Vertical Farming: A Viable Strategy for Sustainable Agriculture

By

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ABSTRACT

Although vertical farming requires further research regarding the potential effects on employment and food security in rural, agriculturally based communities, it can be a sustainable, technology-rich approach that can mitigate adverse environmental impacts caused by the agriculture industry while providing secure food options for a growing urban population. Food products are grown in an indoor, vertical stacking system independent of climate and weather patterns. It is sustainable because it uses significantly less land and water than open-field farms, and it does not require pesticides or herbicides. Vertical farming is an innovative system that uses technology to control factors such as light, temperature, CO_2 concentration, and nutrients to produce higher yields and nutritious, fresh products. Because of these factors, there is a substantially reduced risk of losing crops due to climate change, no soil erosion or surface run-off, and the distance for transporting products to consumers may be less. Thus, the agriculture industry can implement vertical farming to shift food production to become more sustainable for the environment and protect the biodiversity of our ecosystems. This thesis analyzes several critical dimensions of the vertical farming system, including the production, technology, opportunities, implementation into urban economies, and the factors requiring improvement or further research. The thesis also compares vertical farming to traditional open-field farming practices.

Key words: Vertical farming, agriculture, environment, sustainability, consumers

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LIST OF ABBREVIATIONS AND ACRONYMS

Acronym	Definition
CEA	Controlled Environment Agriculture
FAO	Food and Agriculture Organization of the United Nations
HID	High-Intensity Discharge
LED	Light-Emitting Diode
VF	Vertical Farming

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INTRODUCTION

The relationship between humans and the environment is shown by the food produced and consumed. Dearden and Mitchell (2016) state over one-third of the planet's land is used for agriculture, and demand increases along with the population. It will be a challenge to meet these demands without harming the environment. The global population is estimated to grow to approximately 9 billion over the next 30 years, and about 70-80% of those people will live in urban areas (Bricas, 2013; Despommier, n.d.; Gentry, 2019; Kozai et al., 2020). With this population growth, more cropland is required. The amount of cropland needed is estimated to be the size of India (Kamalkumaran et al., 2020). There is a growing concern for future food security, and population pressure creates an even higher demand for food products. Extreme weather events and pests cause crop losses on outdoor farms, making global yields uncertain, and in return, international and local food security is threatened (Despommier, 2009).

Urban regions rely heavily on agricultural production in developing countries because climates become less suitable for some products (Dearden and Mitchell, 2016). However, because developed nations have high demands for fruits and vegetables year-round, products need to travel long distances to get to consumers. When fresh produce travels far, an average of 2400km (Gentry, 2019; Naus, 2018), it loses nutrients and quality while contributing to significant fossil fuel emissions in the process (Gentry, 2019). Fresh fruits and vegetables lose approximately 30% of nutrients within the first three days of export (Gentry, 2019). Unfortunately, food security in urban regions relies on fossil fuels and oil and gas transportation and production (Bricas, 2013).

The agricultural industry is responsible for roughly 30% of global greenhouse gas emissions because of the heavy machinery, packaging, cooling, and transportation required for production (Gentry, 2019; World Bank, 2007), and globalization of agriculture has caused problems regarding the accessibility to affordable and nutritious foods. As a result, access to food is unequal, and many people suffer from famine daily (Dearden and Mitchell, 2016). In addition, more than 2 billion people in developing and developed countries suffer from insufficient micronutrients in their diets because of the over-availability of high calorie, high fat, and high carbohydrate convenience foods (Pinstrup-Andersen, 2018). The impacts of nutrients deficiencies can be detrimental or even fatal. For example, a Vitamin B deficiency can cause chronic diseases, hair loss, tooth decay, and bow-leggedness, while those with a Vitamin A deficiency risk being affected by immune-system complications (Dearden and Mitchell, 2016).

Despite these challenges, it is time to focus on shifting the development of the agriculture industry to more sustainable production systems to mitigate and adapt to climate change. Some industry experts believe that increasing production with more intensive practices and the use of genetic modification, fertilizers, and pesticides is desirable (Despommier, 2009). With rapid advancements in technology, farmers see the benefits of year-round indoor growing (Wong et al., 2020). Ultimately slowing down the agriculture industry would not be beneficial; however, to protect the environment and become more sustainable, a need exists to find new and innovative systems to integrate into the industry. One option is urban agriculture, and Jürkenbeck et al. (2019) define the concept as:

> An industry located within (intra-urban) or on the fringe (peri-urban) of a town, city, or metropolis, which grows or raises, processes, and distributes a diversity of food and non-food products, (re) using largely human and material resources, products and services largely to that urban area. (p.1)

There are varying types of urban agriculture practices ranging from private greenhouse gardens to indoor, controlled production systems that use artificial lighting and soilless systems (Montero et al., 2017). There is also a need to transform the economy into a circular economy that consumes fewer resources and uses them efficiently (Nadal et al., 2018). Dearden and Mitchell (2016) note different approaches, such as:

> Exploration of new marine and terrestrial food sources; continued research to increase yields of existing crops; improvements in the efficiency of natural resource use; family planning programs aimed at reducing population growth rates; elimination of global agricultural tariffs; more efficient food distribution systems to address chronic hunger; and a moderation in demand on the part of the already overfed countries. (p. 330)

Vertical farming is an emerging urban agricultural system that may be more sustainable compared to traditional farming methods. Three types of vertical farms could be implemented into our global food system: in-home farms; in-store farms (i.e., grocery stores); and stand-alone farms that use existing buildings or little land space (Jürkenbeck et al., 2019). These farms operate independently in controlled environments that use significantly fewer resources than traditional farming methods, making it a sustainable choice (Despommier, 2009; Jürkenbeck et al., 2019).

METHODOLOGY

The thesis uses secondary academic sources to inform this research. Reviewing pre-existing literature provides valuable facts, information, and data on vertical farming and brings previous research to light while highlighting areas that may need more consideration. Many of the articles reviewed discuss similar factors of vertical farming, so this thesis attempts to fill gaps in the literature available to date. To demonstrate how vertical farming works, it is structured into eight parts. In part I, a review of traditional agricultural practices is provided to illustrate the impacts of the industry and to show how the world has shifted over the decades to globalized, mass-produced agriculture. Globalized agriculture includes the Green Revolution, intensification, human health, and environmental impacts. Part II will cover the risks and consequences climate change has on agriculture to reveal the need for improved urban production practices that adapt to changing climates and weather patterns. A deeper explanation of vertical farming is provided in part III, regarding the use of resources, land, and existing buildings, waste and emissions, environmental reclamation. Part IV discusses the different production methods involved with vertical farms: hydroponics, aeroponics, aquaponics, and their benefits. Part V describes technologies associated with operating the system, and how these technologies aid in the environmental control factors needed for plant growth. Part VI will demonstrate the potential acceptance and perceived benefits of vertical farming from consumers and the economy. Part VII covers how vertical farms can successfully implement vertical farming into society, and the opportunity to alleviate poverty in both developing and developed regions. Lastly, the thesis provides an overall synthesis to support the claim that vertical farming holds many promises.

PART I: REVIEW OF TRADITIONAL AGRICULTURE PRACTICES

History of the Globalized Food System

Around 9,000 - 11,000 years ago, some regions had begun to domesticate wild animals and different species of plants, giving farmers control over seed size, concentration, and fleshiness of the plants, seed dispersal, and taste (Dearden and Mitchell, 2016). Domestication led to different and improved agricultural practices, such as irrigation and animal feed, which aided in the intensification of food production and increased food availability for growing populations (Dearden and Mitchell, 2016). It was during the 1950s when the global population began to spike. Some countries experienced higher rates of growth that accelerated in the late 1990s. China, for example, had 554 million people in 1950; they are now home to over 1.4 billion people as of 2019, a jump of over 845 million in 70 years (Roser et al., 2019). India experienced a significantly higher growth rate of over 1 billion people in that same period (Roser et al., 2019).

Land and water sources became crucial to meeting demands, and it started to become known that our resources were not as infinite as we once thought (Dearden and Mitchell, 2016). There was a need for increased food production to support growing families, and the demand for more food products triggered an increase in agricultural intensification (Pingali, 2012). The goal of intensification is to produce more outputs than resource inputs by using agrochemicals, such as pesticides and fertilizers, and heavy machinery to cultivate the land, grow products, and harvest products (Dearden, 2016; p. 328).

Exports from developing economies started to become a reliable source for food products due to the high population growth and low-cost labour costs in those regions. Crop productivity rapidly grew from increased research and development investments, infrastructure, innovative technologies, policy endorsements, and a cultural shift in food demand (Johnston and Mellor, 1961; Pingali, 2012). “Miracle seeds” were developed using natural genetic combinations; however, genetically modified organisms (GMOs) use laboratory-mediated gene combinations using unrelated species (Dearden and Mitchell, 2016).

The Green Revolution aimed to increase crop yields, locally grown products, and labor demand (Lipton, 2005) through agricultural intensification and genetic modification. As a result, higher yields are produced quickly, especially staple crops like wheat, corn, rice, and potatoes. According to Pingali (2012), during the Green Revolution, wheat yields increased by 208%, corn yields up by 157%, rice yields up by 109%, and potato yields up by 78%; and without the Green Revolution, the food supply in rural economies would be 20% less than it is now, and the price of food would increase by 35%-65%. Some believe that intensive farming is the answer to protecting food security by using genetic modification and agrochemicals. Still, it is not a long-term solution because of adverse environmental effects (Despommier, 2009). There are ramifications to these practices, including decreased agrochemical efficiency and increased weeds and pests, and in the 1980s, yields began to change due to the deterioration of natural resources (Tsatsakis et al., n.d.).

Sustainable food security is vital as our population will grow by approximately 30% over the next 30 years. A need exists to find sustainable ways to increase food production by at least 70% (Pingali, 2012) because current security relies heavily on the oil and gas industry for transporting and producing products (Bricas, 2013), and for manufacturing many inputs like fertilizers.

The Global Effects of Agriculture

Agricultural activities have a high risk of harming the biodiversity of ecosystems as well as human health. A decline in genetic diversity, changes in gene flow, air pollution, soil degradation, increased pests, and changes in habitat are some of the many impacts of the agriculture industry (Tsatsakis et al., n.d.). Concerning air quality, the food industry is partially responsible for the high levels of pollutants and greenhouse gas emissions in the atmosphere, producing approximately 10 to 12% of the world's total (Brentrup et al., 2016). Thus, the industry is harmful to the environment, but it is also incredibly damaging to human health. Waterborne illnesses in developing economies are one of the biggest concerns regarding the outcome of outdoor farming (Depsommier, 2010).

Threat to Human Health

The intensification of agriculture practices concerns many people; however, the effects are felt most by those living in developing countries. Agriculture is essential to economic growth and poverty reduction in these regions, but current practices and systems concern human health (World Bank, 2007). Agrochemicals have become increasingly popular over the years as invasive pests and plant diseases continue to adapt and change (Despommier, 2010). The use of human fecal matter as fertilizer is used every day in farming, especially in developing countries struggling with mass poverty because it is a cheaper alternative than traditional chemical fertilizers (Despommier, 2010). Nitrate and nitrite-rich fertilizers seep into the soil and into the groundwater, which eventually runs off into drinking water and other bodies of water, which can lead to extreme health risks such as cholera, typhoid fever, and parasitic infections like malaria (Despommier, 2009; 2010). Some parasitic infections such as Ascaris, hookworm, and ringworm are detrimental to a child's mental and physical health because these parasites can cause malnutrition and affect the brain negatively, such as the development of a learning deficiency (Despommier, 2010). The agriculture industry uses approximately 70% of the world's available freshwater supply, thus making it undrinkable due to agrochemical and fecal contamination (Despommier, 2009).

Threat to the Environment and Biodiversity

Although agriculture is a crucial source of economic growth, it negatively affects the environment and ecosystems within it. One of the most significant environmental concerns is pollution. The agriculture industry is responsible for producing greenhouse gas emissions throughout a product's lifecycle (Garnett, 2010). Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions occur from manufacturing activities, product transportation, refrigeration, waste disposal, and packaging (Garnett, 2010; *Greenhouse gases and agriculture*, 2020).

Nitrous oxides emitted from livestock manure and fertilizers, methane released from cattle rumination and digestion, carbon dioxide emitted from fossil fuel-driven machinery, crop residue decomposition (*Greenhouse gases and agriculture*, 2020), refrigeration, and synthetic fertilizer production are significant contributors (Garnett, 2010). According to Bricas (2013), these emissions threaten the biodiversity of ecosystems and contribute to climate change. Furthermore, in some areas, the land is deforested to make room for crops. In addition to these emissions, when land is cultivated for crops, the soil becomes degraded. As a result, it loses its nutrients, which then requires even more fertilizer to regain the lost nutrients, causing harm to ecosystems and wildlife habitats (Bricas, 2013).

One of the essential components in agriculture is synthetic fertilizers (Bekkerman et al., 2020), such as nitrogen, phosphorus, and potassium-based chemicals (Walling and Vaneeckhaute, 2020). While this may sound like a recent development for intensification, synthetic fertilizers have been around for a long time. In addition to transportation, the oil and gas industry produces synthetic fertilizers using natural gas (Zalewski, 2020). Until the twentieth century, organic animal waste was used as fertilizer, but it was not enough to keep up with demands. Thus, began research for developing synthetic fertilizers to support the rising population (Bekkerman et al., 2020). Globally, between 1970 and 2010, the use of synthetic fertilizers increased 200 to 300% and accounted for 30 to 50% of crop yields (FAO, n.d.; Stewart et al., 2005; Walling and Vaneeckhaute, 2020). Compared to organic fertilizers, synthetic fertilizers produce much higher yields (Zalewski, 2020); however, fertilizer use does come with risks. Brentrup et al. (2016) note that “the contribution of emissions released during the production of mineral fertilizers is in most studies as important as the fertilizer-induced emissions from agricultural soils.” Soil acidification, nutrient depletion, decreased organism diversity, eutrophication, human health risks, nutrient run-off, and rising greenhouse gas emissions occur due to improper synthetic fertilizer use (Horrigan et al., 2002; Walling and Vaneeckhaute, 2020). Nitrogen that seeps into the soil can negatively impact and reduce species diversity, and nitrogen that runs off into water sources results in aquatic “dead zones,” reducing marine biodiversity from oxygen depletion caused by sped-up algae cycles (Horrigan et al., 2002). In addition, plant growth is impaired by soil acidity caused by fertilizer chemicals (Horrigan et al., 2002).

According to Dearden and Mitchell (2016), early cultivation in Canada removed most of the carbon in the soil from practices such as intensive tillage, biomass burning, and residue removal. All these factors contribute to the warming of Earth. Therefore, allowing land to remain in a fallow state is considered one of the most efficient ways to mitigate climate change (Despommier, 2009). According to Despommier (2009), there is historical evidence that this theory is true; land that had previously degraded within the demilitarized zone between South and North Korea has been left untouched since 1953, resulting in a full environmental recovery.

In addition to synthetic fertilizers, the use of pesticides has rapidly grown due to monocropping and the increased resistance to these pesticides by insects. These chemicals can significantly hinder biodiversity and drive a decline in non-target species populations (Horrigan et al., 2002).

Meat Production Systems

Meat production contributes to environmental and human health impacts. One concern for human health is the use of antibiotics to promote growth in animal agriculture, and this practice is presumed to be the cause of antibiotic resistance in humans (Horrigan et al., 2002). In addition, animals are associated with most foodborne illnesses caused by poor conditions in factory farms (Horrigan et al., 2002). Regarding the impact on the environment, the soil becomes eroded from animals grazing at a faster rate than it is being restored, and because of this, nutrients are lost, and the land becomes less fertile (Horrigan et al., 2002).

PART II: EFFECTS OF CLIMATE ON AGRICULTURE

The agriculture industry depends on consumer demand and high crop yields, but the levels of productivity are also highly dependent on climate. Crop and livestock yields are directly impacted by temperature and precipitation, wind patterns, floods, and drought (Adams, 1998; Bricas, 2013). Climate and weather patterns can influence crop and livestock production, hydrological cycles, carbon cycles, and the availability of natural resources. Responding to this crisis is crucial to predicting and understanding current and future food security (Adams, 1998). In China, for example, the International Rice Research Institute has studied the fertility loss in rice crops when the temperature reaches 40 degrees Celsius leading to a significant impact on the industry (Dearden and Mitchell, 2016). Changes in yields, input prices, technology, and accessibility to natural resources frequently influence producer and consumer decisions (Adams, 1998). A failure to acknowledge and account for changes in consumption, production practices, and technology will inaccurately reflect the potential effects of climate change (Chaudhry and Mishra, 2019). These approaches are beneficial for the future of vertical farming because they can help determine the possible impacts of climate change on traditional agriculture while also providing insights into implementing urban farming practices worldwide.

Adams (1998) provides an economics approach to predict possible future outcomes using a structural method. There are numerous scenarios to adjust in these models, including:

- Changing the planting and harvest dates,
- Rotating crops,
- Changing crop types,
- Changing water consumption for irrigation,
- Increase or decrease fertilizer use, and
- Changing tillage practices

This interdisciplinary approach estimates the potential effects of climate change on crop yields by using models to simulate crop type changes and regions. Therefore, direct climate effects such as increasing CO_2, moving planting areas, changing crop types, and improving irrigation can all adjust within the model (Adams et al., 1998).

Some options for simulation are to change planting and harvesting dates, crop varieties, the use of fertilizers, the consumption of water, and the cultivation of land (Adams et al., 1998).

Positive Effects

Despite the growing concern of climate change and its effects on traditional agricultural practices, there are some benefits that climate change provides to the industry, depending on the region and current climate patterns within those regions. Firstly, carbon dioxide, for example, is a vital greenhouse gas required for efficient plant production. Therefore, an increase in CO_2 benefits plant productivity in certain areas because it increases photosynthetic rates and reduces transpiration (Adams et al., 1998). Secondly, semi-arid and dry regions that suffer from low precipitation levels, heavier rainfall, and any precipitation changes may benefit from the increased moisture in the soil, making the land suitable for crops (Adams et al., 1998). Finally, some regions will benefit from longer growing seasons; however, it creates an opportunity for more pests to attack crops (Dearden and Mitchell, 2016).

In the Canadian prairies, the agricultural sector does benefit from climate change depending on crop type, cultivation system, and location. In some regions, the trends occurring, such as earlier springs, increased precipitation, fewer cold nights, and fewer frosty mornings, have led to longer growing seasons for farmers (Qian et al., 2013).

Negative Effects

A warmer climate can change the amount and type of pests, negatively impacting crops and livestock (Dearden and Mitchell, 2016). Irrigation and water supplies are also affected by climate, and there is a risk of severe soil erosion (Adams et al., 1998; Bricas, 2013). In regions that suffer from heavy rainfall, climate change may increase the risk of flooding and damage to livestock and crops (Adams et al., 1998). In addition, many pastoral communities will face drought (Dearden and Mitchell, 2016). Researchers have concluded that the global grain supply will be impacted the most by climate change over the next century, and grains will mainly be distributed in the United States to support the livestock sector, leaving little for other regions (Dearden and Mitchell, 2016). For many years, there has been a concern for small-scale farmers when it comes to adapting to climate change because of the lack of capital needed for adaptation strategies (Mendelsohn and Dinar, 1999). Not only will food supply be affected, but GDP from the agricultural sector is anticipated to decline, mostly in developed countries (Dearden and Mitchell, 2016).

PART III: BENEFITS OF VERTICAL FARMING

The issues that the world is currently facing regarding agriculture, environmental degradation, and resource use are closely related to each other. Therefore, it is necessary to solve these challenges by developing a universal methodology for producing food and improving society while using as few resources and having as few emissions as possible (Kozai et al., 2020).

Vertical farming is a sustainable, emerging technique that uses Controlled Environment Agriculture (CEA) to regulate all factors of plant growth inside of a vertically stacked greenhouse. CEA is an approach that uses plant science, engineering, and computer-operated control technologies to enhance the growth and quality of plants and production efficiency (grovtech.com; retrieved 13 Jan 2021). These farms are sustainable because they use less water, less land, produce little waste, and require less fossil-fuel-driven machinery and transportation (Despommier, 2009). The farms do not rely on climate or agrochemicals, and therefore crops can be grown 24 hours per day and seven days per week in a controlled environment that may use renewable energy sources (Despommier, 2009). Vertical farms can be constructed and operated within urban regions with large and growing populations. In areas that do not offer a lot of land space or where building costs are high, farms can be built inside vacant buildings, apartments, schools, and rooftops (Wong et al., 2020), which reduces the ecological footprint.

Although vertical farms are not yet typical, a few farms globally provide evidence of these benefits. For example, at AeroFarms, microgreens and baby greens are grown in a pesticide-free vertical system using 95% less water and controlled fertilization to produce highly productive crops (aerofarms.com; retrieved 13 Jan 2021).

Figure 1. VertiCrop™ Stacking System. (Vancouver, BC; grow.verticrop.com/vertical-farming/)

Figure 2. AeroFarm's Indoor Vertical Farm. (aerofarms.com)

Efficient Use of Water

Water is a resource that is crucial for agriculture, and irrigation practices are incredibly inefficient and unsustainable (Horrigan et al., 2002). Large quantities of water are required to produce fruits and vegetables, but the livestock sector uses the most water to make feed for the animals (Horrigan et al., 2002). Urban areas of developing regions susceptible to environmental changes due to climate change currently face water shortages that impact their agriculture (De Anda, 2017; Vairavamoorthy et al., 2008). There is a need to shift resource management systems to be more efficient with what little resources are available because there are constraints to finding new water sources. Water demand has surpassed current supplies in most of the world (Vairavamoorthy et al., 2008). Vairavamoorthy et al. (2008) note that developments regarding water "should be flexible to accommodate a wide variety of unforeseen, but unavoidable limitations" (p. 332). With the use of innovative, closed loop growing systems, vertical farms use as little as 1% of the water required by open field farms, and they can be up to 350% more efficient (Qiu et al., 2020). Hydroponics, aquaponics, and aeroponics systems use significantly less water, up to 98% less than traditional farming systems, because these systems eliminate the need for water irrigation (Despommier, 2009; SharathKumar et al., 2020; Qiu et al., 2020). In Utah, a vertical farming company called Grōvtech, saves 56,691 gallons of water per tower per day using these systems (grovtech.com; retrieved 13 Jan 2021).

Efficient Use of Land and Existing Buildings

Traditional open-field farms require a large amount of arable land to produce crops, approximately half of that land is used for agricultural purposes (Ritchie and Roser, 2021). The vertical aspect of the farms allows growers to build upwards rather than outwards, therefore using significantly less land area. Evidence shows at AeroFarms, which uses less than 1% of the land needed for traditional growing (aerofarms.com). Vertical farms can also be implemented into existing buildings and rooftops to efficiently utilize space without compromising a low ecological footprint (Despommier, 2009).

Waste Reduction

There are many ways that vertical farms can reduce waste throughout the production process. For example, biowaste such as leaves, stems, and roots can be converted into fertilizer and biofuels to use in further production (Johnston and Mellor, 1961). According to the website aerofarms.com, AeroFarms is part of a global organization passionate about the environment and sustainability, the Circular Economy 100, and one of its goals is to limit the amount of waste produced. This company has patented a cloth medium that acts as a barrier between the plants and nutrient-rich mist to minimize waste. This reusable cloth is made from recycled plastic and can be used for seeding, germinating, growing, and harvesting plants (aerofarms.com).

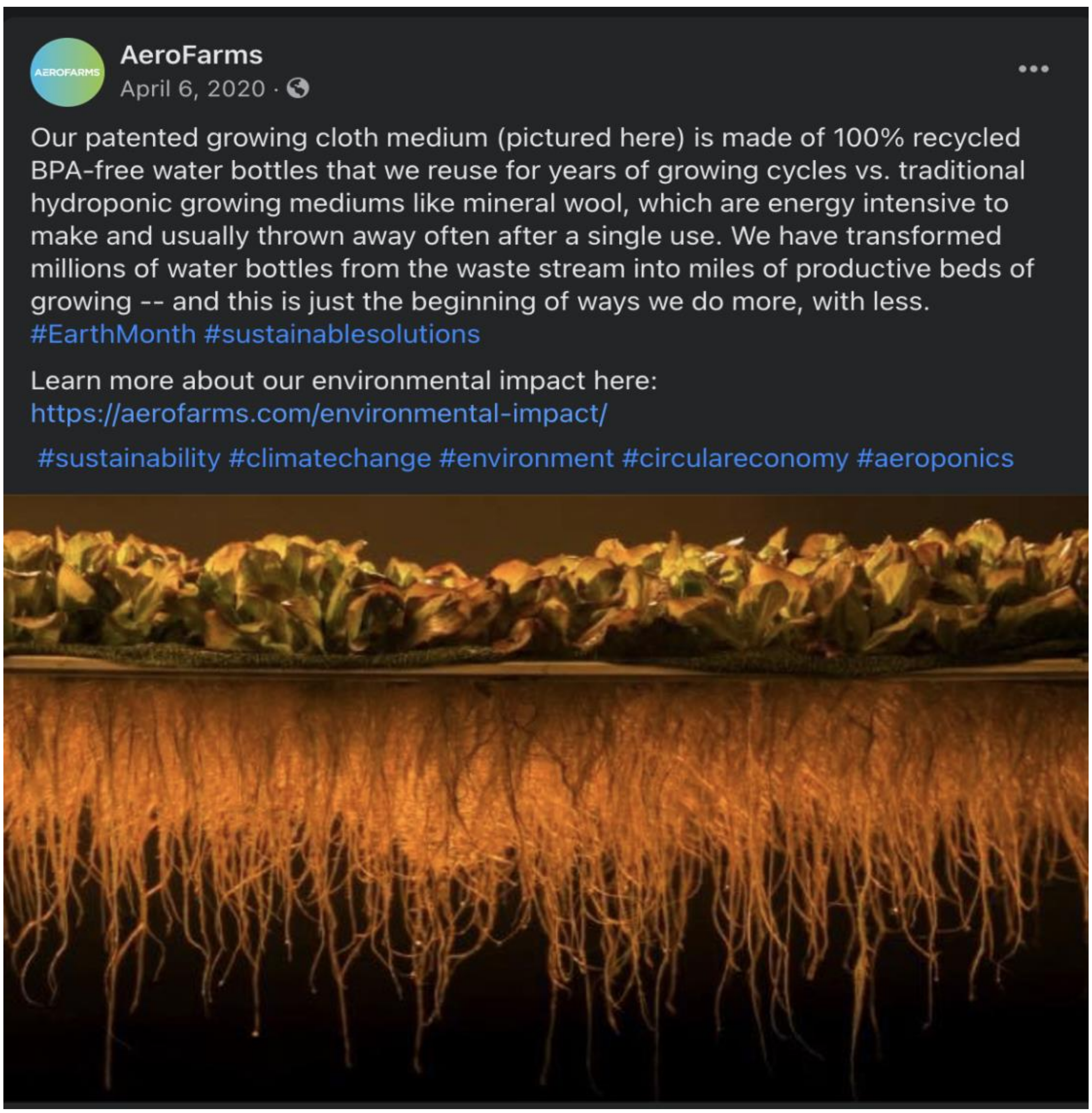

Figure 3. Aerofarm's Cloth Medium. (source: https://www.facebook.com/AeroFarms/photos/1527889260702680)

Reduced Greenhouse Gas Emissions

Current agricultural practices are intensive when it comes to the use of fossil fuels. Processing, packaging, and transporting products requires large quantities of fossil-fuel-driven energy, and these activities are responsible for roughly 26% of global greenhouse gas emissions (Horrigan et al., 2002; Ritchie, 2019). This chart from Ritchie (2019) provides a better look into how emissions produced within the agricultural industry is distributed:

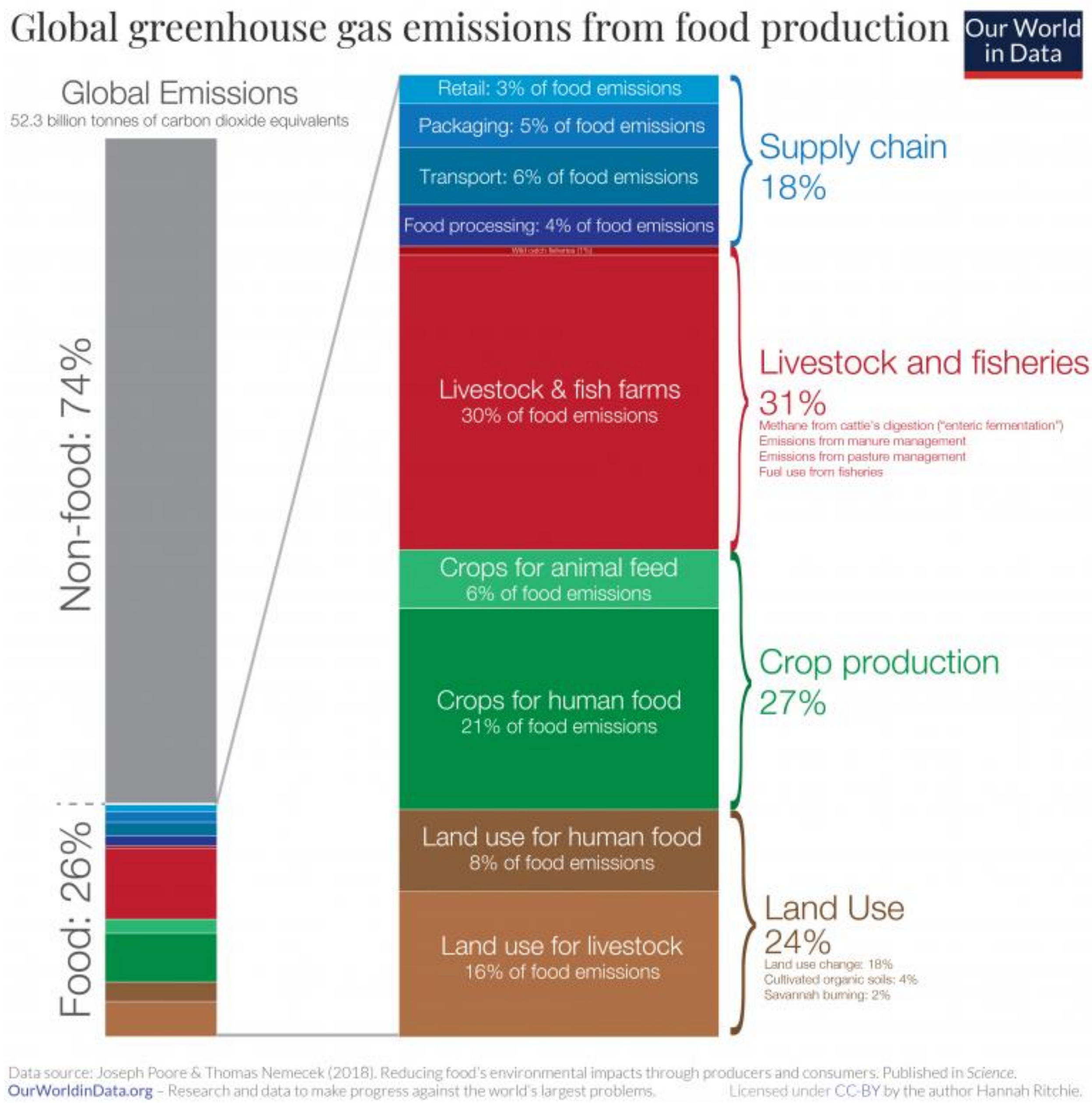

Figure 4. Agricultural Emissions. (source: ourworldindata.org)

Vertical farms can operate in larger urban centers that generally rely on long-distance transportation to get food products, especially seasonal fruits, and vegetables (Despommier, 2010). By working on significant distribution channels, farms can drastically reduce the carbon emissions from different modes of transportation, and there is no need for tractors and other large machinery (Qiu et al., 2020). AeroFarms has managed to cut harmful transportation by approximately 98% of that required by traditional farming (aerofarms.com).

Environmental Reclamation

Lakhiar et al. (2018) note that approximately one-quarter of the world's arable land is unsuitable for crops because it is unproductive and marginal. In addition, there is a lack of soil fertility due to previous agriculture activities, climate change, urbanization, weather events, industrialization, and pollution (Lakhair et al., 2018). Canada, for example, has 193,492 farms that take up 64.2 million hectares of land as of 2018, and the size of farms is continuing to expand due to new growth in technology (*Overview of the Canadian agriculture and agri-food sector 2018*, 2020). Furthermore, vertical farms use water efficiently in a closed-loop system. Hence, the risk of nutrient loss and water contamination significantly reduces, and the long-term health of soils can be retained because these farms do not require land disruption (Qiu et al., 2020).

Examples of Vertical Farms Around the World

Plant Chicago (Chicago, IL; plantchicago.org)	This vertical farm exists inside a 100,000sqft, three-story 19th-century building. Plant Chicago produces mushrooms and tilapia using hydroponics, aquaponics, and a fish breeding system. Waste from the fish is then used as fertilizer for the mushrooms using an "anaerobic digester." The company's mission is to "equip people and businesses with the tools to live more sustainably through community-driven, hands-on programs and innovative

	research projects". In addition, Plant Chicago offers many different educational programs at the farm.
VertiCrop™ (Vancouver, BC; grow.verticrop.com/vertical-farming/)	Located on the rooftop of an existing building, VertiCrop™ produces over 80 types of leafy greens, microgreens, and strawberries using a fully automated closed-loop conveyor hydroponic system. This farm uses a combination of natural and artificial lighting and a water recycling system to limit resources. As a result, the farm uses 92% less water and produce 20x higher yields than traditional farming methods.
AeroFarms (Newark, NJ; aerofarms.com)	AeroFarms uses a “smart” aeroponic system that uses 95% less water than traditional farming and zero pesticides. LED lighting controls the plants’ size, taste, shape, texture, color, and nutrients. This vertical farm grows herbs and micro and baby greens such as arugula and kale. The supply chain is shortened by building farms near large population centers and main distribution routes.
Plantlab Vertical Farm (Den Bosch, Holland; plantlab.com)	This vertical farm is located underground in an existing three-story building. Some of the products grown are beans, corn, cucumbers, tomatoes, and strawberries. This system uses advanced LEDs and an aeroponic and aeroponic system that uses little resources. With being near local demand, Plantlab uses a “complete closed harvest and supply chain system [they] can bring fresh produce within 24 hours from harvest to store. This

	prevents loss of nutrients and flavor, whereby our produce has superior flavor profiles, nutritional value, and outstanding quality compared to any other product on the market" (plantlab.com).

Table 1. Vertical Farms Around the Globe

PART IV: VERTICAL FARMING PRODUCTION SYSTEMS

The concept of vertical farming is not new; greenhouses and hydroponic systems have been used for many years because these systems produce high-quality, nutritionally dense, and fresh food. This closed system can be used for growing native and non-native fruits and vegetables in semi-arid and arid regions. The most common crops to grow are tomatoes, herbs, leafy vegetables, and microgreens (Wong et al., 2020). Three types of vertical farming systems exist, and each system provides economic benefits and disadvantages. However, the environmental benefits outweigh the negatives.

The three standard systems are hydroponics, aeroponics, and aquaponics. These can integrate to recycle water, nutrients, and waste, creating a sustainable production system that uses less water. Using these techniques grows food using approximately 90% less water and up to 50% faster (Gurley, 2020; p. 3). In addition, the vertical farming environment is clean and free from pests which eliminate plant diseases and infections, and contamination from agrochemicals (Gurley, 2020). Evidence from Japan shows that vertical farming is necessary to respond to natural disasters such as the Fukushima tidal wave that impaired the use of traditional cropland (Gurley, 2020). Gurley (2020) notes that Japan now has hundreds of vertical farms and greenhouses since the disaster, which has resulted in high product yields for the country.

Hydroponics

The hydroponic system is most common in vertical farms. It shifts the traditional usage of chemicals and machinery to a modern design that benefits humans and the environment (Chaudhry and Mishra, 2019). In this system, the roots of the plants submerge in a solution containing water and nutrients (Chaudhry and Mishra, 2019), allowing plants to grow without the need for soil. This type of system has a smaller ecological footprint than intensive, soil-based agriculture. It retains water not absorbed by the plant roots and recycles it for other production uses (Schafer, 2018). Plants are grown with the aid of controlled lighting, temperature, oxygen, water, and nutrients (Schafer, 2018). Yields are higher due to the smaller amount of root growth that allows plants to be closer together, and this approach can grow fruits and vegetables that most regions typically import

(Schafer, 2018). According to Johnston and Mellor (1961), hydroponic systems only require approximately 10.8 liters of water per square meter each day, making them very sustainable.

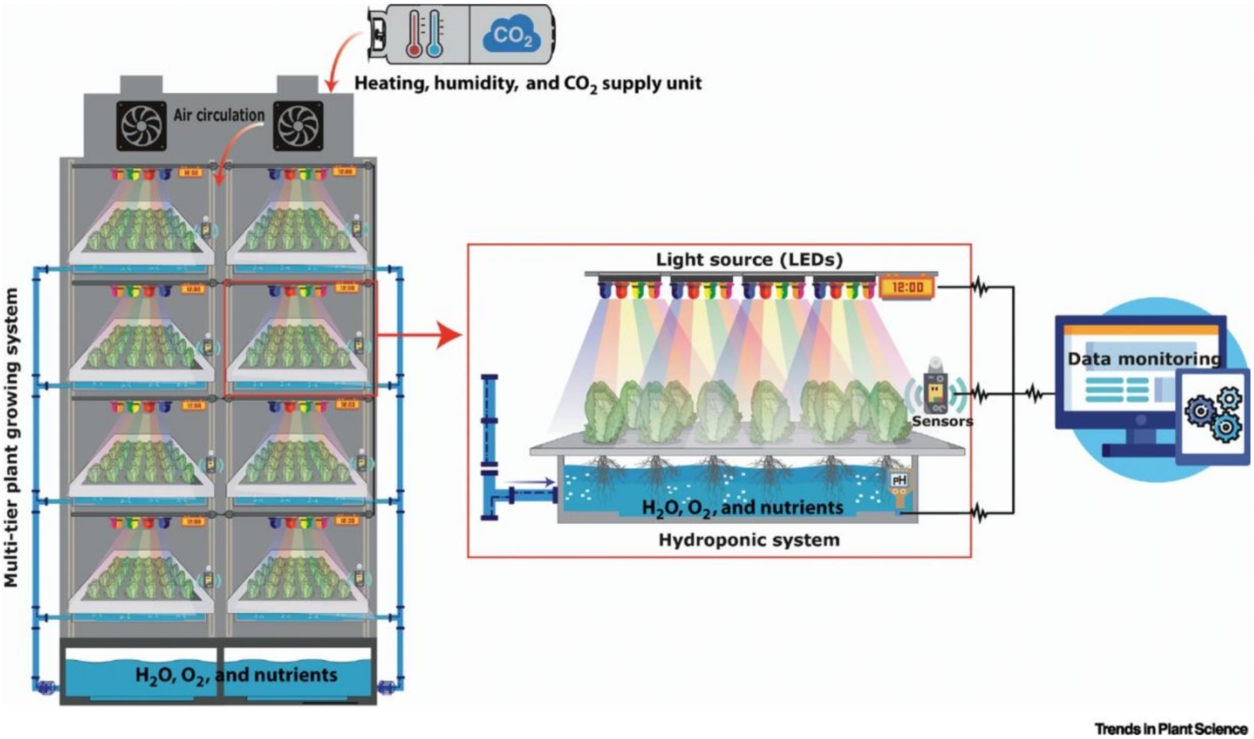

Figure 5. Hydroponic Production System. (source: SharathKumar et al., 2020)

Aeroponics

Initially developed by NASA to find ways to grow plants in space, this technique involves growing plants in an indoor environment using air and mist to control growth (Chaudhry and Mishra, 2019; SharathKumar et al., 2020). NASA created the aeroponic system in 1997 that produced lettuce, peppers, tomatoes, grains, and other vegetables free from pesticides within a sterile environment (Gurley, 2020). In addition, exposed plant roots absorb nutrients from a mist solution for growth with no soil required, making it a viable solution for improving food security (Gurley, 2020).

Aquaponics

Aquaponics is an emerging research area, and it is under-studied for large-scale use (Chaudhry and Mishra, 2019). By combining water, nutrients, and fish in the same ecosystem, the waste from fish is used to fertilize and irrigate hydroponic production beds. (Chaudhry and Mishra, 2019). The plant beds then purify and filter wastewater and return it to fish tanks. The aquaponic system and the hydroponic system work synchronously to filter waste from the tank into recycled water (Zhang et al., 2018). The two systems provide proper nutrients to plants by working together while filtering out the ammonia toxic to fish (Zhang et al., 2018). Aquaponic systems can also utilize rainwater to fill tanks to save water (Johnston and Mellor, 1961). Tilapia is one breed of fish that is optimal for vertical farms because they are hardy and highly adaptable; tilapia grows rapidly and requires little feed input; and can be produced cheaply (Genello, 2015; Johnston and Mellor, 1961). Johnston and Mellor (1961) note that one farm they studied made 341 tonnes of fish each year and 137 tonnes of fish fillet. Here is an example of what an aquaponic system could look like if it were implemented into a vertical farm:

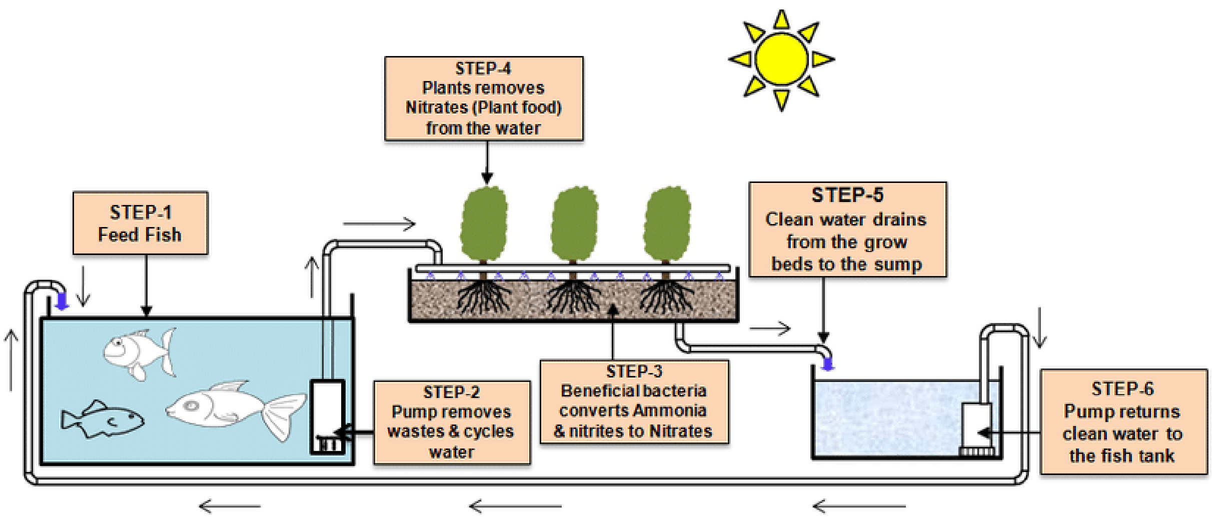

Figure 6. Aquaponic System. (Jena et al., 2017)

PART V: TECHNOLOGY

Technology is rapidly improving, and a technocentric perspective is becoming more popular when meeting human needs. With advanced technology, significant decreases in energy, manufacturing, and transportation costs can be achieved (Johnston and Mellor, 1961). Having a technocentric perspective means that the growth and efficiency of technology can be a valuable tool to tackle the overuse of resources and aid in reclaiming degraded environments (Dearden and Mitchell, 2016; p. 157). An approach that would be practical for the economy and agricultural productivity involves expanding modern technology within this sector (Johnston and Mellor, 1961). Vertical farms are a perfect example of a solution with a technocentric point of view. Sharath Kumar et al. (2020) believe that:

> Vertical farming is a novel plant production system that allows the local production of high-quality fruits and vegetables for growing cities. VF offers a myriad of opportunities to move from genetic to environmental modification and to produce crops of guaranteed quality and quantity independent of weather, soil conditions, or climate change (p. 724)

LED Lighting

The concept of using artificial lighting in greenhouses has been around since the early 1900s (Wong et al., 2020). Farmers used high-intensity discharge (HID) lamps in greenhouses to imitate sunlight; however, these lights are costly due to the amount of heat produced and energy needed to function (Wong et al., 2020). Wong et al. (2020) state that HID lamps were used until LED lighting was invented in the early 1960s, and HID lamps became secondary in greenhouses. It is essential to have adequate and controlled lighting for efficient plant growth (Sharath Kumar et al., 2020). LED lighting is the most commonly used type of light system in vertical farming. The intensity, timing, and spectrum of LED lighting can be manipulated for higher yields and faster growth. AeroFarms uses engineered LED lighting to control the plants' size, shape, texture, color, flavour, and nutrition levels (aerofarms.com).

LEDs can enhance a plant's photosynthetic efficiency by emitting plant-specific wavelengths, timing, and strength and by "matching the absorption spectra of chlorophylls" (Wong et al., 2020). Plants require precise light ranges; blue, mainly, is suitable for producing dense plants with healthy stems and secure roots, while red light helps increase the plant size (Horticulture Lighting, 2020).

Figure 7. AeroFarm's Vertical Farming Aeroponic System. (source: aerofarms.com)

Artificial Intelligence

The use of artificial intelligence (AI) is increasing in the agricultural industry to keep up with high volumes of production and diminishing resources (Steffen, 2020). Like Plenty in San Francisco, some farms use AI to control and monitor growth factors, such as temperature, lighting, and water quality (Bowery Farming, 2021; Steffen, 2020). Plenty's vertical farm robots are designed to improve efficiency and plant quality constantly, and the robots do tasks such as transporting plants and growing racks to different areas (Preetipadma, 2021). AI can improve production efficiency, and it gains knowledge by using cameras and sensors that record data into a network that gives feedback on the quality and the needs that the plants may require (Bowery Farming, 2021)

PART VI: VERTICAL FARMING AND A CIRCULAR ECONOMY

Circular Economy

The economic system that is important for global food security is a circular economy, and according to the Food and Agriculture Organization of the United Nations (FAO.org, n.d.), it is a system that:

...aims to maintain the value of products, materials, and resources for as long as possible by returning them into the product cycle at the end of their use while minimizing the generation of waste. It can contribute to several different Sustainable Development Goals (SDGs), including SDG 2 End hunger (via sustainable food production), SDG 6 Clean water, SDG 7 Affordable and clean energy, SDG 12 Responsible consumption and production, SDG 13 Climate action, and SDG 15 Sustainable use of terrestrial ecosystems. In prioritizing resource efficiency and resilience, the circular economy and the climate mitigation agenda are inextricably linked and mutually reinforcing [paras. 3].

The importance of a circular economy is shown by looking at the COVID-19 pandemic. Agriculture has been tremendously impacted by the pandemic, as lockdown and transportation restrictions caused high quantities of food to be wasted (FAO.org; n.d.). In addition, the FAO notes that the measures put in place during lockdown exposed the need for a circular economy.

Economic Development from the Agriculture Industry

The agricultural sector can contribute to economic growth if productivity and food outputs increase at the same rate as demand (Johnston and Mellor, 1961). Conversely, if food supplies fail to keep up with demand, this could lead to higher food prices and stress on wages in the industry, leading to adverse economic impacts (Johnston and Mellor, 1961). Thus, the agricultural sector is significant in developing economies; however, this comes with financial, social, and ethical challenges despite agriculture accounting for approximately 25% of GDP in many developing countries as of 2018 (Johnston and Mellor, 1961; World Bank 2020).

Labour and land are abundant in these countries, and an extremely high percentage of workers are employed in the agricultural sector (Johnston and Mellor, 1961; Roser, 2013). According to ourworldindata.org, low-income countries have an average of 67.71% of citizens employed in the agricultural sector, with Burundi having the highest at 91.44% in 2017 (Roser, 2013). This data is significant compared to Canada, which has only 1.95% employment in this sector recorded during the same year (Roser, 2013). As a result of a high labor supply, companies can outsource and get away with poor working conditions and lower wages to quickly produce products for the market (Gruner, 2013). By looking at historical and current charts, when a country increases its wealth, the agricultural sector becomes nonessential (Roser, 2013). While these products are cheaper, there is a high risk of food contamination, and recalls are more likely, and in the United States alone, food recalls have cost billions of dollars (Despommier, 2010). In addition, firms have little control over climate influences that occur in these regions. Extreme weather events and soil degradation can damage or destroy crops, resulting in significant financial losses for stakeholders (Despommier, 2009; Despommier, 2010). Approximately 30% of crops are typically lost due to various factors like spoilage from transportation, infestation, and weather disturbances (Despommier, 2009). High quantity and quality yields are not guaranteed with open-field farming, and prices fluctuate because of this instability in the industry.

The significant economic benefits of the VF system are its ability to shorten the length of urban food supply chains, create locally accessible food, and produce nutritious and safe food for consumers (Specht et al., 2016). In addition, the VF supply chain is much shorter because farms are self-sufficient at almost all stages of production, from planting to export, occurring within the same building (Gruner, 2013).

This concept eliminates lengthy, fossil-fueled transportation to grocery stores, and the products are guaranteed to be fresh and nutritious. In addition, all supply chain factors are integrated with a focus on regional and local products, specifically within urban regions. As a result, managers, employees, and consumers can form closer connections with each other and their products (Gruner, 2013).

New food and technology markets are emerging (World Bank, 2007). There is an advantage to being close to cities; there is an opportunity to ethically hire skilled laborers from urban regions that are normally not known for agriculture, and increase the employment rates of those regions (Wong et al., 2020). FAO (2010) states that “a sustainable food system will protect and respect biodiversity and ecosystems, be culturally acceptable, economically fair and affordable, nutritionally adequate, safe and healthy while optimizing the use of natural and human resources.” In a study done by Specht et al. (2016), the researchers found that stakeholders believe urban food production can shorten food supply chains and improve access to locally and sustainably produced food. Urban agriculture and the implementation of vertical farming can potentially contribute to food security and access to healthy food because of this higher food productivity (Cohen, 2012).

PART VII: OPPORTUNITIES FOR VERTICAL FARMING

Vertical farming has seen a growth in popularity over the past decade, and it is a method that addresses worldwide challenges regarding food production, including a rapidly increasing population, water scarcity, and food security and safety (Oliveira et al., 2020). Not only is urban agriculture beneficial for the environment and food security, but there are also some other opportunities that vertical farming can explore. Some of these areas include education for students and corporations (Despommier, 2009; Nadal et al., 2018), revaluation of city systems (Despommier, 2009; 2019; Kozai et al., 2020), development of new protein sources (Tuomisto, 2019), livestock (Peters, 2020), implementation in developing regions (Tuomisto, 2019), and in-home growing.

Education

One of the major opportunities of VF is the inclusion into infrastructure in a wide range of educational institutions. Schools have the advantage of being large, reliable, durable, and weather-resistant (Nadal et al., 2018), making them viable options for greenhouses. In addition, schools usually tend to have on-site cafeterias and kitchens where food is sold (Nadal et al., 2018). For younger children, VF facilities can act as a tool to learn about sustainable food systems, and how it connects us to our resources (Busa, 2014). Putting vertical greenhouses on rooftops of existing schools (or beside existing buildings) represents an opportunity to gain environmental and nutritional education using spaces that already exist (Nadal et al., 2018).

Universities and colleges can partner with vertical farm companies to operate them on campus with public-private partnerships of other approaches to create a “playground” for engineering, horticulture, science, and learning opportunities, including cooperative education options (Despommier, 2009). Vertical farms can also provide nutritious and safe food to university students and other on-campus community members. The economy would directly benefit from creating jobs, environmental and nutritional education, health improvements, building upgrades, and strengthening food security within cities (Nadal et al., 2018). For example, Plant Chicago is a vertical farm that offers educational programs to students and corporate groups (plantchicago.org). Some of Plant Chicago’s programs include:

Aquaponics: Design Challenge - Elementary students learn about the science behind aquaponics and the nitrogen cycle. During this experience, students get to design and build an aquaponics system.

Circular Economy - High school students learn about circular economies. Students are encouraged to propose how small and large communities can reduce waste and increase productivity using minimal resources and closed-loop systems.

Aquaponics: Water Chemistry - Students learn about ammonia, nitrates, nitrites, and phosphates directly from the aquaponic system on site. This program gives the students insights into the water and nutrients needed for fish and plants.

Figure 8. Guerin Prep High School Students Touring and Learning About the Aquaponics Closed-Loop Lab. (source: https://www.facebook.com/plantchicagonotforprofit/photos/a.897839707060263/897842730393294).

Figure 9. Classroom Visiting Plant Chicago and Learning About Closed-Loop Systems. (source: https://www.facebook.com/plantchicagonotforprofit/photos/a.525236094320628/525237007653870).

Figure 10. Students Learning How to Grow Plants Using Hydroponics. (source: https://www.facebook.com/plantchicagonotforprofit/photos/a.525236094320628/525238504320387).

Implementation Into City Systems

There are a few ways that cities and vertical farms can co-exist while benefiting from each other simultaneously. Vertical farming can implement into a city's water system by recycling greywater so that it can be used for irrigation water in the farm's hydroponic and aquaponic systems (Despommier, 2009). Additionally, water harvesting systems can store rainwater to decrease water usage (Despommier, 2019). There is an opportunity for cities with good solar irradiation levels to use solar photovoltaic modules to minimize energy costs for both farms and other infrastructure (Despommier, 2019). Another way to reduce the footprint from both cities and farms is to establish a system that uses urban waste to produce vertical farming. These farms require fewer resources, including nutrients and fertilizer (Kozai et al., 2020).

New Protein Sources

The agriculture industry produces high amounts of emissions into the atmosphere, and livestock alone has around 60% of that (Tuomisto, 2019). Therefore, there is a need to consider the possibility of implementing livestock production into vertical farming approaches. Furthermore, technology is becoming the sought-after solution to the issues surrounding the negative impacts of livestock production, and therefore lab-grown meat alternatives are becoming possible (Tuomisto, 2019).

Tuomisto (2019) notes that the development of lab-cultured meat products is still a new field. The growth rate depends on the support of funding, policy incentives, cost, and perceived interest in consumers. However, studies show that lab-grown meat products would produce 96% fewer carbon emissions than beef, and the environmental footprint from poultry would reduce by 82%. The process of growing meat in a lab requires precise control, just like vertical farming (Tuomisto, 2019). Combining vertical farming systems with lab-cultured meat production may be possible into a unified approach to maximize benefits.

Livestock Industry

So far, vertical farming has focused on producing fruits, vegetables, and baby and microgreens. However, there is an opportunity for vertical farms to help decrease the ecological footprint caused by growing crops to feed livestock. A significant number of grains are required to provide grain-fed animals enough food to produce enough beef to meet demands (Horrigan et al., 2002). According to Horrigan et al. (2002), one cow requires 7kg of grains to produce only 1kg of beef, pigs need 4kg to produce 1kg of pork, chicken requires 2kg, and this quantity is growing. Thousands of acres of land are required to make grains for livestock (Horrigan et al., 2002). This demand increases agrochemical use, soil erosion, water pollution, and pesticide resistance (Horrigan et al., 2002). Given that the population is rising, it is necessary to consider sustainable farming systems that support grain production. Grōv Technologies uses vertical farming techniques to grow about 15% of the wheat and barley needed to feed around 2,000 cows (Peters, 2020). Using as little as 850 square feet of space and 95% less water than traditional farms, in roughly six-day these systems can produce the equivalent of 35-50 acres of farmland (Peters, 2020). Grōv's design is entirely automated by a robot that plant seeds and move them to the system where sensing technology provides light and water adjustments. Harvesting is done automatically (Peters, 2020).

Peters (2020) states that the farm could reach net-zero emissions by 2025 because of "Stellar" smart LED lights do not produce any heat, eliminating the need for high air conditioning costs. In addition, the system can run using renewable energy. As a result, the company saves approximately 50-80% of energy costs (grovtech.com; retrieved 13 Jan 2021). Not only is this system beneficial for farmers, but cows also receive feed that is much higher in nutrients, and therefore the cattle eat less while producing the exact quantities of milk (Peters, 2020).

Vertical Gardens at Home

There is an opportunity for vertical farming to be used at the household level and in backyards. Many local communities in developing countries have adopted the practice of home gardening to alleviate poverty and enhance food security (Galhena et al., 2013). Home gardens are proven to give families better access to nutritious and readily available foods (Galhena et al., 2013). Outdoor home gardens can provide numerous environmental benefits such as nutrient recycling, habitats for wildlife species like birds and insects, pollinators, reduced soil erosion, conservation of land, and pest control (Galhena et al., 2013). There are in-home options designed for those who lack the outdoor space needed for a garden. A Canadian company, Just Vertical, provides in-home hydroponic vertical gardening systems ranging from $699 to $1199 (justvertical.com; retrieved 16 Dec 2020). They offer a variety of seeds such as basil, arugula, chives, kale, cucumber, swiss chard, mint, spinach, pumpkins, and tomatoes, amongst many others, and their system can grow up to 54 KG or 120 lbs of produce each year (justvertical.com; retrieved 16 Dec 2020).

Figure 11. Just Vertical In-Home Vertical Farming Systems. (source: justvertical.com; retrieved 16 Dec 2020).

According to the company, those who shop at Walmart or Costco for their produce products could potentially save up to $261 per year by switching to one of the in-home systems. Another in-home option is from a company called MyGardyn, which offers a vertical growing system operated via a smartphone app, in addition to a subscription to receive seeds. In a small space of 2 square feet, the Gardyn can grow 30 vegetables, herbs, and flowers, including watercress, a variety of lettuces, thyme, catnip, jalapenos, lavender, and marigolds (mygardyn.com; retrieved 16 Dec 2020). According to Gardyn's website, this system uses high-definition cameras, sensors, and LEDs to monitor and adjust growth factors. In addition, only 6 gallons of water is needed for two weeks of plant growth.

PART VIII: AREAS NEEDING FURTHER RESEARCH AND DEVELOPMENT

Start-Up and Running Costs of Vertical Farms

Vertical farming boasts many environmental, social, and economic benefits; however, some areas need to be considered, including the efficiency of capital and energy demand (Nadal et al., 2018). There are higher costs associated with vertical farms than traditional farms because of the initial start-up costs and the cost to supply energy. By contrast, large-scale conventional farms have lower capital and land-related transaction costs (World Bank, 2007). The main concern of implementing vertical farms is the high energy and start-up costs associated with the farms. Because every stage of growth is controlled by technology 24 hours a day, vertical farming systems require a lot of energy for lighting, heating and cooling, and other daily operations of the farm (Despommier, 2009). The cost of energy does differ depending on the location of the vertical farm. For example, desert environments have the advantage of having lots of sunlight to provide solar power to the farms, and windy areas can capture the energy from the wind to support these operations (Despommier, 2009). Currently, the start-up costs of VF run much higher than traditional farms, approximately 3-5 times the price. CambridgeHOK (2021) estimates that the cost of a vertical farm, depending on the size and level of manual labour input, can range anywhere between CAD$1500 to 3500 per square meter. Despommier (2009) recommends cutting initial start-up costs by utilizing existing buildings, and the use of advancements and innovations in technology can aid (CambridgeHOK, 2021).

The long-term benefits and growing advantages are becoming recognized by investors and others within the supply chain due to the reality of the climate risks that will impact future food production using traditional methods and the opportunity to create sustainable profits (CambridgeHOK, 2021). For example, lettuce can be grown in as little as six weeks, and vertical farms can produce corn and wheat 3-4 times a year (Despommier, 2009). With this growth rate, economists within the agricultural industry predict that the initial investment will be paid off in approximately seven years (CambridgeHOK, 2021). Current vertical farming investments show that shares are increasing, using Cubic Farms, for example, which has risen steadily over the last two years:

Figure 12. CubicFarm Systems Corp. Stock (source: https://ca.finance.yahoo.com/quote/CUB.TO?p=CUB.TOand.tsrc=fin-srch; retrieved 24 September 2021).

Implementation in Developing Regions

Although vertical farms are considered sustainable, a need exists to assess outcomes for those in the agriculture industry in developing economies. For example, can vertical farms implement into rural growing regions? Furthermore, given that most of the production is automated will these farms negatively or positively impact employment? The number of those employed in the agriculture industry is relatively low compared to almost 100 years ago. However, there is still an extremely high percentage of agricultural employment in developing regions compared to developed areas; however, many according to this illustration from 2017:

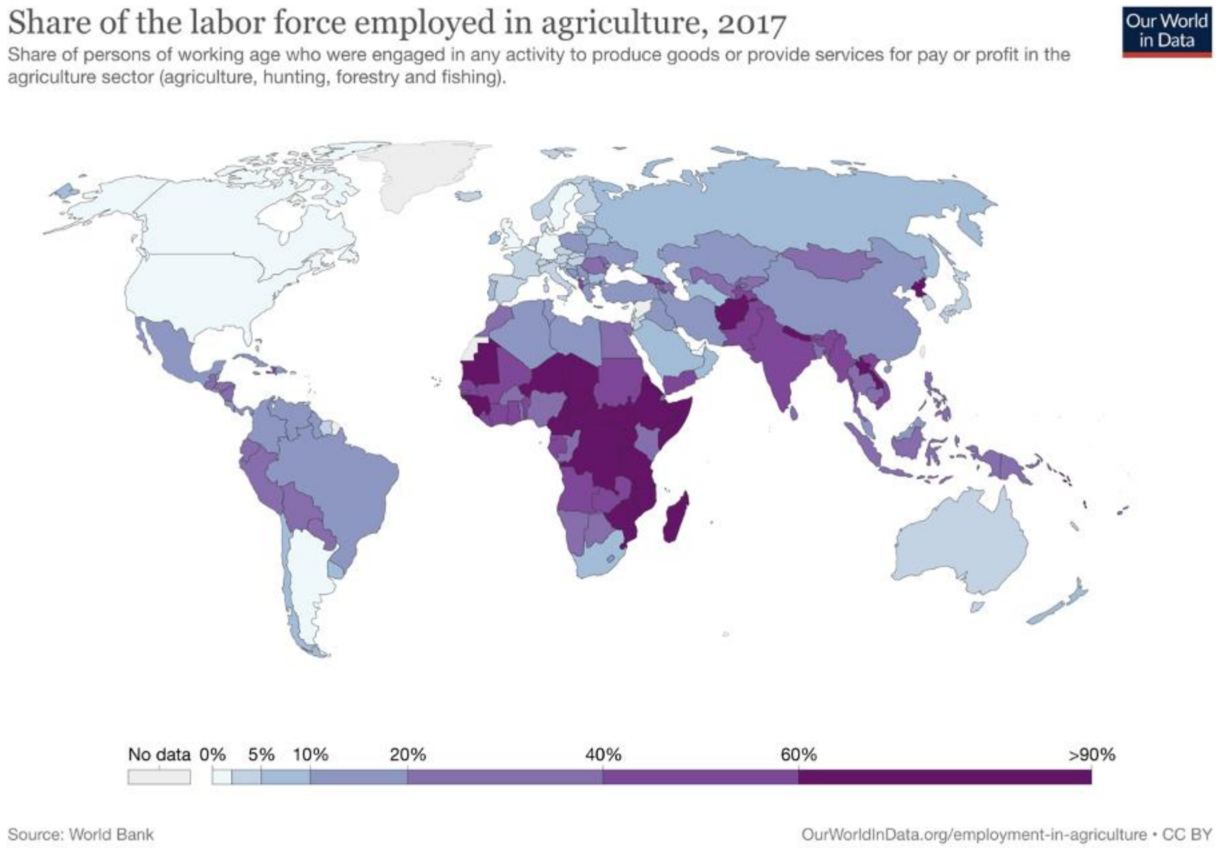

Figure 13. Share of the Labor Force Employed in Agriculture, 2017 (source: World Bank).

The growth of the agricultural sector is crucial for the relief of poverty in many developing countries (FAO, 2010; Ostuka and Kalirajan, 2008). Many factors hinder the ability of some developing countries to engage in global agricultural activities, such as a lack of access to water sources, little or heavy rainfall, invasive pests, and deficient soils (FAO, n.d.). When used in developing countries, vertical farms can provide people with appropriate nutrition that may be typically lacked (Ngumbi, 2015). Currently, vertical farming is dominant in developed countries due to better access to funding and technology. Still, vertical farming could benefit those living in rural communities because food produced in these farms has higher nutrient loads, on top of reduced environmental footprints (Tuomisto, 2019). In regions like Africa, which experiences the highest population growth globally and despite having the highest agricultural industry employment rates, there is a struggle to access safe and nutritious food (FAO, n.d.; Roser, 2013). Urban farmers have begun to grow crops closer to cities using fewer resources; however, without financial investments or research and development, urban agriculture cannot be achieved in low-income areas (Ngumbi, 2015).

In the Kibera community of Nairobi, many residents have adopted “urban sack farming,” a type of farming that uses tall, soil-filled sacks with holes poked throughout various levels (Ngumbi, 2015). Indoor vertical farms that use hydroponic systems can alleviate many issues in these regions; however, finding investors is challenging. For example, a master’s student at the University of Pretoria proposed an indoor, hydroponic farm in the Old Pretoria West Power Station in South Africa. Still, this project did not receive funding, despite winning an international award (Ngumbi, 2015). In developed countries, investors are more likely to see the potential in these sustainability projects and more willing to fund them. Nevertheless, developing countries face two main challenges - water and energy (Ngumbi, 2015). Africa faces frequent power outages that would impact the effectiveness of vertical farming, so innovative and sustainable energy sources are a necessity for production, which can be made available thanks to international partners such as the US Agency for International Development (Ngumbi, 2015). In Mexico, there are limitations to expanding the agriculture industry because over half of the land is dryland, and water availability is exceptionally scarce (De Anda, 2017), so VF could be a viable option for the country as well.

Perceptions of Sustainable Food Systems

Many consumers benefit from the globalized agriculture industry when it comes to the year-round availability of products. However, people are becoming more aware of the dangers that the industry poses to the environment and our food safety and security (Vaughn, 2016). Some studies have shown that local food products are less likely to be wasted because consumers tend to see the value that these products hold (Jurgilevich et al., 2016). According to a study by Vaughn (2016), consumers generally perceive local food as a better option that is more sustainable. Still, consumers also agree that this type of food is expensive, and the options are minimal (Vaughn, 2016). Technology, automation, and genetic modification often integrate into sustainable agricultural systems, but consumers tend to be skeptical about using these technologies (Frewer, 2011).

Perceptions of Vertical Farming

Local food is becoming more popular. A study conducted by Jürkenbeck et al. (2019) found that consumers who consciously tried to eat healthily and sustainably were more likely to consider and accept vertical farming. The researchers also concluded that consumers were more likely to accept vertical agriculture if promoted as sustainable. However, despite the societal pressure on consumers to purchase eco-friendly and sustainable products, this is not economically feasible for everyone (Guthman, 2003). Because organic and healthy food is more expensive, only those who can afford it are “ethical” and “sustainable” consumers, while those who cannot afford high-priced foods are “villains" for consuming unsustainably (Busa, 2014; Pollan, 2008). As Busa (2014) suggests, society sees local food consumption as a heroic act, while those who buy cheap food are anti-heroes. To address the cost concerns for these products, vertical farms can immediately cut transportation costs from the equation, potentially making their products more affordable to consumers (Kalantari et al., 2017).

Another study done by Specht et al. (2016) in Berlin, Germany, compared the social acceptance and general perception of different types of buildings related to agriculture. The results showed that most stakeholders understood the benefits of farming in vertical spaces. Furthermore, consumers accepted this form of production; however, there was some hesitation due to the amount of technology and automation involved (Specht et al., 2016). In addition, Kamalkumaran et al. (2020) note that farmers can sell vegetables produced in vertical farms more frequently than vegetables grown in open-field farms, and prices are less likely to fluctuate because seasonality and climate are no longer factors.

PART IX: DISCUSSION AND CONCLUSIONS

The Earth's climate and the biodiversity of ecosystems are changing rapidly due to many human activities, including agriculture (Despommier, 2009; Ritchie and Roser, 2020). Not only is the industry harmful to the environment, but a warming climate can be harmful to the security of the industry (Despommier, 2010). Finding a single solution to support global sustainability is unlikely. However, more sustainable alternatives to current practices, including those in the agriculture industry, can benefit. During the 1980s, niche markets emerged, and there was increased demand for organic and "clean" food products; consumers became focused on being healthier and focused on more sustainable diets (Guthman, 2003). A sustainable diet is nutritious, economical, available, socially accepted, uses resources efficiently, and is environmentally conscious (Macdiarmid, n.d.). There are many opportunities in the agriculture industry to make sustainable changes to mitigate environmental and human health impacts. Still, due to a lack of knowledge about large-scale food production, many lack awareness of where most food is produced (Guthman, 2003). With the greater availability of research and information, consumers are beginning to become more aware of issues surrounding large-scale agriculture (Guthman, 2003). Vertical farming is a very efficient system that can contribute to sustainable diets if more widely implemented. To summarize the key benefits and disadvantages of vertical farming mentioned throughout this paper, the following table contrasts features of vertical farming to traditional farming methods:

VERTICAL FARMING ADVANTAGES	**TRADITIONAL FARMING ADVANTAGES**
Products can be grown year-round because the system is indoors, and advanced technology and automation can control growth factors.	Employment is cheap because the agricultural industry is most dominant in developing countries with minimal labor laws and laxer environmental standards.

There are zero crops lost to weather disruptions.	The traditional farming industry provides jobs to over 50% of developing region's economies
The use of fossil fuels is substantially reduced.	Livestock can be mass-produced using intensive methods.
No pest infestations or herbicides are needed. The use of genetically modified plants is also minimal.	
It uses 70-98% less water than traditional farms, and this water can be recycled, leaving more drinking water available to people.	
Farmers can rotate different types of crops frequently because growing systems are dynamic.	
New markets become available, expanding job opportunities in urban economies.	
The indoor aspect means less risk of run-off, usually containing toxic chemicals or fecal matter.	
The production and packaging process occurs in the same building, making the food fresher and unlikely to spoil.	
Farmers can utilize existing spaces to cut costs and reduce the environmental footprint by lowering the demand for viable cropland.	

Yields are higher and plants can grow at quicker rates than in traditional farms.	
Food is safe, nutritious, fresh, and tasty.	
Boosts local employment.	
The start-to-finish aspect of vertical farming allows employees and management to have closer relationships with each other and the food they grow, which helps boost productivity, wellness, and motivation in the workplace.	
Biodiversity is protected, and land can be restored.	
Farmers can control all factors of growth, independent of climate.	
Gray water can integrate city water systems and vertical irrigation systems to be more sustainable.	
Waste is minimal.	
Farms are located close to their markets.	
VERTICAL FARMING DISADVANTAGES	**TRADITIONAL FARMING DISADVANTAGES**
Vertical farms rely heavily on technology and automated systems; therefore, the costs associated with providing enough energy for production can	High environmental footprint from greenhouse gas emissions and the overexploitation of natural resources

be high if other options like solar energy or wind are not utilized	
Not a lot of economic knowledge or research is available because it is an emerging approach	Deforestation, land and soil degradation, and habitat loss
Lab-grown meat is still new and would take a lot of time to see its perceived benefits and reduce costs. There are also many regulatory challenges.	Run-off of chemicals and fecal matter can cause drinking water contamination, and natural ecological cycles like the carbon cycle are destroyed.
There are limitations to what can be grown in vertical farms because of the vertical stacking design	Agriculture uses 70% of the world's water supply
	Fertilizer made from feces puts human health at risk of parasitic and foodborne illnesses.
	Crops are susceptible to damage from wind, flooding, drought, temperature changes, pollution, and pests.
	Agriculture uses ⅓ of the world's land for permanent cropland, arable land, and permanent pastures.
	Crops are becoming resistant to fertilizers, and pests are resistant to

	pesticides, so there is no need to improve chemicals and increase their use.
	Promotes biodiversity loss

Table 2. Comparison Between Vertical Farming and Traditional Farming Methods

To achieve sustainable dieting through food systems such as vertical farms, there is a need for appropriate policies, training, and incentive programs to encourage businesses and organizations to become more sustainable throughout development and production stages (European Commission, 2020). The European Union plans to develop a policy framework to promote a circular economy (European Commission, 2020). The Union's goal is to normalize "sustainable products, services, and business models… and transform[s] consumption patterns so that no waste is produced in the first place" (European Commission, 2020). This framework provides potential solutions to promoting sustainable food systems regarding waste management and food production. Some of the policy goals include:

- The support of local farming with the help of financial aid, tax incentives, and providing local opportunities (European Commission, 2020).
- The promotion of nutrient recycling and nutrient flow regulation and support for farmers practicing these activities (European Commission, 2020).
- Educating consumers about food chains, waste management, and intelligent production (European Commission, 2020).
- Promote sustainable food production and close material loops as much as possible (European Commission, 2020).
- Support local energy production and the use of bio-waste (European Commission, 2020; Jurgilevich et al., 2016)

Vertical farming fits many of the European Commission's main goals surrounding food production and fits their criteria for a localized and sustainable food system. Having a short supply chain while still providing nutritious and secure food is crucial for advocating localized systems, and these systems focus on waste reduction, nutrient cycling, storage reduction, reduced transport, and efficient production that meets demands (Jurgilevich et al., 2016). To make the transition to becoming more sustainable in the food industry, consumer perceptions, individual behaviours, world views, technologies, and infrastructures must shift (Jurgilevich et al., 2016).

Many factors need to be considered when developing and integrating environmental management strategies and approaches. The inclusion of local community members and stakeholders is essential when developing these strategies and frameworks (Dearden and Mitchell, 2016; p. 157). To increase the popularity of vertical farming, consumers need to be aware of them and the benefits this type of system carries. Companies can achieve consumer awareness through different marketing approaches, such as marketing inside and outside the grocery stores, media providing information for consumers about the environmental and societal benefits, and shareholder and consumer support in decision making (Specht et al, 2016). Awareness marketing such as sustainable consumption ads on TV will only do so much, so it is left to other forms of communication to educate consumers. Therefore, “supermarkets, food service, and public catering need to be involved in efforts to increase amounts and attractiveness of plant-based foods and to decrease, for example, the portion size of meat being served” (Jurgilevich et al., 2016). Jurgilevich et al. (2016) note that policymakers can promote sustainable choices tailored to varying community circumstances by addressing regional consumption behaviors and challenges.

Future food security relies on the ability to detect the agricultural challenges regarding climate change and find ways to shift food production to become more sustainable to protect the planet’s ecosystems and human health. Vertical farming provides so much more than just healthy food products. It provides an opportunity for education and aid in mitigating environmental damage caused by traditional farms. In short, vertical farms are a small step in the right direction. Still, more research, green incentives for farmers, and consumer knowledge is required for this system to become widely adopted.

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