *et al*, 2013).

In the developed countries, losses during the first stages of the life cycle of food are smaller, but retail, food service and consumer levels account for more than half of the decrease (Gustavsson *et al*, 2011; Block *et al*, 2016). In European Union, the estimated rate for these three latter stages is 70% with retailer stage usually having the lowest share (Stenmarck *et al*, 2016). Cultural post-harvest quality standards, the perceived market-readiness of produce and programmed overproduction that protects from losses due to natural weather also play a part in food loss in developed countries (Plazzotta *et al*, 2017).

The differences of food waste and food loss rates in different regions might seem big. But for a perspective of the differences between the food waste in developed countries and food loss in the developing world, the waste rate in North America and Europe reaches 95-115 kg per person each year, while in South and Southeast Asia and Sub-Saharan Africa it is only 6-11 kg per year.

The differences between stages at which food is lost or wasted point towards the need to focus efforts in the first stages of the food life cycle in developing countries and in the latter stages in developed countries (Block *et a*l, 2016; Mattsson *et al*, 2018). Producing food closer to consumers and thus cutting out stages where food could be lost before the consumer could have a positive impact, as proponents of vertical farming are pointing out (Benke and Tomkins, 2017).

While there are no concrete studies comparing food waste and loss between conventional agriculture, vertical farming and hyperlocal farming (Martin and Molin, 2019), some assumptions can be made. As almost every aspect of plant's growth is controllable in vertical farms, food loss at the farming stage is minimal (Martin and Molin, 2019). Because the produce from the farm enters the food supply chain at a later stage than with conventional agriculture, the potential loss by long distribution is also minimized while waste at consumer remains. However, the latter is, in turn, avoided with hyperlocal growing solutions that allow to harvest only what is needed right before consumption.

While around third of food is lost across all food products, fruits and vegetables have the highest numbers, reaching 50% in European and other developed countries (De Laurentiis *et al*, 2018). Among them, lettuce has been highlighted as one of the worst performers with substantial losses occurring in all stages, except retail and totaling up to 60% in Europe (Plazzotta *et al*, 2017; De Laurentiis *et al*, 2018; Mattsson et al, 2018; Blake, 2015; Strid and Eriksson, 2014; Beausang *et al*, 2017).

The majority of the loss in lettuce production comes from the need to cut a significant amount of core and outer leaves off of most lettuce varieties before packaging for consumers (Plazzotta *et al*, 2015). This process not only reduces the quantity of the grown produce, but also the quality, as plant tissue is torn and starts losing its resiliency to physical and nutritional degradation (*ibid*). The production of baby lettuces - those without large inedible cores, but largely consist of small leaves - does not yield as high losses (*ibid*). For the same reason, the common practice of growing small leafy green varieties in novel hydroponic, vertical and hyperlocal farms could prove very beneficial in terms of environmental impact reductions.

1.4 Vitamin-rich food and nutrition

Concerns around food sustainability are starting to focus on not just how many resources are used to produce food measured in mass, but how much is used to deliver nutrient content by the time food is eaten (Sokolow *et al*, 2019). Food LCA literature often only focuses on either increasing efficiency of how we produce food, or restraining demand, which is how food is consumed (Garnett, 2014). These views lack a larger perspective to lead to a meaningful action (*ibid*). This perspective is needed to deeply understand complex environmental problems that in essence are socio-economic and reach further than a typical LCA study can comprehend (*ibid*).

A major challenge of our time is providing enough nutritious food to everyone while at the same time reducing its impact on the environment (Foley *et al*, 2011). This, in essence, entails both improvement of efficiency and managing demand. It also means taking into account social wellbeing and different options that are available in regions with diverse social and economic circumstances (*ibid*). A systems perspective, as Garnett (2014) described, is therefore needed for achieving food sustainability and security. Following this logic, the current study also applies a wider view and accounts for waste and shows nutritional value per environmental impacts generated, in addition to just looking at the life cycle impacts of different production systems.

Globally, a quarter of calories from food are lost with food waste (Lipiński *et al*, 2013). At first glance, the high rate of food loss and waste and the fact that more than 2.2 billion people are overweight or obese (The Global Burden of Disease Obesity Collaborators, 2017; WHO, 2020) indicate there is a surplus in the current food system.

On the other hand, 690 million people globally suffer from acute hunger lacking both calories and micronutrients (FAO, 2020). Another 2 billion people who get enough calories come short of the required amount of micronutrients in their diets - even in developed countries (Ritchie and Roser, 2017). And around 75% of deaths in developed countries are attributed to unbalanced diets containing enough calories but too little necessary micronutrients (Committee of World Food Security, 2012). The same trend is recognized in the developing countries where the number is 40% but rising (*ibid*).

This points at a severe inefficiency in the food system in terms of distributing food and attaining food security (Garnett, 2014; Ritchie and Roser, 2017). By definition, food security entails the availability, access, utilization and stability of nutritious and clean food (Committee on World Food Security, 2012). Current high levels of physical postharvest loss and wastage along with nutritional degradation during long food supply chains have been found to cause malnutrition FAO, 2020). Overcoming these inefficiencies that produce physical and nutritional degradation is critical if we want to achieve food security around the world (*ibid*).

Vegetables that are popular for their healthy nutritional value - like lettuce - contain rich amounts of bioactive compounds: minerals like potassium, calcium, phosphorus, vitamins A and C, but also phenols and flavonoids (Cruz *et al*, 2014). However, within current food supply chains, high amounts of these are lost before consumption, therefore deepening the problem of malnutrition (FAO, 2020). Studies have found this nutritional loss happens due to insufficient nutrient management at growing stage and later, at distribution, production, retail and consumer stages due to rough handling that damages the structure of the plant, long transportation distances, inadequate storage and undesirably high temperatures (*ibid*).

Novel farming methods that shorten the supply chain and provide a more controlled growing environment could thus play an important part in advancing food security and delivering more nutrients to our diets. In fact, many novel urban farms are built with the intention of totally controlling and analysing the growing environment to maximise preferred nutritional contents or other attributes of the produce (Tomkins *et al*, 2017). However, these too use the same supply chains as traditionally farmed produce, although to a lesser extent, and therefore accumulate nutrient loss.

Growing at the place of consumption could enable preservation of nutrients in entirety when harvested shortly before consumption. Tests done by the producer of the hyperlocal growing devices that are in focus of this study have found that the antioxidative activity of store-bought lettuce that is in an enclosed package can be 1.81 times lower than the lettuce grown with the hyperlocal device. And lettuce without enclosing packaging can have these levels 3.05 times lower than hyperlocal.

1.5 Life cycle assessment

LCA examines the environmental aspects and likely impacts throughout a product's life cycle, from cradle-to-grave, from raw materials extraction to production, use and disposal (Curran, 2015). Life cycle assessment is an effective tool to utilize when trying to evaluate environmental impacts of either a process or a product (Curran, 2015). It enables to set boundaries of the study according to focus of interest and available data, model real life processes and compare the environmental impacts of all the different stages that make up the object of study (*ibid*).

Similarly to all industrial processes, food production, distribution and consumption yields different impacts along the whole supply chain and LCA is an effective and widely accepted tool for finding out these impacts and improving them based on the research (Zarei *et al*, 2019). Assessing the entire food supply chain allows to identify where and how resources are employed and what impacts they cause, without shifting the burdens from one analysed process to others that might not be considered (Cellura *et al*, 2019).

Life cycle assessments generally follow a set of standardized processes to achieve better comparability of results and avoid skewed results (Curran, 2015). The methodology is defined by the standard created by International Organisation for Standardisation (ISO) (*ibid*). The ISO 14040 standard describes the principles and framework of LCAs and ISO 14044, specifies requirements and gives guidelines for performing a LCA (*ibid*).

The first step is goal and scope definition, where the purpose of the study is defined along with the expected outcome (Roy *et al*, 2009). It is also the step where system boundaries - what will be studied and what are other relevant processes that will be left out - are set (*ibid*). And a key to every LCA, the functional unit set - the comparative value through which all the impacts are calculated and results are published (Curran, 2015).

Functional units in many LCAs and also usually in food LCAs are set as a mass of some product (Roy *et al*, 2009). While LCAs are designed to study products and processes from cradle to grave, their system boundaries can be set to be cut off at a certain point (Curran, 2015). For example, a LCA can study production of vegetables from farm to farm gate, meaning that no further distribution, retail, consumption, or disposal stages are modelled (Stoessel *et al*, 2012).

Next step is the life cycle inventory (LCI) analysis that consists of gathering data (Roy *et al*, 2009). The data can be either gathered with high detail, studying a specific product in a certain production facility, or aggregated using LCI databases with mostly market average data that is not specific to a single product (*ibid*). All processes studied or aggregated during the LCA phase are assigned inputs and outputs directed to and from them (*ibid*). The inputs are either raw materials and resources or other processes and outputs are emissions to the environment or other following processes (Curran, 2015).

After completing LCI comes the life cycle impact assessment (LCIA) (Curran, 2015). Its aim is to understand and assess the environmental impacts of the LCI based on the scope of the whole analysis and its goals (Roy *et al*, 2009). The LCI results are assigned various impacts and further classification, characterization, normalization and valuation is conducted (*ibid*). These steps give the LCI results equivalency factors, for example, how methane emissions translate into CO_2 emissions; aggregate the impacts into common categories, for example global warming potential; and assess the relative importance of different environmental impacts by giving them weights. When using LCA software, most of these steps are automatically taken care of (Curran, 2015). The last step is interpretation of results which brings out significant impacts found during the LCA and concludes with suggestions based on the focus of the study (Roy *et al*, 2015).

2 METHOD AND MATERIALS

The current thesis is focused on comparing the environmental impacts of producing and consuming food with conventional farming methods and hyperlocal methods. The comparison will be made using life cycle assessment (LCA) methodology. Lettuce production and consumption will be used as an example for comparing the two methods. Lettuce is found to be the food product with one of the highest waste rates and is among one of the most consumed fresh food products in Europe (Plazzotta *et al*, 2017; De Laurentiis *et al*, 2018; Gustavsson, 2011). Therefore, researching alternative methods for lettuce's whole production and consumption supply cycle could be beneficial.

Lettuce production and consumption will be assessed from cradle to grave. In addition to comparing life cycle impacts of the two methods, as additional steps, weighing will be done that takes into account the higher rate of physical and nutritional food loss cited in previous research that conventional agriculture produces. The region of production and consumption for both methods is Europe. Modelling of the life cycle inventories of farming methods and subsequent life cycle impact analysis was conducted with OpenLCA 1.10.3 software.

2.1 Systems studied

According to ISO definition, in LCA, a product system is a set of materially and energetically connected unit processes that performs one or more defined functions (Cellura *et al*, 2012). The interactions between unit processes are not necessarily direct and may be influenced by changes in the market supply and demand, which connects these processes (*ibid*).

In the current study, one product system is compiled from different unit processes to reflect hyperlocal food production and consumption of lettuce and the second product system is compiled using existing data to reflect conventional production and consumption of lettuce. System boundaries are from cradle to grave, with the exception of farming infrastructure and equipment not being included. Data for systems are compiled using information from secondary LCI databases that were updated in 2020.

The OpenLCA program allows users to choose various inputs to the processes chosen for the models. This is of course true only if there is more than one option available in databases and linked to the process. For example, the production of heat energy can be chosen to be produced by numerous processes in different regions, a coal power plant in India or a municipal waste incineration plant in Germany.

As the region of interest in this study was set as the whole Europe, the providers of different processes in the modelling were selected as "Europe" or "Rest of Europe" or "EU28". An exception was made when the process modelled was known to take place in a specific country or when no European providers for the processes existed. "Rest of Europe" usually indicates countries other than Switzerland, where the majority of LCA databases are compiled and hence, country-specific data is available.

Unit processes with the characteristic of Allocation at the point of substitution (APOS) were used from the database throughout the modelling process. Unit processes were chosen as they contain visible upstream and downstream input and output processes and thus allow to choose appropriate regions of production or modify any other required values within the processes, such as the specific mass of a product that is produced. The opposite would have been system processes that are considered black boxes and only show elementary flows as inputs and outputs.

2.1.1 Conventional farming system

The data for conventional farming method was taken from the Ecoinvent version 3.7.1 database where conventional lettuce production has already been modelled. The LCI data in the Ecoinvent database is based on a wide food products LCA study "Life Cycle Inventory and Carbon and Water FoodPrint of Fruits and Vegetables: Application to a Swiss Retailer" carried out by Stoessel *et al* in 2012. The process "Lettuce production in a heated greenhouse" was chosen to represent conventional farming methods in the current study.

Heated greenhouse production was chosen over open field production since it is more closely comparable to indoors hyperlocal farming as both enable year-round growth. As the data came from the Ecoinvent database, it had updated values and impacts under processes from 2020, not values from 2012 when the study was first conducted. Therefore, previous studies that have used the same LCA of lettuce production from 2012 might have resulted in slightly different results in different impact categories.

The lettuce farm in the Stoessel *et al* 2012 study used a highly resource efficient conventional farming methods - integrated farming techniques and hydroponics. Integrated farming is a set of production management methods that focus on efficient and sustainable use of all farming resources, while also focusing on economic profitability (EISA, 2012). Water, fertilizer and pesticide use is strictly accounted for, optimized for each plant and natural methods of pest control are used where possible (Tasca *et al*, 2017). Highlighting this fact is the amount of irrigation water accounted for in the dataset, 16 liters per 1 kg of produce. The global average for lettuce production is 161 L per 1 kg of lettuce produced (Sokolow *et al*, 2019).

The "Lettuce production in a heated greenhouse" database details lettuce production in a heated greenhouse from cradle to gate, to an extent. It does not account for farming infrastructure and storage facilities but starts with seedling production, including pesticide, fertilizer, land and water use for both irrigation and post-harvest cleaning. Electricity and heating are considered for year round production. Processes end with washing the produce with 0,4 L per 1kg or produce and storage of lettuce for 0,3 months at the farm facilities.

The study was conducted using Swiss energy inputs and transportation values but the authors highlight that the database is open for adjustment for modelling based on specific European countries, the whole Europe or the world (Stoessel *et al,* 2012). In the current study, Swiss data was substituted by European average heat generation market and average European ENTSO-E electricity grid values and used for the calculations.

The previously compiled Swiss lettuce dataset has two disadvantages as it does not include any data on food loss nor does it cover a lettuce packaging process or steps after lettuce leaves the farm warehouse. Within the current study, these food losses were modelled into the calculations only at the later weighing in order to answer the third research question. Additional processes from the latest Ecoinvent version 3.7.1 database were added to the model to reflect distribution from farm to retail, storage in retail, transportation to home, at home consumption and subsequent end of life processes.

After performing a LCA for the conventional method, to answer the third research question, the conventional lettuce system is modelled as packaged lettuce with 50% food waste rate and lettuce without packaging with 60% waste rate.

2.1.2 Hyperlocal farming system

The life cycle of hyperlocal lettuce production and consumption is modelled using relevant processes in the latest Ecoinvent version 3.7.1 database, ESU Food and Agribalyse 3.0.1 database. Building up this model, the boundaries and composition of the conventional lettuce production system that it is being compared to were taken as a reference and as close as possible comparison was made. Doing so achieves better quality and comparability of the results of a life cycle assessment (Curran, 2015).

The growing device chosen for this study grows up to 25 plants at a time with the use of LED grow lights. It uses a growth medium based on coconut coir and peat which includes nutrients and seeds. Compiled together it is called a plant pod. Its watering system is passive, meaning no electricity is taken up by water pumps. All specifications and values to build up a model using these devices were acquired from the producer. The values, such as distances or raw material transportation or mass of coconut coir or mixture of fertilizers in the plant pod are not shared here due to the producer's intellectual property and business information confidentiality.

Infrastructure was not included, as previous studies (Martin and Molin, 2019; Sanjuan-Delmás *et al*, 2018) have proven their total contribution to the impacts are minute when infrastructure is used for a long time and materials are recyclable. Within the current system, the details of the structure of the garden, power cable, adapter and printed circuit board of the hyperlocal growing device are expected to last a lifetime and LED lights' circa 10 year lifespan is also considered as infinite. Hence their production and end of life are not taken into account. Infrastructure of conventional greenhouse production was also not included in the study.

For the hyperlocal farming system, only the materials that are needed to continuously deliver resources and produce growth in the garden are modelled: the plant pod and the upstream production processes of the materials that it consist of, transportation of the materials from raw material extraction to production and packaging, the seeds, fertilizers and packaging that are used, along with their upstream production processes, electricity used to power LED grow lights and water used by consumers to grow the plants.

2.1.3 Modelled variables in both systems

Both systems start with raw material extraction. These were not manually modelled but were upstream processes linked to the processes that were manually selected for the comparison of both farming methods.

Energy use

Low voltage electricity from the average European ENSTO-E mix was used in conventional greenhouse consumption and hyperlocal consumption. For conventional farming, only the electricity mix was changed from Switzerland to the aforementioned mix, no input values - such as how many kWh it takes to grow lettuce - were changed. For the hyperlocal farming, information of the power of the LED grow lamp was received from the producer and its working cycle of 16 hours on and 8 hours off per day was calculated into power consumption over one day. This was multiplied by 35 days, which, according to the tests conducted by the producer, is the time observed when the garden grows a lettuce plant to its harvest-ready size of 35 grams.

The conventional lettuce production had heat energy generation previously modelled from both natural gas and sources other than natural gas. For both of these, again, European average production was selected as inputs. No heating or cooling was considered for hyperlocal production. Heating or cooling a home is something that would be done either way, with or without the growing device growing plants at home.

Land use

Land use in conventional lettuce production was previously already modelled, nothing was changed in this regard. No land use was manually modelled into hyperlocal production as it was assumed to take place at home on a small area, which is already occupied for living. Land use from linked upstream processes, however, such as peat extraction or cultivation of lettuce to produce seeds was included in calculations.

Transportation

Transportation was added throughout the models of both supply chains. For conventional production, bulk transportation from farm to direct-to-customer retail was used with no wholesale distribution step. This transport method was considered a lorry with a cooling reefer. Cooling of the lettuce between transportations, at the retail store, was modelled to consume 1 MJ/kg of electricity according to previously existing values in the dataset. Additionally, private transportation methods were added from retail to home that included pre-existing calculations of the average European means of grocery shopping with appropriate shares in car (86%), public transport (3%), bike ride or walking (9%). The distance in the dataset had been modelled as 6.2 km in the dataset and the volume of groceries in the bag as 7.3 kg per shopping round.

For hyperlocal production, transportation of peat and coconut husk were first added using sea freight from their appropriate extraction locations to the manufacturing of plant pods. From there, lorry transport was modelled to the location of assembly with end-consumer packaging. As a last step, another lorry transportation was modelled to reflect transportation to consumers. No courier deliveries to homes or estimates for consumers visiting a retail store and buying the plant pods were made as these don’t have to take place as often as it happens with buying fresh produce and any estimations would have been highly inaccurate. Moreover, as the plant pods in their packages weigh very little, it was not assumed to be a critically important factor in the whole model.

To compare the systems equally, both the production-to-retail distance in conventional system and assembly-to-home distance of hyperlocal system were assumed the same, 2500 km, reflecting an average distance of the grown produce or plant pods travelling in Europe. A shortcoming in the already existing conventional farming system was the lack of transportation of fertilizers, pesticides and seeds to the farming location. Therefore, seed and fertilizer transportation was not taken into account in the hyperlocal farming model as well.

Water use

Conventional farming had the use of irrigation water (16 l per kg of yield) and tap water for cleaning the lettuce (0.4 l per kg of yield) modelled. Additional tap water use at the consumer level was modelled for washing the store-bought produce. For this, 4 l consumption was modelled, reflecting an assumed washing time of 30 seconds per kg of lettuce, multiplied with the waterflow output per minute of an average domestic faucet. Water use in upstream processes such as fertilizer production or electricity generation was also accounted for, but by the datasets themselves.

Water use of upstream processes for the hyperlocal production were also accounted for. Additionally, water use for plant pod production and tap water use at the consumer level to fill the water tank of the device was modelled according to the best estimate from the producer. As the plants of hyperlocal production are grown at homes with no pesticides or other additives, cleaning time for the lettuce before consumption was assumed to be two times shorter than for conventional store-bought lettuce (2 l per kg of produce).

Fertilizer use

Pre-existing data in the conventional farming model for fertilizer use was not changed. It reflected fertilizer use through an appropriate mixture of ammonium nitrate as N, phosphate as P2O5 and potassium sulfate as K2O.

The same fertilizer datasets were used for hyper-local production as well. Exact fertilizer volumes and mixture as ammonium, phosphate and potassium in each plant pod was calculated using data from the producer. Other secondary minerals in the fertilizer mix were not accounted for to achieve better comparability with the conventional production method.

Pesticide use

A dataset of organophosphorus compounds was already existing in the conventional farming system to reflect the use of pesticides. As indicated above, the conventional method under study used integrated farming technique, which among other resources, focuses heavily on the reduction of pesticide use. Therefore, the amount of pesticide used was low compared to world average in farming. No pesticides are used in the hyperlocal farming method and thus none were modelled.

Packaging

In the pre-existing data, high density polyethylene (HDPE) plastic packaging for pesticides and fertilizers was considered in the conventional farming method. Additional packaging was modelled for lettuce that left the farm. A conventional box of 100 g lettuce was bought from a grocery store and its empty polypropylene (PP) plastic tray with polypropylene film surrounding it was washed, dried and weighed. The weight was converted into an appropriate figure for packaging 1 kg of lettuce (0.148 kg).

Similarly, real life values for the packaging in the hyperlocal system were weighted and modelled. The carton board packaging and the low density polyethylene (LDPE) plastic film around it that the producer uses were weighed. As one of these boxes holds 9 plant pods, an adjusted weight of this packaging per one plant pod was calculated and, subsequently, multiplied by the amount of plant pods necessary to grow 1 kg of lettuce (0.15 kg of carton and 4.40E-3 kg LDPE).

Additional packaging that is commonly used during distribution for added protection or loading structure, such as loading crates, was not modelled for either production system as no concrete data was available and these volumes would only have been equally inaccurate assumptions.

Consumption and end of life processes

Both end-user consumption steps were modelled with lettuce or plant pods arriving at the consumer's home inside of their enclosing package. Both included washing of the lettuce as mentioned before. The spent washing water was modelled as a waste flow directed into municipal water treatment. Conventional system included storage of the lettuce in the fridge for 3 days - an estimated assumption. Fridge storage was not modelled for the hyperlocal produce as the device itself keeps lettuce fresh until harvested for consumption.

Water evapotranspiration was modelled as water emission to air in the consumer step of hyperlocal production. This was calculated according to the best estimate from the producer regarding how much water growing one lettuce plant requires 1 l of water. The water content of one harvest-ready lettuce plant (35 ml) was then assumed along with the water content in the finished and ready to be thrown away wet plant pod (44 ml). Subsequently, the rest of the water, an estimate of 96% was calculated as water vaporizing during the plant growth. For conventional production system, the water evapotranspiration was already included in the initial production step.

Treatment of biowaste and packaging waste was modelled according to the latest available EU average waste treatment data for both of the systems. For the cardboard package from the hyperlocal system, an 82.9% recycling and 17.1% incineration rate was used (Eurostat, 2021). For the LDPE film around the cardboard packaging, an average for all plastics, 41.8% recycling and 58.2% incineration rate was used (Eurostat, 2021). The same rates were used for the PP packaging of the conventional lettuce system.

90.8% of biowaste was assumed to be sent into treatment and 9.2% was assumed to be home composted in both of the systems. As there are no conclusive EU-wide rates for home composting, an average from available data was used to determine this rate (Favino *et al*, 2020; Eunomia 2009; European Bioplastics, 2015). According to European Compost Network (2019), a total of 118.75 t of biowaste is generated and collected for treatment in Europe and an average of 40% of it is recycled. Of that, 30.5 t goes to industrial composting, 12.4 to anaerobic digestion facilities and 4.6 t to plants that combine both methods (*ibid*). The rest goes to municipal waste treatment.

Thus, 32.7% of biowaste was modelled to go into industrial composting streams, 12.9% to anaerobic digestion, 9.2% to home composting, as mentioned before, and an additional 24% to landfills and 27% to incineration according to Eurostat data (2021). For the hyperlocal system, 55 g of biowaste per grown plant - the weight of a used and still wet plant pod - was considered. For the conventional system, no biowaste was calculated at first as no food waste was assumed in the models that would answer the first two research questions. In the conventional system, biowaste rates were only used in the calculations for answering the last research question.

Growth medium

Both conventional and hyperlocal production methods use peat as a growing medium. Coconut coir, a byproduct of the coconut industry, is also used in the plant pod of the hyperlocal production. The volume of peat required to grow 1 kg of lettuce was already existing in the conventional lettuce dataset - 63.7 g.

The volume figures and specific composition of peat and coconut coir in the hyper-local method’s plant pod were gathered from the producer. The total weight of one plant pod was considered 11 g. As mentioned above, the transportation of these raw materials from their appropriate production sites was used in the model. Additionally, heat energy and water for producing the plant pod was modelled according to best estimates from the producer.

2.2 Functional unit

All impacts of life cycle assessment are expressed in relation to a functional unit which considers the main function of the assessed product (European Commission, 2010). When different systems are compared, the same functional unit is used (Curran, 2015). When food is studied using LCA, impacts in relation to the mass of food is usually taken as a functional unit (Nordborg *et al*, 2017). Normally, this would be 1 kg of food product consumed at a specified cut off point (Curran, 2015).

Various studies have brought out the need to account for the indirect environmental impacts of wastage in food production and consumption while performing LCAs (Heller *et al*, 2019). This could be done by choosing the functional unit as a unit of food eaten, not a unit of food produced and thus taking into consideration the wastage happening at the different steps throughout the lifecycle and adding the losses as a subsequent requirement of increased production (*ibid*). The same logic was used in this study.

1 kilogram of lettuce consumed at home was set as the functional unit for both conventional and hyperlocal farming systems in this study.

The pre-existing dataset of conventional production had already been modelled using 1 kg of lettuce produced as the functional unit. The hyperlocal production, however, was modelled by considering one plant pod as a reference volume of processes at first. Later on, at the consumer step, the amount of plant pods that are needed to produce 1 kg of lettuce (28,57) was calculated and with this, upstream processes were automatically updated to answer to the functional unit of 1 kg of lettuce consumed at home.

2.3 Life cycle impact assessment (LCIA)

Life cycle impact assessment for comparing both farming systems was carried out using the 2016 ReCiPe (H) midpoint method with 3 impact categories: climate change, measured in CO_2 equivalent with the warming potential over the course of 100 years; agricultural land transformation, measured in square meters per year; water depletion, measured in cubic meters.

Agricultural land occupation refers to the amount of agricultural area occupied, in m^2 during one year (Huijbregts *et al*, 2017). In addition to showing agricultural land use, the impact indicator indirectly expresses biodiversity loss since agricultural land use is found out to be the biggest contributor to biodiversity loss (Elshout *et al*, 2014).

Water depletion indicator shows water used in cubic meters, but it does not reflect just the volume of water consumed (Goedkoop *et al*, 2008). It assumes higher impact for water that is drawn and used in a product or process in one area,but consumed or released in another (*ibid*). If water is drawn and released in the same area, it can be considered as no water was used (*ibid*). Moreover, it takes into account whether the water comes from a water scarce source or a place with no water stress (*ibid*).

The goal of the ReCiPe method is to translate the detailed list of LCI results into a comprehensible list of environmental impact categories (Huijbregts *et al*, 2017). The method applies impact mechanisms with global scope and unlike other approaches (Eco-Indicator 99, EPS Method, LIME, and Impact 2002+) it does not take into consideration potential impacts from future extractions but assumes such impacts have been included in the inventory analysis (*ibid*).

The H in the ReCiPe midpoint (H) means “hierarchist” and expresses a consensus model, not an “egalitarian” one that is based on long term precautionary thinking, or an “individualist” model that is based on short term thinking and expresses optimism that technology can avoid future problems (*ibid*).

The individualistic perspective is based on the impacts that are not disputed and expresses technological optimism and the assumption that humans can adapt well to changes (*ibid*). The hierarchist view takes a scientific consensus regarding specific time frames and plausibility of environmental impacts (*ibid*). The egalitarian perspective expresses the precautionary view and takes into account the longest time frame and all impact pathways that data can provide (*ibid*). The hierarchist model is considered as a default for impact assessments (*ibid*).

Initial comparison of life cycle impacts that answers the first and second research questions assumes 0% food loss for both systems. Later on, to answer the third research question, the processes in the conventional farming system were calculated as having 50% for packaged lettuce and 60% for unpackaged lettuce. The detailed loss and waste rate calculations were based on multiple lettuce waste and LCA studies as there is no concrete Europe-wide information available (Heller et al, 2019; Mattsson et al, 2018; Blanke 2015; Strid and Eriksson 2014; De Laurentiis et al, 2018).

For the not packaged lettuce, 60% waste rate was summed up as 9% loss at farm, 3% during transport, 6% during retail and 42% waste at consumer. The 50% waste rate of packaged conventional lettuce was summed as 20% happening during production due to cleaning of the inedible core and outer leaves are left intact for the unpackaged lettuce. 10.8% was considered to be lost at retail and 19.2% at consumer. No loss during transportation was considered as lettuce in enclosed packaging is well protected during travel and loss is minimal. Appropriate processes along the supply chain were added weighing factors based on these waste rates. For example, if the food waste rate is 50%, the same amount of extra packaging was considered to be needed.

To answer the third research question which weighs in nutritional value loss, multiplication by 3 was carried out on all of the life cycle impact assessment results of conventional lettuce production without packaging. 1.8 multiplication was done on the packaged lettuce. That multiplication was an addition to the food loss rates accounted for in the previous step. These results are made to express the volume of conventionally farmed lettuce it takes to deliver the same amount of nutrients for at-home consumption as it takes with 1 kg of hyperlocally produced lettuce.

The weighing factors were based on previous tests done by the producer of the hyperlocal devices on antioxidative activity levels as measured in ascorbic acid (Vitamin C) between conventionally farmed lettuce and lettuce grown hyperlocally. The store-bought lettuce which was not enclosed in sealed packaging showed ascorbic acid levels 3.05 times lower than hyper-locally produced lettuce. The store bought lettuce that was enclosed in hermetic packaging, like the one considered in this study as the conventionally farmed lettuce, showed results 1.81 times lower than hyperlocally produced lettuce.

What caused the lower nutritional value, at what rate did it happen or how long the conventional lettuce had been in transit and on sale, is unknown. Thus, these values are used as best available knowledge to calculate the impacts created by different farming methods in order to provide the same amount of nutrition.

3 RESULTS

The following chapter shows the results of life cycle impact assessment of conventional and hyperlocal lettuce production and consumption. The results will be shown over three impact categories: climate change, expressed through CO_2 emissions created; agricultural land occupation, expressed through m^2 per year of land use; water depletion, expressed through m3 of water consumed. The results will be brought out in the appropriate succession according to the research questions.

First, the overall life cycle impacts of hyperlocal lettuce production and consumption are brought out, followed by comparison to the results in the same impact categories with the conventional lettuce production. Both of these results are brought out using heatmap tables where the processes with higher shares in the total impacts of an impact category are shown with a darker shade of red. Then, the results of modelling with higher food loss and waste rates into the conventional system are shown and compared to hyperlocal systems. Results from additional weighing with nutritional value degradation will be added on top of these waste rates at the end and subsequent impacts are compared to impacts from hyperlocal system with no waste or nutritional loss weights.

3.1 Life cycle impacts of hyperlocal production

The majority - 8.82 kg or 94.34% - of CO_2 equivalent emissions throughout the whole life cycle of hyperlocal production and consumption come from electricity production, as shown on table 1. This is followed by two lorry transport processes, although with considerably smaller impacts, 0.14 kg and 0.08 kg accordingly. Next notable impacts come from plant pod production with peat production being responsible for 0.07 kg, electricity consumption at the plant pod manufacturing 0.06 kg and coconut coir production 0.04 kg. Recycling of carton and LDPE from the package of plant pods yields a net positive CO_2 impact, decreasing the total impact by -4.99E-03 kg and to -8.24E-06 kg accordingly.

The distribution of impacts by agricultural land occupation are somewhat different. The majority - 0.78 m^2a or 75.58% - of the impact comes from electricity production for LED grow lights that are used at home to grow the plants. The next most impactful processes are different from the CO_2 emissions category. Coconut coir production results in 0.20 m^2a of agricultural land occupation and carton board production 0.04 m^2a.

Electricity for plant pod production takes up 2.48E-03 m^2a and lorry transports 1.11E-03 and 6.40E-04. Similarly to CO_2 emissions category, the recycling of carton and LDPE plastic packaging results in negative scores, meaning positive impact for agricultural land occupation, -1.71E-05 m^2a for carton and -3.22E-07 m^2a for LPDE plastic film.

Water depletion impacts among processes varies significantly compared to climate change and agricultural land occupation. The highest contributing process to water depletion is the production of seeds for plant pods with 8.29E-05 m^3, followed by collection and treatment of domestic biowaste with 1.31E-05 m^3. The production of LDPE film consumes the third largest amount, 4.86E-06 m^3 and composting at home the fourth largest amount, 1.26E-06 m^3. The process with highest impact for the previous two categories, the electricity generation for LED grow lights, only results in 3.12E-07 m^3 or 0.30% of the total in the water depletion category.

Table 1. Life cycle impact assessment results for hyper-local production and consumption.

LCIA results of conventional lettuce			
Process	**Climate change, kg CO2-Eq**	**Agricultural land occupation, m2a**	**Water depletion, m3**
Total life cycle impacts	**9.35E+00**	**1.04E+00**	**1.00E-04**
Electricity at consumer for grow lights	8.82E+00	7.83E-01	3.12E-07
Lorry transport, assembly to consumer	1.42E-01	1.11E-03	1.31E-07
Lorry transport from production to assembly	8.21E-02	6.40E-04	7.55E-08
Peat production	7.16E-02	8.13E-05	4.97E-10
Electricity for plant pod production	6.27E-02	2.48E-03	2.20E-09
Coconut coir production	4.59E-02	2.05E-01	3.53E-09
Plant pod packaging - carton box	3.70E-02	4.17E-02	3.46E-09
Collection and treatment of domestic biowaste	3.41E-02	3.70E-04	1.31E-05
Sea freight of coconut coir	2.19E-02	7.05E-05	8.42E-10
Plant pod packaging - LDPE plastic film	1.36E-02	1.76E-08	4.86E-06

Water for rinsing before consumption	9.56E-03	5.70E-04	7.61E-10
Fertilizer production	8.08E-03	3.18E-04	5.43E-09
Composting at home	3.57E-03	3.22E-05	1.26E-06
Sea freight of peat	9.60E-04	2.65E-06	3.14E-11
Lettuce seed production	5.60E-04	8.00E-04	8.29E-05
Water for plant pod production	3.90E-04	2.36E-05	3.13E-11
Wastewater from plant pod production	0.00E+00	0.00E+00	0.00E+00
Collection and incineration of carton package	0.00E+00	0.00E+00	0.00E+00
Collection and incineration of LPDE plastic film	0.00E+00	0.00E+00	0.00E+00
Water treatment from rinsing before consumption	0.00E+00	0.00E+00	0.00E+00
Collection and recycling of LPDE plastic film	-8.24E-06	-3.22E-07	-6.26E-12
Collection and recycling of carton package	-4.99E-03	-1.71E-05	-1.22E-09

3.2 Comparison of life cycle impacts of conventional and hyper-local lettuce

The following section details the comparison of life cycle impacts of conventional and hyperlocal lettuce. The figures of conventional lettuce here represent a system where no weighing with food waste rates or nutritional degradation was modelled. Hence, no data is shown for collection and treatment of domestic biowaste and home composting.

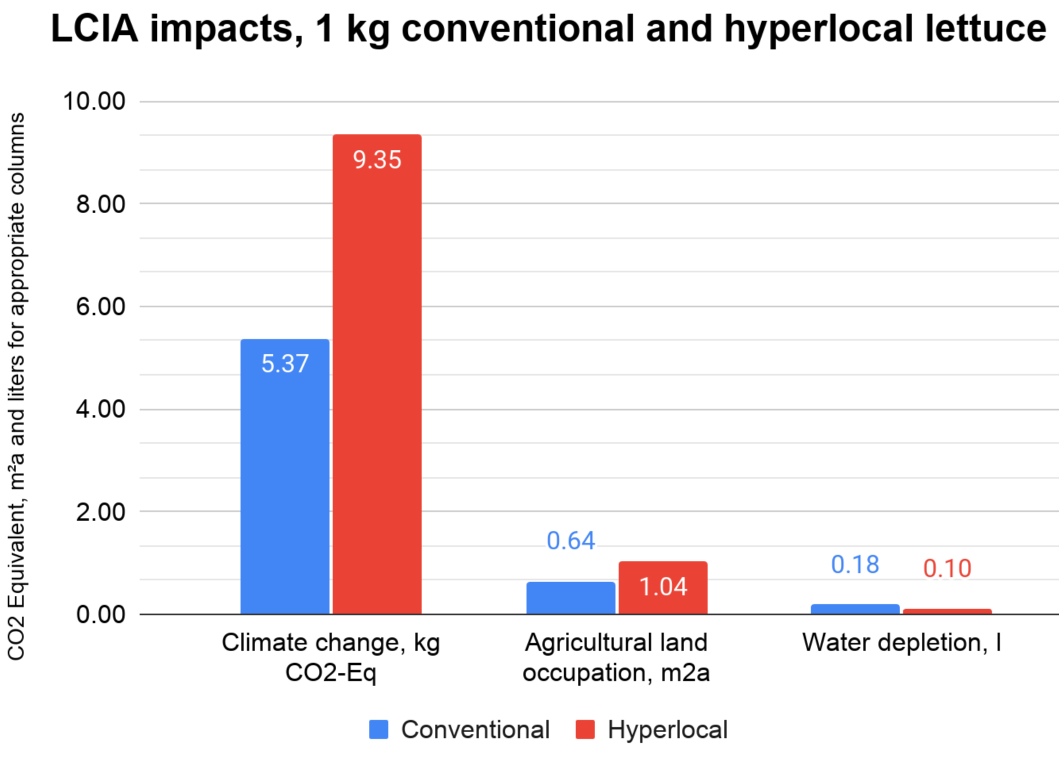

Figure 1. LCIA impacts comparison of 1 kg conventional and hyperlocal lettuce production and consumption

The results of the climate change impact category show 42.57% smaller emissions of CO_2 equivalents per 1 kg of lettuce than the emissions from hyperlocal lettuce, 5.37 kg CO_2 Eq and 9.35 kg CO_2 Eq accordingly, as shown on figure 1. The contributions from different processes to the CO_2 emissions of conventional lettuce, as shown in table 2, are similar to the contributions of hyperlocal lettuce, as shown in table 1. The majority, 4.14 kg CO2 Eq comes from energy production - from heating of the greenhouse for the conventional lettuce and from running the LED grow lights for the hyperlocal lettuce. The percentages of these processes to the total impacts in climate change category are 94.34% for hyperlocal and 77.04% for conventional lettuce. In a similar fashion, lorry transportation from farm to retail is the second biggest contributor for conventional lettuce, although with a significantly smaller share than greenhouse heating, 3.48E-01 kg CO_2 Eq.

Farm to retail lorry transport of conventional lettuce is followed by polypropylene plastic production for lettuce packaging with 2.68E-01 kg CO_2 Eq. This is higher in terms of percentage of contributions to climate change among the conventional lettuce system but also higher than the emissions from carton + LPDE plastic packaging in the hyperlocal lettuce, where the results were seventh and tenth among the whole system, resulting 3.70E-02 kg CO_2 Eq for carton box and 1.36E-02 kg CO_2 Eq for LDPE plastic as shown in table 1.

The next five processes with highest climate impacts in the conventional lettuce system are those that are avoided and do not exist in the hyperlocal system or have any comparable process like greenhouse heat generation did with electricity production for LED grow lights. These are transport of lettuce among other groceries from retail to home, resulting 2.03E-01 kg CO_2 Eq, electricity for greenhouse operation with 1.82E-01 kg CO_2 Eq, cold storage of lettuce at retail with 1.25E-01 kg CO_2 Eq, lettuce storage at home in fridge with 4.37E-02 kg CO_2 Eq and fertilization process at greenhouse with 2.00E-02 CO_2 Eq. Unlike the collection and recycling of packaging in the hyperlocal system brought with it a positive impact, slightly lowering the total CO_2 emissions, the same can’t be said for the conventional system where the recycling of PP plastic packaging yielded a <1.00E-24 result and for that, did not show up in LCIA results in OpenLCA.

Agricultural land occupation shows a similar difference in the total number between conventional and hyperlocal lettuce as it did with climate change - conventional lettuce takes 38.46% fewer square meters of agricultural land per year than hyperlocal lettuce. Table 2 shows the majority of the total of 0.66 m^2a in the conventional lettuce system comes from energy generation for the greenhouse, 5.61E-01 m^2a for heat and 1.62E-02 m^2a for electricity. This follows the hyperlocal system, where the highest land occupation impact came from energy production for LED grow lights. The second highest impact of conventional lettuce comes from the greenhouse physically occupying agricultural land, 5.64E-02 m^2a. Next comes cold storage at retailer, 9.84E-03 m^2a, a process that is not in the hyperlocal system. This is followed by 4.21E-03 m^2a from PP plastic packaging production, which takes up close to ten times smaller agricultural land area than 4.17E-02 m^2a from the carton packaging plus 1.76E-08 m^2a from LDPE plastic film production of hyperlocal system. The sixth and seventh most impactful processes in terms of agricultural land occupation are transport of groceries from retail to home with 3.97E-03 m^2a and the storage of lettuce at home in a fridge with 3.14E-03 m^2a. Both are processes that hyperlocal production and consumption doesn’t have.

Figure 1 shows that water depletion is the only impact category where hyperlocal lettuce has lower score in kilogram versus kilogram of production and consumption over conventional lettuce. Figure 1 shows results translated into liters from m^3 for better comparison, following the logic of 1 m^3 of water = 1000 l. Tables 1 and 2 reflect the water depletion results as per the standard of LCIA results, in m^3. Conventional method yields 1.80E-04 m^3 water depletion compared to 1.00E-04 of hyperlocal method, a 44.44% difference. The majority of the water depletion impacts come from seed production for lettuce, 8.29E-05 m^3, as it was with hyperlocal production. However, the next most impactful processes, grocery transport from retail to home with 4.94E-05 m3, lettuce storage at home in a fridge with 3.70E-05 m^3 and cold storage in retail with 1.41E-05 m^3, are not in the hyperlocal system.

Two processes - collection and treatment of domestic biowaste and composting at home are shown with no values in table 2 that shows the results of the conventional system. This is because waste from food was given 0 value in this phase where kilogram versus kilogram of production and consumption was modelled to compare the two systems. They are, however, shown in the table to indicate that they were not left out of the conventional system and to make the results from table 1 and 2 better comparable. Table 2 shows the process of land occupation of greenhouse in a similar way with no values under climate change and water depletion categories. This is due to the process only impacting agricultural land use.

Table 2. LCIA results of conventional lettuce.

LCIA results of conventional lettuce

Process	**Climate change, kg CO2-Eq**	**Agricultural land occupation, m2a**	**Water depletion, m3**
Total life cycle impacts	5.37E+00	6.60E-01	1.80E-04
Heat generation for greenhouse	4.14E+00	5.61E-01	1.31E-07
Lorry transport from farm to retail, with cooling reefer	3.48E-01	2.15E-03	3.18E-07
Lettuce packaging - PP plastic production	2.68E-01	4.21E-03	3.03E-09
Consumer transport of groceries from retail to home	2.03E-01	3.97E-03	4.94E-05
Electricity for greenhouse operations	1.82E-01	1.62E-02	6.46E-09
Cold lettuce storage at retailer	1.25E-01	9.84E-03	1.41E-05
Lettuce storage at home in fridge	4.37E-02	3.14E-03	3.70E-05
Fertilizing process	2.00E-02	1.17E-03	1.23E-09

Fertilizer production	1.66E-02	6.46E-04	4.22E-09
Collection and recycling of PP plastic package	8.73E-03	-4.60E-10	2.42E-08
Irrigation water sourcing	1.45E-03	3.66E-05	5.69E-11
Tap water for rinsing at home	1.25E-03	7.51E-05	9.95E-11
Fertilizer package production	9.00E-04	1.18E-05	7.68E-10
Lettuce seed production	5.60E-04	1.17E-03	8.29E-05
Pesticide production	5.10E-04	2.23E-05	6.44E-11
Water for rinsing lettuce at farm	1.30E-04	7.51E-06	9.95E-12
Pesticide package production	3.73E-05	1.18E-05	1.22E-11
Collection and treatment of domestic biowaste	-	-	-
Composting at home	-	-	-
Collection and incineration of PP plastic package	0.00E+00	0.00E+00	0.00E+00
Water treatment from rinsing at home	0.00E+00	0.00E+00	0.00E+00
Land occupation of greenhouse	-	5.64E-02	-

3.3 Comparison of environmental impacts when food waste and nutritional loss is taken into account

The following results answer the third and fourth research question. They show how impacts among different categories change when the conventional system is modelled as two scenarios depicting real life production and consumption. The first model considered the lettuce with the same packaging as the kilogram versus kilogram comparison model did, for which the results were shown in the last section. As a result of this packaging, a total of 50% waste rate was considered and nutritional value loss compared to hyperlocal lettuce was assumed 1.8. The second model contained no packaging for the lettuce, reducing the impacts from packaging production, but yielded a higher, 60% waste rate and 3.0 times less nutrients compared to hyperlocal lettuce.

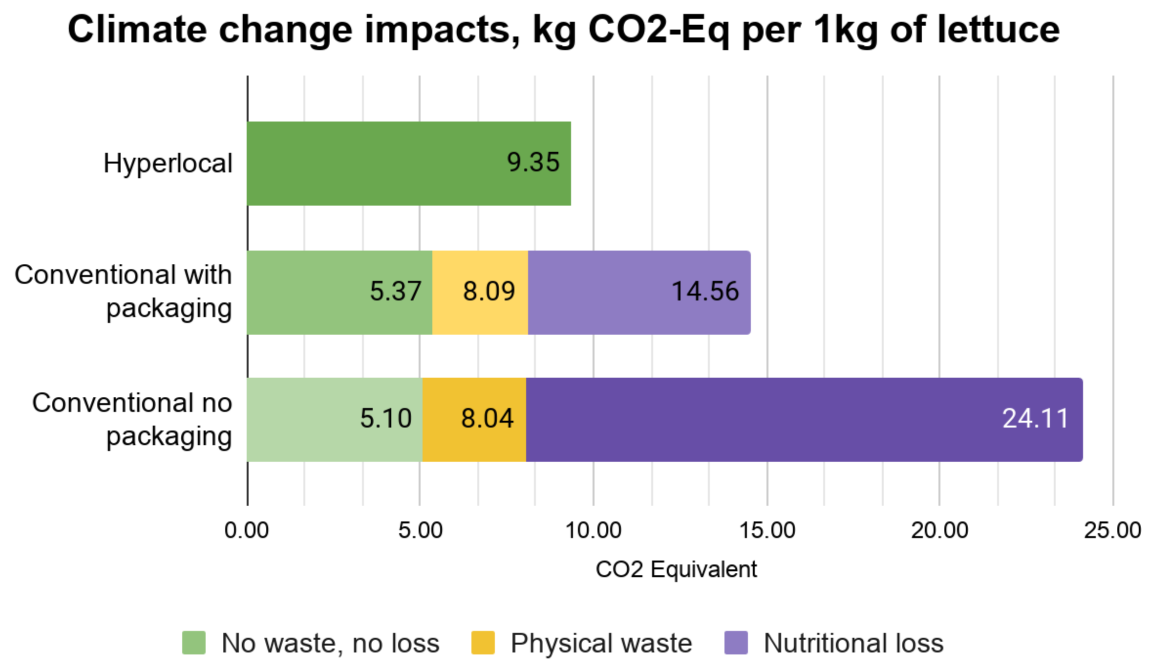

Figure 2. Comparison of climate change impacts of conventional and hyperlocal production and consumption, kg CO_2 Eq per 1 kg of lettuce.

Figure 2 includes the additional modelled conventional system reflecting the production and consumption of conventional lettuce without packaging. The numbers in figure 2 marked by the label "No waste, no loss" are the same that were shown before in tables 1 and 2 and in figure 1. The second label "Physical waste" reflects the 50% and 60% waste rates of conventional lettuce with packaging and without. The third label "Nutritional loss" shows the results when weighting with 1.8 and 3.0 times lower nutritional value was modelled for the conventional lettuce.

The results of figure 2 show that when waste rates are modelled, the climate impacts of conventional and hyperlocal lettuce decrease their initial kilogram versus kilogram difference of 42.57% shown on figure 1. The conventional lettuce with packaging is producing slightly more CO_2 Eq than conventional lettuce without packaging and is still 13.48% lower than hyperlocal lettuce. When 1.8 lower nutritional value for the packaged conventional lettuce is taken into account, the total climate change impact rises to 14.56 kg CO_2 Eq, making the impacts from hyperlocal lettuce 35.78% lower with its 9.35 kg of CO_2 Eq emissions. When the same weighting, but with 3.0 lower nutritional value is done with the conventional lettuce without packaging, it results with 24.11 kg CO_2 Eq, making the impacts from hyperlocal lettuce 61.22% lower at the same 9.35 kg CO_2 Eq of hyperlocal lettuce.

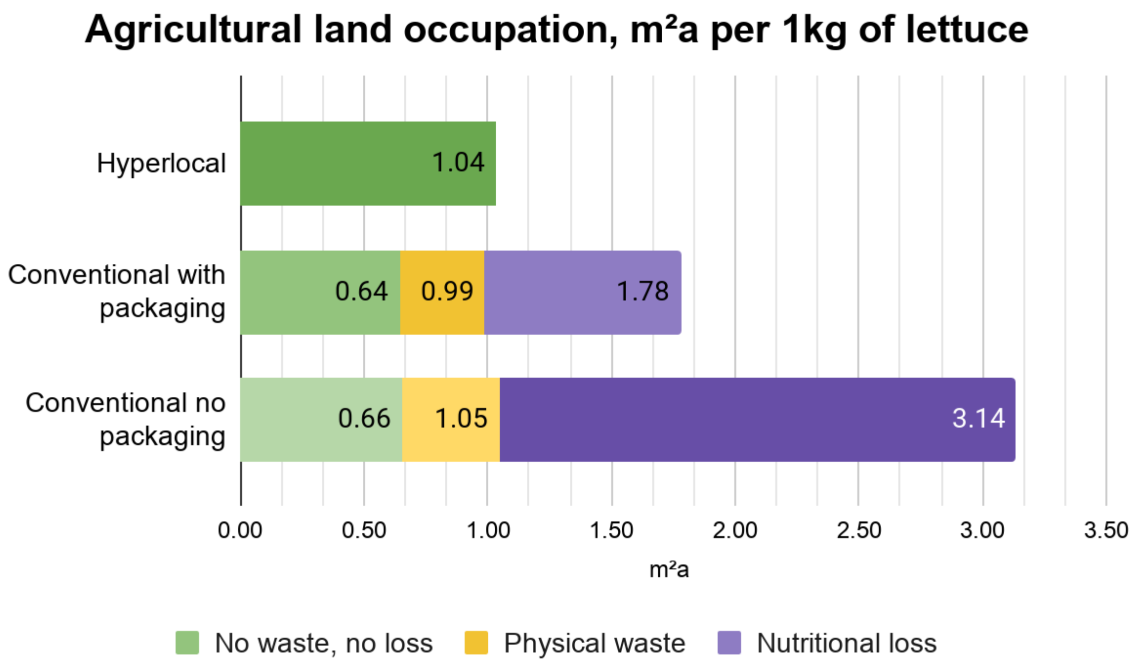

Figure 3. Comparison of agricultural land occupation of conventional and hyperlocal production and consumption, m^2a per 1 kg of lettuce.

Figure 3 follows the same logic of figure 2, showing the comparison of three different systems by three different modelled scenarios - first the production and consumption with physical waste and nutritional value degradation, secondly with physical waste and for the third with physical waste and nutritional value altogether.

With hyperlocal production taking 1.04 m^2a per 1 kg of lettuce, the conventional packaged lettuce is taking 38.46% less at 0.64 m^2a while conventional lettuce without packaging is taking 36.53% less at 0.66 m^2a. When physical food waste is added, the values become closer. Conventional lettuce without packaging exceeds hyperlocal with 1.05 m^2a while conventional lettuce still has 4.81% smaller impact on land occupation than hyperlocal at 0.99 m^2a. Adding nutritional degradation to the model, the impacts of hyperlocal become 41.57% smaller than conventional packaged lettuce that takes up 1.78 m^2a and 66.88% smaller than conventional lettuce without packaging that takes up 3.14 m^2a.

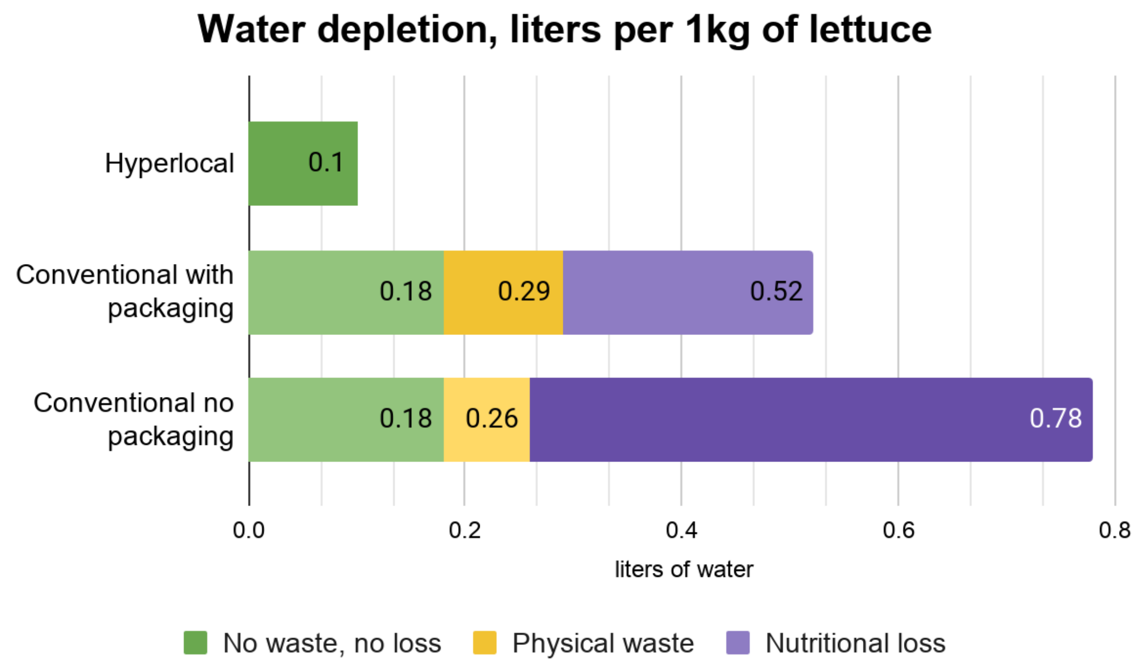

Figure 4. Comparison of water depletion of conventional and hyperlocal production and consumption, l of water per 1 kg of lettuce

Figure 4 follows the same logic of figure 2 and 3, showing the impacts of three systems, modelled in three different ways regarding physical and nutritional loss of lettuce. The water depletion impact category is the only one where in just the kilogram versus kilogram comparison the hyperlocal lettuce already has the smallest impact. At 0.1 l the water depletion from hyperlocal is 44.44% less than from conventional lettuce, both packaged and not, at 0.18 l. When adding the physical food waste rates, the difference between hyperlocal and conventional packaged lettuce becomes 65.52% at 0.29 l and 61.54% for non-packed conventional lettuce at 0.26 l. When weighing with nutritional value, the impacts of hyperlocal lettuce become 80.39% smaller than packaged conventional lettuce at 0.52 l and 87.18% smaller than conventional lettuce without packaging at 0.78 l.

4 DISCUSSION

The following chapter answers the research questions and hypotheses, provides context to the results and compares them with previous studies. The discussion follows the order of research questions and is divided into chapters according to them. First, the life cycle assessment of the hyperlocal and conventional farming are discussed, followed by results obtained after weighing with food waste and nutritional value degradation.

When looking at the comparisons with previous studies, it is important to keep in mind that to the knowledge of the author, the cradle-to-cradle modelling with added distribution, retail, consumer and end of life steps that were used in the current study has not been conducted on lettuce production and consumption before in other studies, nor have any other LCA studies looked at growing food with electronic indoor gardens. This makes comparisons difficult and inaccurate in terms of total results, but nevertheless, individual processes and different aspects of the observed production and consumption methods can still be set into context of previous studies.

4.1 Life cycle impacts of hyperlocal and conventional lettuce

The results shown in table 1 validates that the first hypothesis is true only for CO_2 emissions. The hypothesis stated that more than 90% of the impacts in the hyperlocal method come from electricity use of LED grow lights. The CO_2 impact from LED grow lights is 94.34% of the total. For the agricultural land occupation and water depletion categories, however, the first hypothesis is false as the impacts from electricity production in these categories are 75.58% among land occupation and 0.30% among water depletion impacts. Regarding the climate change impacts, the results are aligned with the majority of literature on indoor farming technologies using LED grow lights that show the electricity consumption to cause the bulk of CO_2 emissions (Martin and Molin, 2019).

The results shown on figure 1 and table 2 show that the second hypothesis is not true. The hypothesis stated that conventional farming methods have lower impacts in every category when comparing kilo to kilo production and consumption. While climate change and agricultural land occupation are indeed smaller for the conventional system, water depletion is not.

The following subsection highlights the differences of the biggest contributing processes among both systems in all three impact categories.

4.1.1 Source of energy as a key indicator

The aforementioned Martin And Molin (2019) study modelled and observed the use of LED grow lights in a small indoor vertical farm setup and showed that the electricity consumption is responsible for only a quarter or up to around half of the CO_2 emissions, depending on what materials they modelled for production processes. What is important to take into account, however, is that according to European data (Eurostat 2020) more than 50% of the Swedish electricity mix that was used in the Martin and Molin (2019) study is produced from renewable sources compared to less than 20% for the European electricity mix that was used in the current study where LED lights contributed 94.34% of greenhouse gas emissions.

A conclusion can be made that if the farming process uses grow lights, then the method of electricity production becomes the most important factor in terms of greenhouse gas emissions. A higher rate of renewables in the production mix drives down the CO_2 impact of growing under artificial lighting significantly. Another LCA study on vertical hydroponic lettuce farming demonstrated how electricity is responsible for over 60% of greenhouse gas emissions (Romero *et al*, 2018). However, in the farming operation that the study observed, there were no grow lights used, but the electricity consumption came from pumps that need to circulate water with nutrients. The study also conducted a sensitivity analysis to test the same hypothesis that electricity mix is an important factor. When they modelled the use of wind power instead of usual French electricity mix, the CO_2 impacts of the whole production halved.

The LCA study conducted by Romeo *et al* (2018) provides a great comparison for the results of the conventional method observed in this study as it used the same heated greenhouse process from the Ecoinvent database as was used here. They also compared the heated greenhouse production to open field production, in addition to the aforementioned hydroponic vertical farming. Their results in greenhouse gas emission, water depletion and agricultural land occupation categories coincide with results from this study that are shown in table 2. But only up until the point the produce leaves the farming gate, as their study did not model processes after farm gate (*ibid*.). Their comparison with open field production demonstrated that the heated greenhouse production caused 24.5 times higher CO_2 emissions than open field production, 0.29 kg CO_2 Eq compared to 7.1 kg CO_2 Eq when considering 10.4 kg/m^2 per year yield for open field and 20 kg/m^2 per year yield for greenhouse (*ibid.*). Again, this proves that the source of energy production becomes crucially important as the energy consumption for heating the greenhouse is comparably high, like it was with running the lights for the hyperlocal system.

It would be interesting to see how conventional open field production compares to the two modelled systems in this study as open field production does not require any heating, cooling or lighting. From the climate change aspect, lettuce produced on open fields can be significantly smaller than in heated greenhouses or with growing solutions using artificial lights like the hyperlocal production modelled in this study when kilo to kilo production is considered. But as Romeo *et al* (2018) have shown, the results between the production systems become more equal if land use or water depletion are taken into account and when smaller yield from an open field is considered.

The open field production in Switzerland studied by Stoessel *et al* (2012) gives a 0.16 kg CO_2 Eq result for 1 kg of lettuce produced in the Ecoinvent LCIA database. An important side note is that this result is not shown in their article from 2012 where the results are weighted with market demand, but it is possible to calculate using the Ecoinvent database where the production process is modelled. 0.16 kg CO_2 Eq is significantly lower than the CO_2 emissions of hyperlocal lettuce in this study (9.35 kg CO_2 Eq) and conventionally produced lettuce in a heated greenhouse (5.37 kg CO_2 Eq). But the open field production does not contain any steps after the farm gate. Nor does it account for food losses that are higher in open fields where produce is more exposed to weather and where harvesting discrepancies with demand could happen more often than in greenhouse productions that generally operate more flexibly. It also does not account for nutritional value loss, which, again, can be higher for open field production as the produce is damaged more, spends more time without packaging and is less frequently packaged.

A rough estimate can be deducted when looking at the processes that follow after the conventional lettuce leaves the farm gate in the current study. The processes shown in table 2 that come after lettuce leaves the farm amount to 1 kg of CO_2 Eq. Thus, when no waste and loss of nutritional value is considered and the same processes are added that were considered in the greenhouse farmed lettuce system, the open field production could yield 1.16 kg of CO_2 Eq from cradle to grave. When adding a flat 60% increase signifying waste rate, the results would be 1.86 kg of CO_2 Eq. And when multiplying this with 3 to signify nutritional value loss, the result is 5.57 kg of CO_2 Eq, only slightly higher than heated greenhouse production with no waste or nutritional value loss. As highlighted, this result is in no way exact as open field production needs to be modelled with different inputs to depict real life situation. The calculation was only done as an example and needs further studying and modelling with appropriate values. Also, an important thing to note is that open field production usually produces higher impacts in other categories like eutrophication, water and land use (Romeo *et al*, 2018).

It was demonstrated how the source of the energy mix plays a significant part in the results of both electricity use and heat generation. It could be hypothesised that using hyperlocal method with LED lights to grow lettuce in Sweden is as climate change friendly as conventionally produced lettuce in a heated greenhouse with an average European energy mix when just the kilogram to kilogram comparison is made. But a more wider sensitivity analysis should be carried out to see how much the use of the studied hyperlocal solutions differ from country to country or from consumer to consumer within each country as there are more options to choose your own electricity mix. An LCA study that looks at installing solar panels for at-home food production, among other electricity needs, for example, could yield interesting results.

Another way of mitigating the impacts from electricity consumption would be to use novel demand response solutions that turn appliances on and off the grid according to the available electricity on the market. When there is little output coming from renewable sources and non-renewable sources start producing and selling to the market, the growing device could shut off and turn back on a few hours later when there is more renewable energy again. This, of course, would require a better understanding of how the frequent changes in the light schedule could affect plant growth and the longevity of the LED light.

4.1.2 Differences in transportation

All transportation processes of the hyperlocal system shown in table 1 contributed 2.64% or 0.22 kg CO_2 Eq in total in the climate change category. This result coincides with previous studies that have shown a small share of 4% for transportation in the total greenhouse gas emissions of food systems (Mok *et al*, 2014). The transportation emissions in the hyperlocal production are further mitigated because water-heavy produce that is otherwise transported in conventional systems is substituted with dry materials for plant pods that produce the water-heavy produce at home, skipping the heavy transportation step. The share of transportation among agricultural land occupation impact category for hyperlocal lettuce is also small, as expected, 1.75E-03 m^2a or 0.18% in total. This is understandable as the effects of oil production for fuels and the raw material extraction and construction of highways has a small share in occupying farmable land area, when large quantities of goods are calculated to be transported on those roads and with these fuels. Transportation has a similarly small share in water depletion, resulting in only 0.20% of the impacts.

The transportation impacts of conventional lettuce are significantly different. There is no long distance transport of raw and dry materials for plant pod production, the added visit to grocery stores and the aforementioned aspect of transporting water-heavy produce along the whole supply chain result in more than twice as high impacts from transportation. The climate change impacts of the conventional system are, as shown in table 2, 0.55 kg of CO_2 Eq or 10.23% of all the impacts of the system. A significant rise over the 0.22 kg CO_2 Eq of hyperlocal lettuce. Of this 10.23%, 6.47% is due to lorry transport from production to retail and 3.78% due to consumers' grocery shopping. The significance of going to grocery shopping coincides with the observation that Weber and Matthews (2008) made about short distance food transportation having a comparable impact with long distance lorry shipping because of scaled processes with improved efficiencies. Their comparison was between 50 apples being transported for 50 km by car and 2000 apples being transported by lorry over 2000 km.

It is interesting that going grocery shopping also contributes significantly to water depletion where it is responsible for 26.85% of the impacts in the conventional system. The majority of the impacts of water depletion in the conventional system come from fuel production because the impacts in the water depletion category essentially show the transferring of water scarcity from one region to another. Thus, a production process that takes up water in one location and moves the product - fuel - for consumption in another location has a higher impact multiplier than for example water coming from a tap and going to wastewater treatment in the same city. Another reason that might contribute to the high impact of consumer transportation is that the process used to model consumers going to grocery stores was from the ESU food database. Majority of processes in the modelled systems were from the Ecoinvent database and they could be modelled slightly differently in terms of how impacts are allocated in fuel production and consumption of cars.

The hidden upstream processes and high levels of assumptions in modelling transportation of food that Garnett (2014) and Mok *et al*, (2014) point towards, were accounted for in this study, to an extent. Some of the upstream and accompanying processes that longer transportation brings along, like packaging, was indeed modelled. However, no pallets, master cases or stronger structural packaging that is used in bulk transportation were considered. But to keep results better comparable, they were not included for both systems. Also, the datasets did not include any use of logistics IT systems or infrastructure of logistics hubs Garnett (2014) mentions. The error margins that high levels of assumptions bring along were mitigated with the decision to set the transportation distance from production to the next step as the same, 2800 km. Surely, all year round heated greenhouse production would allow producing food closer to consumers, but no data for average distance of travel for food that's produced in heated greenhouse was found.

Further studies should take the transportation's accompanying processes into account, such as the production, use and disposal of extra packaging materials used in the transportation of both conventionally grown lettuce and in shipping of the plant pods of the hyperlocal production. The results showed that due to mainly transporting dry matter the impacts of transportation in hyperlocal production were considerably smaller. The plant pods are already using light materials like peat and coir which have been found to reduce transportation emissions compared to alternatives (Barrett *et al*, 2016). But a further sensitivity analysis testing different weight of the plant pods and different packaging materials in terms of weight for their enclosing boxes could show places of improvement.

4.1.3 Packaging choices

Packaging in both systems was modelled differently. Hyperlocal lettuce used mainly carton and a thin LDPE plastic film to provide added protection to the pre-seeded plant pod from the surrounding environment and conventional system used PP plastic tray and film around it. The PP packaging altogether weighs 10% less per functional unit, a kilogram of lettuce, than the carton plus LDPE packaging of hyperlocal production, and among the three observed impact categories, their shares differ in terms of which one has higher impacts.

The climate change impact from the production and disposal of packaging in conventional system is 0.28 kg CO_2 Eq or 5% of total CO_2 impacts, while for hyperlocal it is 0.05 kg of CO_2 Eq. This can be explained by the relatively high CO_2 emissions from plastics production compared to carton production. In agricultural land occupation, however, the total from conventional is 4.55E-03 m^2a and from hyperlocal it is 4.56E-02 m^2a. This is explained by the use of wood in carton production, which to a degree in the mathematical models of the analysis, comes at the cost of agricultural land. In water depletion, hyperlocal has a higher impact of 4.86E-06 m^3, compared to 2.72E-08 m^3, and it is mostly because of LDPE production that needs bigger quantities of water and makes up 4.73% of total water depletion.

The packaging of both systems does not make up a significant share of the environmental impacts. However, it is important to consider that other impact indicators such as ecotoxicity or the littering problem of plastics, that does not reflect well in LCA impact assessment categories, could play a bigger role when taken into account in addition to the three used here. But judging from the current three impact categories, it could be argued that the amount of packaging that is used is justified as the protection which the product loses with fewer or no packaging could lead to higher waste rates and thus higher impacts. A similar trade was observed by Heller *et al* (2018) where more packaging and the subsequent higher success at protecting food and not letting it go to waste results in lower environmental impacts compared to fewer or no packaging that causes higher waste rates.

For the hyperlocal system, additional studies should take into consideration more impact categories and model the use of lighter carton for packaging, or other lighter alternatives such as bioplastics or conventional plastics from fossil fuels.

4.1.4 Growth medium and seeds

Growth medium of the hyperlocal system shows small impacts in the climate change category but brings significant burdens on agricultural land and water depletion, as seen in table 1. The processes related to the production and use of the growth medium are the production of peat, coconut coir, electricity for plant pod production, seeds, fertilizers, domestic biowaste treatment and home composting. Transportation is left out here as these steps were touched upon before.

A kilogram on lettuce consumed at home results with 0.23 kg of CO_2 Eq or from the used growth medium. That is 2.43% of the total climate change impacts in the hyperlocal system. Growth medium causes 0.21 m^2a of agricultural land depletion or 20.17% of the total in the hyperlocal system. Majority of this comes from coconut coir production. This shows that both reduction of the volume of coconut coir in the growth medium and careful selection of the coir's provider could reduce the impacts significantly. An important factor to consider is that coir itself yields smaller impacts than peat, the other material in the growth medium. So, a decrease of coir at the expense of increasing the volume of peat would not be advisable. Previous studies have also demonstrated that increasing peat in the composition of growing medium increases impacts (Martin and Molin, 2019) and using by-products like coconut coir in growth mediums is the most sustainable option (Barret *et al,* 2016).

The growth medium causes 9.73E-05 m^3 or 94.75% of total water depletion impacts in the hyperlocal system. The majority of it comes from lettuce seed production. These results can of course vary significantly depending on the water-efficiency of the seed producer. In the current study, a lettuce seed production process studied in 2019 in France from the Agribalyse 2.0 database was used in the model. The seed producer used the open field farming method where 1742.5 m^3 of water was consumed to produce 55 kilograms of lettuce seeds. Sensitivity to specific production sites or farming techniques aside, this demonstrates that even when the production of the growth medium itself is water-efficient, and growing with the hyperlocal device at home also consumes little water, an upstream process that's controlled by third parties could result in high water depletion impacts. The same seeds were modeled for the conventional production system and a similarly high share of 45.11% of water depletion impacts, or 8.29E-05 m^3, as seen in table 2, came from their use.

4.2 The importance of food waste and nutritional value degradation

Life cycle assessment of the whole production, distribution, consumption and end of life processes of hyperlocal and conventional methods have so far in this study given great insight into hotspots with highest impacts and places with greatest improvement potential. Further insight can be gained about the performance of both of these methods when real life usage scenarios are observed that account for food waste along the conventional supply chain and put the impacts of the systems into the perspective of providing nutrition to the consumer.

Figures 2, 3 and 4 show that when food waste and nutritional value degradation along the supply chain of conventional lettuce is added to the model, the impacts in all three observed categories change considerably. The third hypothesis stated that when factoring in physical food loss, the impacts between both systems level out and when nutritional value degradation is added, the hyperlocal method becomes less impactful compared to conventional. The hypothesis can be deemed true when considering that the hyperlocal system already had a lower water depletion impact before factoring in waste and nutritional value.

Climate change impacts show significantly higher results for the hyperlocal system when no food waste or nutritional value is modelled, as seen on figure 2. When food waste is added, the impacts from both the packaged and not packaged conventional lettuce still remain smaller, but by a narrow margin, 8.09 kg and 8.04 kg CO_2 Eq compared to 9.35 kg CO_2 Eq of hyperlocal. Modelling with nutritional value shows that hyperlocal lettuce can provide the same nutritional value to the consumer with 35.78% lower climate change impacts than the conventional lettuce in a sealed plastic package and with 61.22% lower impacts than conventional lettuce without packaging.

Agricultural land occupation results on figure 3 also show higher impacts for the hyperlocal system when no food waste and nutritional value is considered. When food waste is taken into account, the impacts from conventional lettuce without packaging rise to 1.05 m^2a over the 1.04 m^2a of hyperlocal, with packaged lettuce still having a smaller 0.99 m^2a impact. Going further, hyperlocal lettuce can provide the same nutritional value to the consumer with 41.57% lower agricultural land occupation rate than the conventional packaged lettuce and 66.88% lower impacts than the conventional lettuce without packaging.

Water depletion impacts, as seen on figure 4, were 44.44% smaller for the hyperlocal lettuce already in the kilogram versus kilogram production model. This was mostly due to the added cold storage necessity during transportation, retail, and consumer steps along the conventional supply chain. As highlighted in the previous chapter under transportation impacts, it is important to keep in mind that the water depletion impact category in the LCA impact assessment method does not correlate directly with water use. Processes that use up a lot of water in one place but move the consumption of the product to a further region yield higher impacts.

The most water-heavy process, the production of the lettuce seeds was modelled equally in both conventional and hyperlocal systems. Because the conventional greenhouse production was advanced and had a very water-efficient irrigation system, its water use was even lower than what users of the hyperlocal system consume when filling their devices with tap water. This can be explained by the higher evapotranspiration rate of plants in home environments compared to controlled environment greenhouses, where humidity is higher and vapor can be collected for reuse. Therefore, it would be beneficial to further study not only open field lettuce production, as stated in the previous chapter, but also a less advanced and not so resource efficient greenhouse production to have a better comparison of possible farming systems.

When food waste is taken into account in the water depletion category, the impacts from conventional lettuce without packaging rise to 65.52% compared with the hyperlocal, while lettuce without packaging has a 61.54% difference. To provide the same nutritional value to the consumer, hyperlocal method results with 80.39% water depletion difference from the packaged lettuce and 87.18% from the lettuce without packaging.

The results of conventional lettuce over the three impact categories suggest what Williams and Wikström (2011) and Heller *et al* (2018) have brought out - packaging produce with plastics is not necessarily bad in many impact categories as it keeps the food fresh and intact, leading to lower waste rates. When considering the environmental impacts of providing a certain amount of nutrients to the consumer, the packaged conventional lettuce clearly has a lead in efficiency over the one without packaging. But they still come short of the lettuce grown at home as homegrown lettuce can be consumed right after harvest, meaning that all of the environmental impacts its growing has caused are put into full use. Of course, it is possible that people harvest their produce at home and consume it later, meaning that the nutritional value of hyperlocal lettuce degrades as well. To strengthen the results and eliminate this uncertainty, a study on harvesting and consumption behavior of the users of hyperlocal growing solutions should be done.

As described in the material and methods section before, the hyperlocal method was not modified for food waste and nutrition calculations as the nutritional value of its lettuce was taken as the point of comparison and no food waste was considered to come from the method. Only biowaste from the used up plant pods by the consumer was taken into account and this was already accounted for in the base model. The 50% and 60% waste rates for packaged and not packaged conventional lettuce were modelled according to previous studies on lettuce waste along the whole supply chain (Heller *et al*, 2019; Mattsson *et al*, 2018; Blake 2015; Strid and Eriksson 2014; De Laurentiis *et al*, 2018). There are some uncertainties for using these data.

Food waste studies typically warn that accounting for food waste rates throughout the whole supply chain does not yield exact results as the rates are highly dependent on the specific producer's practices and used technology, methods of distribution, retailer's policy regarding the age and looks of produce in store and their ability to calculate demand. At the consumer level the data can be even more skewed as the waste rates are estimated based on volumes of produced and sold food compared to treated biowaste or calculated using data from waste diary keeping, interviews and questionnaires at consumer level. Thus, the 50% and 60% waste rates in this study that were used to model and reflect real world situation cannot be considered as directly measured and average results of whole Europe, but as best estimates based on previous studies.

Similar shortcomings can be brought out for the nutritional values. The used multipliers 1.8 and 3.0 were taken from previous lab tests that only considered one aspect, antioxidative activity measured through the quantity of ascorbic acid in three differently grown and sold lettuces. Why one lettuce contained more nutrients than the other from the grocery, was it due to how the lettuce was grown or did their nutrient content degrade during the supply chain, why did it happen and at what point did it happen, remains unknown. Previous studies have shown the lower nutritional values can be caused by insufficient nutrient management at production, rough handling that damages the structure of the plant during the whole supply chain, long transportation distances, shortcomings in storage and produce staying in undesirably high temperatures (FAO, 2020). Further studies should thus focus on measuring the nutrient content at different stages of the conventional supply chain to find this out. It would also be very insightful to assess more than one indicator to find out how the different nutrient levels vary between hyperlocal and conventional lettuce.

SUMMARY

The study compared the life cycle impacts of hyperlocally and conventionally produced and consumed lettuce with the aim of finding out the environmental impacts and to pinpoint the most critical processes to improve. To the knowledge of the author, it was the first LCA done to analyse a hyperlocal food growing device and to compare the results with conventionally produced and consumed lettuce. It also utilized an approach of modelling food waste and subsequent higher production needs. The addition of finding out the environmental impacts of providing the same amount of nutrients with different food systems, not just by the mass of food, proved to be an insightful method and should be further utilised among food LCAs.

The environmentally critical aspects of growing food were first highlighted in the literature overview. The LCA was conducted using secondary LCI data which was modelled with OpenLCA software and results were compared in climate change, agricultural land occupation and water depletion categories. Three research questions were answered along with three hypotheses. The modelling considered Europe and European averages were taken as input data.

The first research question was set to find out the life cycle impacts of hyperlocal lettuce production. And the accompanying hypothesis proposed that over 90% of the life cycle impacts of hyperlocal lettuce come from the electricity use of LED grow lights. This hypothesis was proven true only in climate change impact category where it was responsible for 94.34% of the CO_2 emissions, but not in the agricultural land occupation category where it was responsible for 75.58% of land use, with the majority of the rest being the result of coconut coir production for growth medium. In the water depletion category only 0.30% of impacts came from electricity consumption. As an interesting and somewhat surprising find, the majority of it came from an upstream input process, lettuce seed production instead.

The second research question compared the life cycle impacts of hyperlocal and conventional lettuce. The accompanying hypothesis proposed that conventional lettuce has lower impacts in all impact categories compared to hyperlocal. The hypothesis was proven true in climate change and agricultural land use categories but not in water depletion category. While the additional processes making up the conventional system which are not in the hyperlocal system such as retail step, consumer transportation and produce refrigeration did not add up to make conventional system more impacting in climate change and land use, they did so in the water depletion category. A notable difference in the impacts of different processes between two systems came from the raw materials used for growth medium production in the hyperlocal system, mainly from coconut husk, that causes agricultural land use. The conventional system doesn’t have a comparable process for this and the importance of choosing sustainable providers for growth medium was suggested. An important finding for both systems was that the specific energy production mix plays an important role in the total life cycle impacts of both systems, especially the hyperlocal. When more sustainable sources are used, their impacts could become drastically lower.

The third research question compared conventional and hyperlocal methods with the added assumptions that conventional system causes 50% food waste rate with packaged lettuce and 60% food waste rate with non-packaged lettuce and that the first has 1.8 times lower and the second a 3.0 times lower nutritional value than hyperlocal lettuce. The accompanying hypothesis stated that when food waste rates are added, the impacts of both methods become levelled and when nutritional value is added then the hyperlocal system has lower impacts. The impacts did become similar with food waste accounted for. The results also showed hyperlocal lettuce is significantly more efficient than conventional lettuce at utilising the environmental resources it uses up and the impacts it causes to provide nutritional value.

Further studies should be conducted that would consider lettuce grown on open fields as research suggests open field production has lower environmental impacts in many categories compared to greenhouse production that was studied here. Also, further studies need to be conducted that would compare nutritional value of differently produced and distributed lettuces using more nutritional value indicators as the current study only applied antioxidative activity measured in ascorbic acid content. An important part of looking at the total life cycle of hyperlocal devices would be the modelling of the materials used to make the device and modelling different lengths of people using the devices at home. The current study only looked at the resources needed to operate and continuously grow with these devices and their use was considered as indefinite. The hyperlocal method also needs further modelling with different real life scenarios regarding last mile transportation.

KOKKUVÕTE

Töö eesmärk oli uurida hüperlokaalse ja traditsioonilise lehtsalati kasvatamise ja tarbimise olelusringi, leida suurimat mõju omavad aspektid neis ning pakkuda lahendusi mõjude leevendamiseks. Töös uuriti lisaks olelusringi moodustavate erinevate protsesside mõjudele ka seda, kuidas toidu raiskamise ja toitaine väärtuse kao arvestamine keskkonnamõjusid muudab. Selline lähenemine osutus kasulikuks, viidates nende aspektide olulisusele sarnaste uuringute tegemisel. Lisaks lihtsalt toidu keskkonnamõjude arvutamisele toodetud või tarbitud toidu massi järgi peaksid sarnased uuringud keskenduma ka toidu kaost tekkivale suurenenud tootmise vajadusele ning vaatlema toitu kui toitainete, mitte lihtsalt toidu massi pakkujat.

Olelusringi hindamine viidi läbi sekundaarandmete põhjal. Selleks loodi olemasolevate andmebaaside põhjal OpenLCA tarkvara abil mudelid. Keskkonnamõjusid näidati kolmes kategoorias: kliima muutuse põhjustamise potentsiaal, põllumajandusmaa kasutus ja magevee ammendumine. Töös käsitleti regioonina Euroopat ja kasutati Euroopa keskmisi andmeid.

Esimese uurimisküsimuse raames uuriti hüperlokaalse lehtsalati olelusringi mõjusid. Seda puudutanud hüpotees ütles, et üle 90% keskkonnamõjudest tuleneb seadme hüperlokaalse kasvatusseadme kasvulampide elektrienergia vajadusest. Hüpotees vastas tõele vaid kliimamuutuste kategoorias, kus see põhjustas 94.34% mõjudest. Põllumajandusmaa kasutuse puhul oli see 75.58% ning suurem osa ülejäänud maast hõivas kasvusubstraadis kasutatava kookose koore tootmine, viidates antud toormaterjali tootja valimise olulisele. Vee ammendumise mõistes tarbis elektri tootmine vaid 0.3%. Suurem osa vee ammendumisest tuli aga üsna üllatuslikult seemnete tootmisest, mis on tootjast kaugemal olev, kuid nähtavasti terve toote olelusringi lõikes oluline protsess.

Teine uurimisküsimus võrdles mõlema meetodi olelusringi mõjusid. Hüpoteesiks oli, et traditsioonilise tootmise puhul on mõjud igas kategoorias väiksemad kui hüperlokaalsel meetodil. Antud hüpotees ei vastanud tõele vee ammendumise kategoorias, kuid näitas olulisi erinevusi ülejäänud kahes. Kuigi traditsioonilise meetodi puhul on mitmeid protsesse, mida hüperlokaalse puhul ei ole, näiteks tarbijate poes käimine, poes ning kodus külmiku töötamine, siis need lisa tegevused suuri erinevusi teistes kategooriates peale vee ammendumise juurde ei toonud. Märgatav erinevus oli hüperlokaalse meetodi puhul kasutatava kasvusubstraadi materjali vajadus, mis mängis olulist rolli eriti põllumajandusmaa hõivasime poolest. Mõlema tootmise keskkonnasäästlikumaks muutmise puhul on oluline energia tootmise viis, eriti hüperlokaalse puhul, kus elektri mõjud on kliimamuutuste kategoorias suured.

Kolmas uurimisküsimus võrdles mõlemat meetodit, lisades juurde 50% toidu raiskamise määra pakendatud traditsioonilisele lehtsalatile ning 60% pakendamata variandile ning arvestades neist esimese puhul 1.8 korda väiksemat ja teise puhul 3.0 korda väiksemat toitaine sisaldust kui hüperlokaalse lehtsalati puhul. Hüpoteesis sõnastati, et toidukao arvestamisega muutuvad keskkonnamõjud võrdseks ning toitaine väärtust arvestades on hüperlokaalsel märgatavalt väiksem mõju. Toidukadu arvestades muutusid mõjud võrdsemaks ning toitaine väärtuste arvestamisel tuli selgelt välja hüperlokaalse meetodi edu pakkuda inimestele sama keskkonnamõju tekitamise lõikes suuremat toitaine sisaldust võrreldes traditsioonilisega.

Edaspidised uuringud peaksid võtma võrdlusesse ka avamaa lehtsalati kasvatuse, mille keskkonnamõjud on uuringute järgi paljudes mõju kategooriates märgatavalt väiksemad kui kasvuhoone kasvatusel. Samuti peab põhjalikult uurima erinevate toitainete taset lehtsalatites, kuna antud uuringus käsitleti vaid antioksüdatiivset aktiivsust askorbiinhappe taseme kaudu. Samuti peaks mudeldama hüperlokaalse kasvatusseadet ennast ning võrdlema mõjusid erinevate seadme kasutusigade kontekstis. Antud uuring vaatles vaid igapäevaseks taimekasvatuseks vajalike ressursside kasutust. Samuti peaks hüperlokaalse mudeli tugevamiseks uurida taimede ja nende kasvatamise seadmete nn viimase miili transporti.

REFERENCES

Aktar, W., Sengupta, D., & Chowdhury, A. (2009). Impact of pesticides use in agriculture: their benefits and hazards. Interdisciplinary Toxicology, 2(1), 1-12.

Association for Vertical Farming (2016). Urban Agriculture Integration Typology. Retrieved 14. April 2021, from: https://vertical-farming.net/vertical-farming/integration-typology/

Barbosa, G., Gadelha, F., Kublik, N., Proctor, A., Reichelm, L., & Weissinger, E. et al. (2015). Comparison of Land, Water, and Energy Requirements of Lettuce Grown Using Hydroponic vs. Conventional Agricultural Methods. International Journal Of Environmental Research And Public Health, 12(6), 6879-6891.

Barrett, G., Alexander, P., Robinson, J., & Bragg, N. (2016). Achieving environmentally sustainable growing media for soilless plant cultivation systems – A review. Scientia Horticulturae, 212, 220-234.

Beausang, C., Hall, C., & Toma, L. (2017). Food waste and losses in primary production: Qualitative insights from horticulture. Resources, Conservation And Recycling, 126, 177-185.

Benke, K., & Tomkins, B. (2017). Future food-production systems: vertical farming and controlled-environment agriculture. Sustainability: Science, Practice And Policy, 13(1), 13-26.

Blanke, M. (2015). Challenges of Reducing Fresh Produce Waste in Europe—From Farm to Fork. Agriculture, 5(3), 389-399.

Block, L., Keller, P., Vallen, B., Williamson, S., Birau, M., & Grinstein, A. et al. (2016). The Squander Sequence: Understanding Food Waste at Each Stage of the Consumer Decision-Making Process. Journal Of Public Policy & Marketing, 35(2), 292-304.

Brechner, M., Both, A.,J. (2013). Hydroponic Lettuce Handbook. Cornell University.

Cellura, M., Longo, S., & Mistretta, M. (2012). Life Cycle Assessment (LCA) of protected crops: an Italian case study. Journal Of Cleaner Production, 28, 56-62.

Cordell, D., Drangert, J., & White, S. (2009). The story of phosphorus: Global food security and food for thought. Global Environmental Change, 19(2), 292-305.

Cruz, R., Gomes, T., Ferreira, A., Mendes, E., Baptista, P., & Cunha, S. et al. (2014). Antioxidant activity and bioactive compounds of lettuce improved by espresso coffee residues. Food Chemistry, 145, 95-101.

Chance, E., Ashton, W., Pereira, J., Mulrow, J., Norberto, J., Derrible, S., & Guilbert, S. (2017). The Plant-An experiment in urban food sustainability. Environmental Progress & Sustainable Energy, 37(1), 82-90.

Committee on World Food Security (2012). Coming to terms with terminology. Retrieved 5 May 2021 from: http://www.fao.org/3/MD776E/MD776E.pdf

Curran, M., A. (2015). *Life cycle assessment student handbook*. Wiley.

Del Borghi, A., Gallo, M., Strazza, C., & Del Borghi, M. (2014). An evaluation of environmental sustainability in the food industry through Life Cycle Assessment: the case study of tomato products supply chain. Journal Of Cleaner Production, 78, 121-130.

De Chabert-Rios, J., & Deale, C. (2016). Taking the local food movelment one step further: An exploratory case study of hyper-local restaurants. Tourism And Hospitality Research, 18(3), 388-399.

De Laurentiis, V., Corrado, S., & Sala, S. (2018). Quantifying household waste of fresh fruit and vegetables in the EU. Waste Management, 77, 238-251.

de Vrese, P., Stacke, T., & Hagemann, S. (2018). Exploring the biogeophysical limits of global food production under different climate change scenarios. Earth System Dynamics, 9(2), 393-412.

EISA (2012). European Integrated Farming Framework. Retrieved 10. May 2021 from: http://www.sustainable-agriculture.org/wp-content/uploads/2012/08/EISA_Framework_english_new_wheel_170212.pdf

Elshout, P., van Zelm, R., Karuppiah, R., Laurenzi, I., & Huijbregts, M. (2014). A spatially explicit data-driven approach to assess the effect of agricultural land occupation on species groups. The International Journal Of Life Cycle Assessment, 19(4), 758-769.

Eunomia (2009). Assessment of the options to improve bio-waste in the European Union. Retrieved 24. April 2021 from: https://ec.europa.eu/environment/pdf/waste/compost/ia_biowaste%20-%20final%20report.pdf

European bioplastics (2015). Home Composting. Retrieved 20. April 2021 from: https://docs.european-bioplastics.org/publications/bp/EUBP_BP_Home_composting.pdf

European Commission (2010). International Reference Life Cycle Data System (ILCD) Handbook. Retrieved 9. April 2021 from: https://eplca.jrc.ec.europa.eu/uploads/ILCD-Handbook-General-guide-for-LCA-DETAILED-GUIDANCE-12March2010-ISBN-fin-v1.0-EN.pdf

Eurostat (2020). Electricity production, consumption and market overview. Retrieved 20. Arpil 2021 from: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_production,_consumption_and_market_overview

Eurostat. (2021). Recycling rate of packaging waste by type of packaging. Retrieved 9. May 2021, from: https://ec.europa.eu/eurostat/databrowser/view/cei_wm020/default/table?lang=en

Evans, R., & Sadler, E. (2008). Methods and technologies to improve efficiency of water use. Water Resources Research, 44(7).

FAO (2008) An Introduction to the Basic Concepts of Food Security. Retrieved 6. May 2021 from: http://www.fao.org/3/al936e/al936e.pdf

FAO (2015). Food wastage footprint & climate change. Retrieved 10. April 2021 from: http://www.fao.org/documents/card/en/c/7338e109-45e8-42da-92f3-ceb8d92002b0/

FAO (2017). Save food for a better climate. Retrieved 19. April 2021 from: http://www.fao.org/3/i8000e/i8000e.pdf

FAO (2020). The state of food security in the world 2020. Retrieved 18. April 2021 from: http://www.fao.org/3/ca9692en/online/ca9692en.html#chapter-1_1

Favino, E., Giavini, M., Agricultural School of Monza Park (2020). Bio-waste generation in the EU: Current capture levels and future potential. Retrieved 10. May 2021 from: https://biconsortium.eu/sites/biconsortium.eu/files/documents/BIC-ZWE%20report%20-%20Bio-waste%20generation%20in%20the%20EU%20-%20current%20capture%20and%20future%20potential.pdf

Foley, J., Ramankutty, N., Brauman, K., Cassidy, E., Gerber, J., & Johnston, M. et al. (2011). Solutions for a cultivated planet. Nature, 478(7369), 337-342.

Garnett, T. (2014). Three perspectives on sustainable food security: efficiency, demand restraint, food system transformation. What role for life cycle assessment? Journal Of Cleaner Production, 73, 10-18.

Gleick, P. (2003). Global Freshwater Resources: Soft-Path Solutions for the 21st Century. Science, 302(5650), 1524-1528.

Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A., Struijs, J., Zelm, R. (2008). ReCiPE 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level.

Gustavsson, J., Cederberg, C., Sonesson, U., van Otterdijk, R., Meybeck, A. (2011). Global Food Losses and Food Waste.

Heller, M., Selke, S., & Keoleian, G. (2018). Mapping the Influence of Food Waste in Food Packaging Environmental Performance Assessments. Journal Of Industrial Ecology, 23(2), 480-495.

Huijbregts, M., Steinmann, Z., Elshout, P., Stam, G., Verones, F., & Vieira, M. et al. (2016). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. The International Journal Of Life Cycle Assessment, 22(2), 138-147.

Juraske, R., Mutel, C., Stoessel, F., & Hellweg, S. (2009). Life cycle human toxicity assessment of pesticides: Comparing fruit and vegetable diets in Switzerland and the United States. Chemosphere, 77(7), 939-945.

Kulak, M., Graves, A., & Chatterton, J. (2013). Reducing greenhouse gas emissions with urban agriculture: A Life Cycle Assessment perspective. Landscape And Urban Planning, 111, 68-78.

Kummu, M., de Moel, H., Porkka, M., Siebert, S., Varis, O., & Ward, P. (2012). Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. Science Of The Total Environment, 438, 477-489.

Le Campion, A., Oury, F., Heumez, E., & Rolland, B. (2019). Conventional versus organic farming systems: dissecting comparisons to improve cereal organic breeding strategies. Organic Agriculture, 10(1), 63-74.

Lipiński, B., Hanson, C., Lomax, J., Kitinoja, L., Waite, R. & Searchinger, T. (2013). Reducing Food Loss and WasteRetrieved 10. May 2021 from: https://pdf.wri.org/reducing_food_loss_and_waste.pdf

MacDonald, G., Bennett, E., Potter, P., & Ramankutty, N. (2011). Agronomic phosphorus imbalances across the world's croplands. Proceedings Of The National Academy Of Sciences, 108(7), 3086-3091.

Margni, M., Rossier, D., Crettaz, P., & Jolliet, O. (2002). Life cycle impact assessment of pesticides on human health and ecosystems. Agriculture, Ecosystems & Environment, 93(1-3), 379-392.

Martin, M., & Molin, E. (2019). Environmental Assessment of an Urban Vertical Hydroponic Farming System in Sweden. Sustainability, 11(15), 4124.

Mattsson, L., Williams, H., & Berghel, J. (2018). Waste of fresh fruit and vegetables at retailers in Sweden – Measuring and calculation of mass, economic cost and climate impact. Resources, Conservation And Recycling, 130, 118-126.

Mayer, A. (2019). Making Agriculture Part of the Climate Change Solution. Bioscience, 69(10), 771-777.

McWilliams, J. (2009). Just Food. Little Brown and Company.

Mok, H., Williamson, V., Grove, J., Burry, K., Barker, S., & Hamilton, A. (2013). Strawberry fields forever? Urban agriculture in developed countries: a review. Agronomy For Sustainable Development, 34(1), 21-43.

Nordborg, M., Davis, J., Cederberg, C., & Woodhouse, A. (2017). Freshwater ecotoxicity impacts from pesticide use in animal and vegetable foods produced in Sweden. Science Of The Total Environment, 581-582, 448-459.

Plazzotta, S., Manzocco, L., & Nicoli, M. (2017). Fruit and vegetable waste management and the challenge of fresh-cut salad. Trends In Food Science & Technology, 63, 51-59.

Rama, I., & Lawrence, P. (2008). Food Miles – A Critical Evaluation.

Ramankutty, N., Evan, A., Monfreda, C., & Foley, J. (2008). Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. Global Biogeochemical Cycles, 22(1).

Ritchie, H., Roser, M. (2017). Micronutrient Deficiency. Retrieved 28. April 2021 from: https://ourworldindata.org/micronutrient-deficiency

Romeo, D., Vea, E., & Thomsen, M. (2018). Environmental Impacts of Urban Hydroponics in Europe: A Case Study in Lyon. Procedia CIRP, 69, 540-545.

Roy, P., Nei, D., Orikasa, T., Xu, Q., Okadome, H., Nakamura, N., & Shiina, T. (2009). A review of life cycle assessment (LCA) on some food products. Journal Of Food Engineering, 90(1), 1-10.

Sanjuan-Delmás, D., Llorach-Massana, P., Nadal, A., Ercilla-Montserrat, M., Muñoz, P., & Montero, J. et al. (2018). Environmental assessment of an integrated rooftop greenhouse for food production in cities. Journal Of Cleaner Production, 177, 326-337.

Sim, S., Barry, M., Clift, R., & Cowell, S. (2006). The relative importance of transport in determining an appropriate sustainability strategy for food sourcing. The International Journal Of Life Cycle Assessment, 12(6), 422-431.

Sokolow, J., Kennedy, G., & Attwood, S. (2019). Managing Crop tradeoffs: A methodology for comparing the water footprint and nutrient density of crops for food system sustainability. Journal Of Cleaner Production, 225, 913-927.

Specht, K., Siebert, R., Hartmann, I., Freisinger, U., Sawicka, M., & Werner, A. et al. (2013). Urban agriculture of the future: an overview of sustainability aspects of food production in and on buildings. Agriculture And Human Values, 31(1), 33-51.

Statista (2021). Projected vertical farming market worldwide in 2019 and 2025. Retrieved 23. April 2021, from:
https://www.statista.com/statistics/487666/projection-vertical-farming-market-worldwide/

Stoessel, F., Juraske, R., Pfister, S., & Hellweg, S. (2012). Life Cycle Inventory and Carbon and Water FoodPrint of Fruits and Vegetables: Application to a Swiss Retailer. Environmental Science & Technology, 46(6), 3253-3262.

Strid, I., Eriksson, M. (2014). Losses in the supply chain of Swedish lettuce – wasted amounts and their carbon footprint at primary production, wholesale and retail.

Tasca, A., Nessi, S., & Rigamonti, L. (2017). Environmental sustainability of agri-food supply chains: An LCA comparison between two alternative forms of production and distribution of endive in northern Italy. Journal Of Cleaner Production, 140, 725-741.

The Global Burden of Disease Obesity Collaborators (2017). Health Effects of Overweight and Obesity in 195 Countries over 25 Years. The New England Journal of Medicine. 377(1), 13-27.

Stenmarck, Å., Jensen, C., Quested, T., Moates, G. (2016). Estimates of European Food Waste Levels.

Tukker, A., & Jansen, B. (2006). Environmental Impacts of Products: A Detailed Review of Studies. Journal Of Industrial Ecology, 10(3), 159-182.

United Nations (2015). World Urbanization Prospects: The 2014 Revision.

Williams, H., & Wikström, F. (2011). Environmental impact of packaging and food losses in a life cycle perspective: a comparative analysis of five food items. Journal Of Cleaner Production, 19(1), 43-48.

WHO (2003). Regional per Capita Consumption of Raw and Semi-Processed Agricultural Commodities. Retrieved 10. April 2021 from: https://apps.who.int/iris/bitstream/handle/10665/42833/9241591080_eng.pdf?sequence=1&isAllowed=y

WHO (2020). Obesity and overweight fact sheet. Retrieved 12. May 2021 from: https://www.who.int/news-room/fact-sheets/detail/obesity-and-overweight

WRI (2019). Creating a sustainable food future. Retrieved 28. April 2021 from: https://research.wri.org/wrr-food

Zarei, M., Kazemi, N., & Marzban, A. (2019). Life cycle environmental impacts of cucumber and tomato production in open-field and greenhouse. Journal Of The Saudi Society Of Agricultural Sciences, 18(3), 249-255.