

Vertical Farming Feasibility

The opportunities and challenges of adapting vertical agriculture

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Abstract

Consistent food supply in the environment is critical for every species. Humans, in particular, have been practicing farming for thousands of years, however, traditional agriculture has significant negative effects on the environment. As the human population continues to increase and land becomes more and more valuable, that the day will come when people cannot completely rely on the produce from conventional farms anymore. This study focuses on the technologies and challenges of adapting vertical farming as a new solution to feed the population around the world and potentially change our food system. The main goal of this study is to analyze the theory and the potential of vertical farming in addressing the issues that exist in today's food system. An analysis of the major technologies of vertical farming is explained, based on real examples. This study also conducts a comparison between the greenhouse system and vertical farming to figure out the differences between them and the potential benefits behind vertical farming. Finally, to evaluate the feasibility of vertical farming, this study gives an opinion about the challenges to be overcome in this field and defines if vertical farming is a good way to supply food to cities in an energy efficient and sustainable way.

1. Background

The term "vertical farming" was coined by an American scientist named Gilbert Bailey in 1915 (site). However, intelligent people in South America have practiced vertically layered food growing techniques for centuries. In the past 20 years, architects and scientists have constantly looked into the idea of vertical farming and have achieved notable improvements. Today, following the technological revolution, a more advanced type of urban farming is attracting the world's attention, where people can grow produce in a fully controlled vertical indoor urban environment. The idea of vertical farming is finally taking root. Over the past few years, vertical farms have sprouted up all over the world. The U.S., along with some European and Asian countries, have been conducting research and have made significant advancements on vertical farming technology over the past decade.

The UN predicts that the global population will reach 9 billion by 2050. Around 4 billion of the total population will be living in cities, meaning the associated stresses on our planet will become more intense. An issue of top concern is there is global water crisis, waiting to be addressed. According to the Food and Agriculture Organization of the United Nations, agriculture, which accounts for 70% of water usage worldwide, has played a major role in water contamination around the world. Even though more people have taken action to preserve water quality, water-use efficiency, and other water management issues, there is still an overall lack of wastewater management in many countries. Farms discharge large quantities of agrochemical, organic matter, drug residues, sediments and saline drainage into water bodies. The resultant water pollution poses demonstrated risks to aquatic ecosystems, human health and productive activities (UNEP, 2016). Water is essential for food production. On average, 70% of all freshwater is used for agriculture. Experts estimate that about 20% of freshwater is for industry and the remaining 10% is for human activities; thus, agriculture uses the majority of the world's fresh water. Over the past 50 years, in efforts to keep up with human population growth, the agricultural water use throughout the world has more than doubled. Besides this threat of water supply, another pressing issue is that one third of our land has been degraded in the last 40 years due to erosion and pollution (site). This has begun raising a major crisis of degraded soil that could have potentially disastrous consequences as global demand for food soars(site).

"We aren't quite at the tipping point yet, but we need to do something about it. We need a radical solution, which is to re-engineer our agricultural system." - Duncan Cameron, Professor of the University of Sheffield.

As noted before, since more than 4 billion of the world's population will be living in

cities in the near future, far more than the urban population that we have today, how do people expect the number of farmers in 2050 to be able to grow enough food to feed everyone? Considering the facts that 70% of fresh water contamination comes from agriculture, 70% of fresh water usage goes to agriculture, and 33% of arable land has been lost in the last 40 years, we need to find new ways to feed our planet.

2. Introduction

As the human population keeps increasing and land becomes more and more valuable, how do we ensure global food security? The answer is growing upwards. Vertical farming is a potential high-tech solution to address the problems that have been caused by traditional farming.

In July 2017, an agriculture company named Plenty, based in San Francisco, attracted the largest-ever agriculture technology investment led by the SoftBank Vision Fund to solve global fresh produce shortages. As one of the leading agricultural companies, Plenty has been combining technology with proven plant science and optimal agriculture methods to build a new type of indoor farming. This investment from SoftBank is aiming to provide support for the company to fulfill its mission of solving the increasing critical need to make fresh produce available and affordable for people around the world.

Starting in Silicon Valley, interest in vertical farming flourished after news of this broke. However, compared to North America, the food shortage problem is more rampant in other parts of the world. For instance, the entire population of the Bay Area in California is approaching 8 million, far less than most of Asia's big cities. A typical example is China. China has over 102 cities that have a population over a million, 30 of which are over 8 million, and 13 of which have over 10 million. By 2030, the urban population in China is estimated to reach 1 billion, which is 70% of the current Chinese population. Therefore, there are many reasons to believe that the practice of vertical farming will bring benefits to countries like China in terms of the environment and economy. As seen in the case of China, the potential market of vertical farming is huge, and not just ideal for America. Vertical farming is applicable to many countries of the world.

In traditional farms, fruits and vegetables take days, weeks, even months to grow. This requires a lot of labor and is very time consuming. With the development of agricultural technology, modern vertical farms use Controlled-Environment Agriculture (CEA) technology. With CEA, all environmental plant factors, such as the light, humidity, temperature, and gases can be controlled by a small number of agricultural specialists. This allows vertical farms to grow fresh and nutrient-rich food

more efficiently.

Instead of transporting food from thousands of miles on freeways and the need for storage, vertical farms are making locally-grown produce possible anywhere. Crops from vertical farms will therefore have a much smaller carbon footprint, and more efficient water and land use.

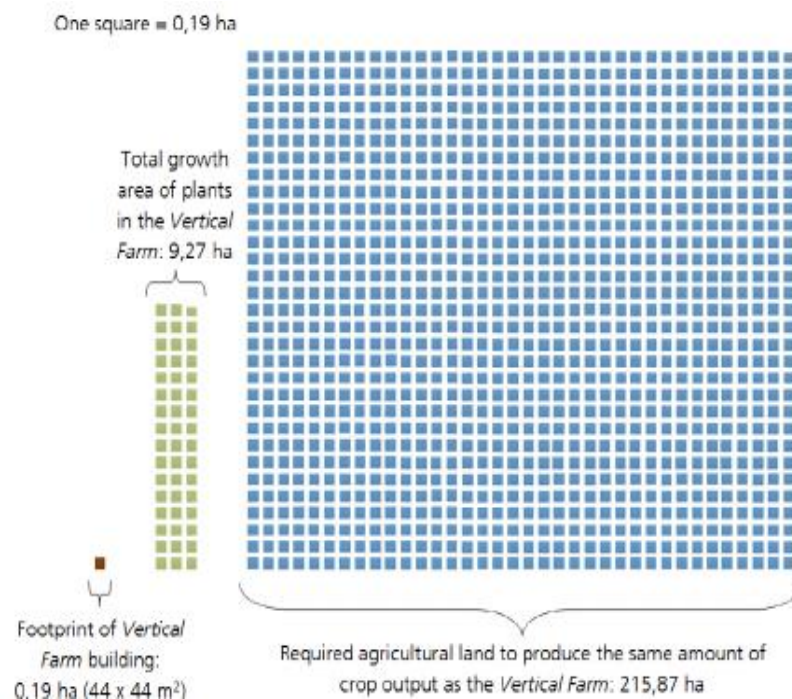


Figure 1. Vertical Farm compared to Traditional Agriculture (site 20)

Analyzing the feasibility of vertical farming is important as it provides information that can assist in solving food shortages and environmental problems associated with the urban development process, as well as determining the potential monetary values associated with different types of crops. Studies that compare the different aspects of crops from conventional farms and vertical farms are relatively few; therefore, it is important to have a better understanding of the potential values behind vertical farming. Not only it is beneficial for the environment, it could also be an opportunity for agricultural scientists and specialists to lead a revolution of the food system.

The first goal of this study is to analyze the theory and the potential of vertical farming in addressing issues that exist in today's food system. One method would be to conduct a comparison between the greenhouse system and vertical farming. Since traditional farming is not likely to disappear, vertical farming will probably never take the place of outdoor farming, however, since the greenhouse system and vertical farming are similar in many ways, comparing those two systems provides a clearer image of what vertical farming can actually bring to society. Thus, when investors are

planning on investing in a greenhouse they might consider the option of considering vertical farms. The second goal of the project is a theoretical data analysis. It includes evaluating essential factors of a vertical farm in order to make it ecological sustainable. Only by learning from past experience can we give valuable recommendations to the people who are interested in building vertical farms in the future.

3. Vertical Farming Technology

To make vertical farming possible and successful, indoor farming technology is one of the most important factors. Since 2007, the application of vertical farming has been increasing(site). Vertical farming is cultivating vegetables vertically by using new farming methods. These methods combine the architectural design and farm design together in a high-rise building inside cities. This technology needs both agricultural and architectural technology to be developed coherently.

3.1 General structure of Vertical Farming

Due to the location, types of crops, and environmental factors, vertical farms vary in design (site 6). Figure 1 shows the general structure of vertical farming. There are 7 main sections in a standard vertical farm, which include environmental controls, water and nutrient tanks, a germination and cleaning layer, food processing with a staff and control room, delivery area, a waste management layer and a fish farm.

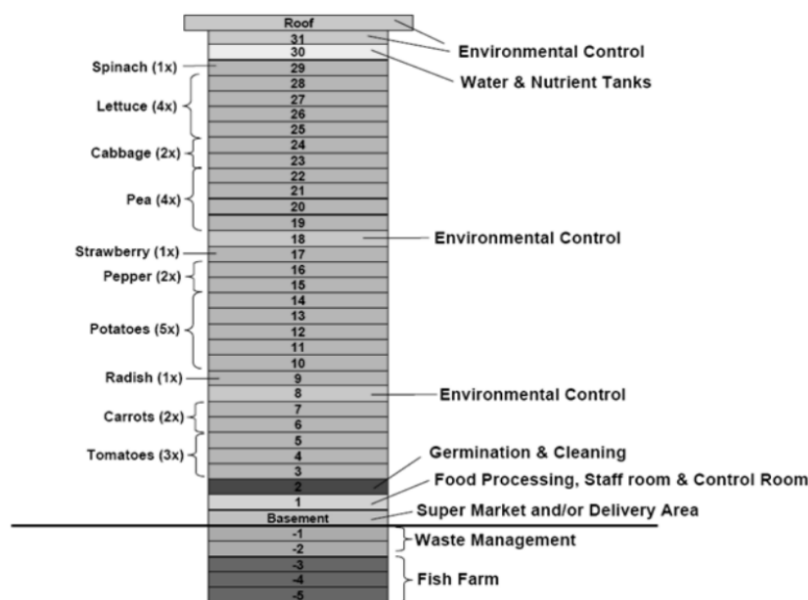


Figure 2. General Layout of a Vertical Farm

For example, in order to supply 15,000 people with food, a building design requires the following properties: the size of the vertical farm should be 93ha (about the size of a city block), 37 floors, 25 of which are only for growing of crops and 3 of which are

for aquaculture. In addition to the food production floors, 3 uniformly distributed floors are for environmental control and 2 floors are for waste management. Furthermore, there is one floor for the cleaning of growth trays, sowing and germination. An additional floor is allocated for food packing, including processing the crops and fish. Another floor is purposed for selling fresh produce and food delivery at the basement of the building structure. This design makes the overall dimension of the building 167.5 meters high, 44 meters long and 44 meters wide, the aspect ratio is 3.81. To help transport the produce down to the respective floors, a spacious elevator is installed in the middle of the building, which is big enough for a forklift truck. This standard vertical farming system requires 217,000L of water per day, 14,000L of which is absorbed and leaves the building with the water waste. The water not absorbed by the vegetables is accumulated and circulated again in a water recycling system. The water is processed and sprayed once more before the loop is closed, allowing the water to be used to maximum effect (site 8). This structure allows the vertical farm to produce unique produce, because they are provided to the customers upon being harvested with nearly no transportation or storage cost.

3.2 Lighting of Vertical Farming

Sunlight is necessary for crop growth. Vertical farms cannot survive without enough lighting. In order to manage the production line, whether the vertical farm is planning on using 100% artificial light, or both artificial and natural light, must be taken into account. There are two types of lighting that are commonly used in vertical farms: LED (light emitting diode) and HPS (high-pressure sodium) (site 9). The normal range of light intensity utilized is 50-200mol/m²/s or about 4100- 16400 lx including high-pressure sodium lamps. In a closed space, 18 hours of lighting is required for optimal vegetation growth. Using materials with high transparency and thermal rates can also help by raising the amount of sunlight that penetrates the building. Even though natural lightning is the main energy source from outside of the building, there also needs to be daylight concentration. Specialized direction and distribution strategies for sunlight can be used effectively throughout the year.

Because plants are stacked in vertical farms, sunlight is not able to reach all the layers, especially those at the bottom of the building. In order to let every single plant receive enough lighting, artificial lighting is essential to supply the energy of vertical farms (site 10). In addition, building angle and shape, time of day, and the different seasons are all factors which affect the amount of light absorbed. (see the Figure 2.) A well-designed lighting system can decrease the need for artificial lighting, therefore reducing the cost of the final produce.

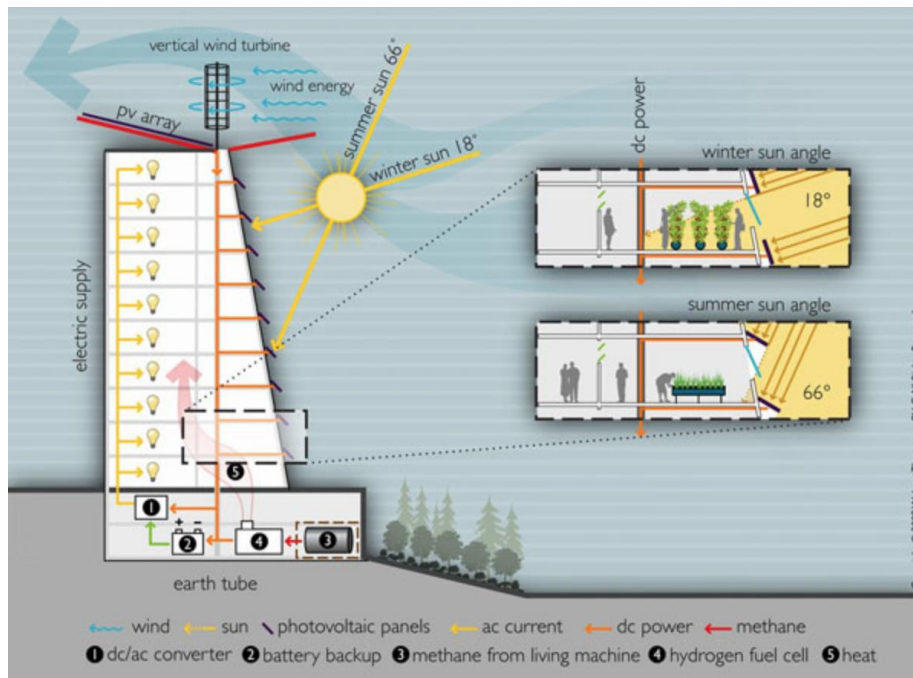


Figure 3. Vertical farming building use the maximum of sunlight (Photo credits to Weber Thompson/ www.verticalfarm.com)

3.2.1 LED Lighting System

As mentioned above, there is a need for artificial light in vertical farming. There are many alternatives available, but LED lights have become the most commonly used source in vertical farming(ref). Besides the fact that the cost of LED lights have decreased by 60% in the past few decades (site here), becoming much more affordable, LED lights normally have a long-lasting life and high energy efficiency. LED lights are also able to target particular light wavelengths to better manage the photo-period and provide plants with exactly the light spectrum they need (site 14). In addition, by regulating the proportion of red color (R) and far-red (FR) of LEDs, the wavelength of LEDs can lead to more optimal units. Scientists indicate that the photosynthesis of LEDs is more efficient than green and white. In addition, if 10-20% blue light is added to red light, the shape of the crop will usually be more normal (site 15).

3.3 Water Use of Vertical Farming

As mentioned in the background information, 70% of fresh water goes to conventional farming -- a large proportion compared to industrial water use. Traditional irrigation can cause a large portion of water to be wasted due to evaporation. What's worse is that the water that leaves farms as run-off is contaminated by fertilizers, pesticides and other chemicals (site 16). This makes the water unsuitable for drinking and means that those affected end up spending more energy on water treatment to make it potable for human use again. When conventional farms are upgraded to vertical farms, the water use problems mentioned above can be mitigated. The strict

environmental control system in vertical farms allows plant growth without the application of any fertilizers or pesticides, which allows the water to be reused inside the system. The amount of water needed for hydroponic agriculture was estimated to be 1L for each square foot a day (or 10.71 per square meter) (site 17). Depending on the type of crop, 200-600L of water is needed to provide 1 kilogram of dry product. Relatively conservative water usage is one of the aspects that makes vertical farming special -- there are even some techniques aimed at resisting the lack of water in order to minimize the water use in vertical farming.

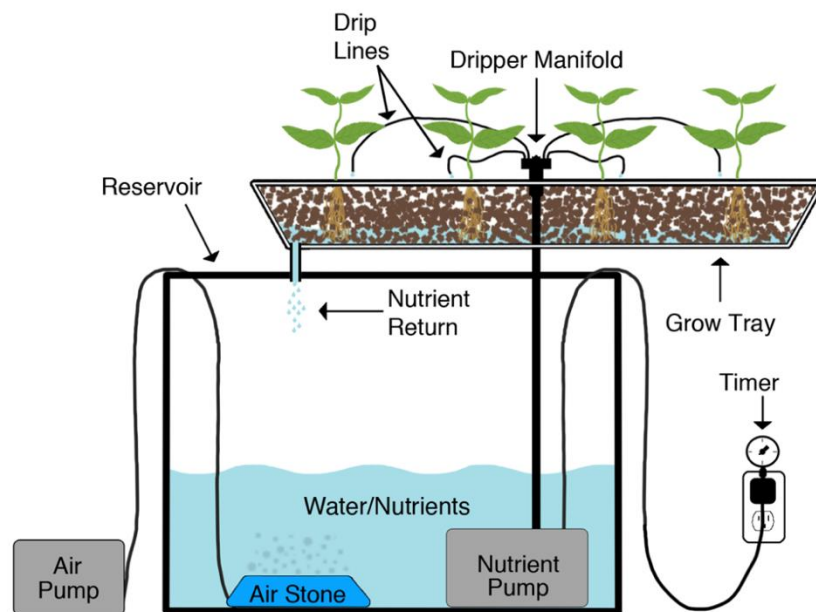


Figure 4. Hydroponics technique (site 25)

3.3.1 Water recycling and dehumidification

Generally, water inside a vertical farm is pumped to the top of the building and allowed to fall and irrigate the plants (site 18). Vertical farms can not only use collected rainwater from the roof, they can also use gray water, which is water that has already been used once. This way there will be little water wasted and there will be little impact on the water table.

Evaporation is a natural process(site), however in vertical farms, dehumidification techniques allow evaporated water to be used again. Dehumidification devices are installed on every floor to retain water and save it for later use. This technique can help to collect 220,000 m³ of water each year (site 19). A good example of using dehumidification techniques would be Aerofarms. At Aerofarms, water and its solutes are directly sprinkled to plant roots in the form of a mist (site 7). This method of irrigation uses 1.2 times less water to grow the same amount of crops as a traditional farm, which means it's more economical and more environmentally friendly(site 19). This also makes contributions to the global water cycle.

3.4 Energy Use of Vertical Farming

Vertical farms require proper lighting and temperatures for crops to grow. Energy is needed for equipment to run, including elevators, fans and ventilators. Heat pumps are used to control the climate, water pumps are used for diluting nutrients, and agitators used to manipulate plants (site 21). Imagine what would happen if a vertical farm went without electricity for a day. Plants would not be able to get enough light, the irrigation system would shut down and the climate control system would not be able to work. Providing consistent energy is critical to making vertical farms sustainable.

In order to capture as much solar energy as possible, vertical farms usually have a roof equipped with solar panels. These reusable energy devices are able to convert 30% of the solar energy they take in into electricity. Inside the vertical farm, pressure sodium lamps then turn 12-22% of the electricity to light to help plant growth. Solar collectors are also a good way to collect solar energy, but are more costly than installing solar panels on the roof. In order to receive the right amount of energy that a vertical farm needs, there was a model devised to obtain the number of solar panels required to provide energy needs (calculation to be done based on light and water provision estimations) (site).

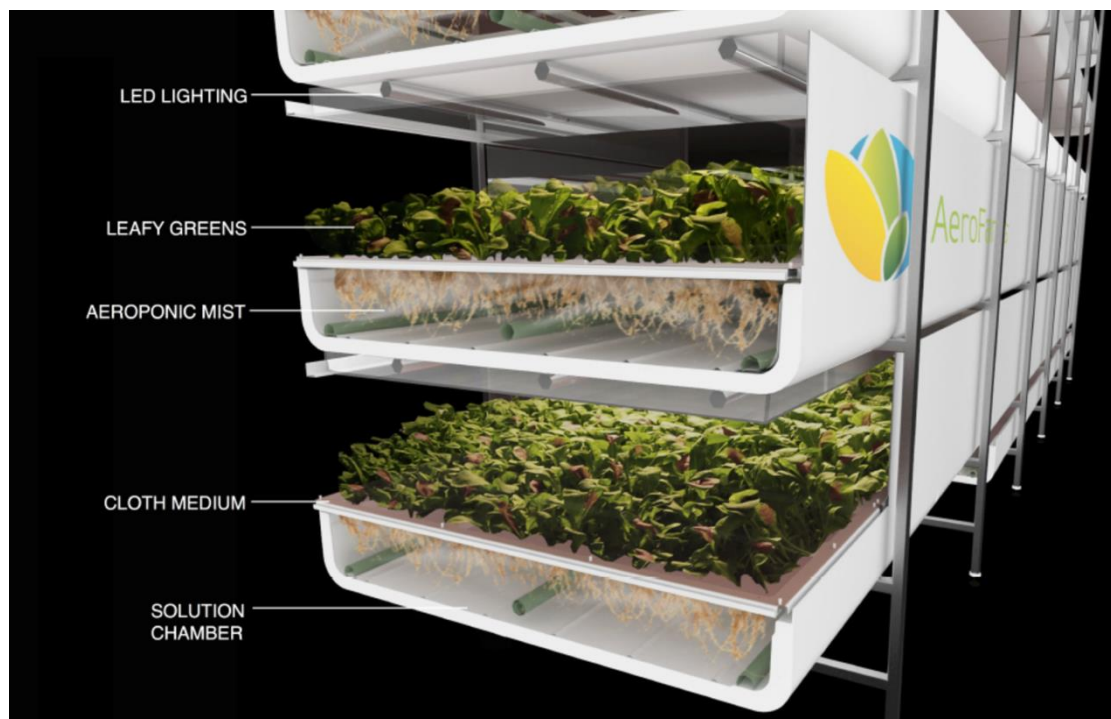


Figure 4. Plants Growing System at Aerofarms (<https://aerofarms.com/technology/>)

4. Greenhouse system VS. Vertical farming

For most places on the planet, growing food outdoors is not possible throughout the whole year. In fact, only 10% of the world's land is arable (World Bank 2017) so increasing demand for local food is one of the main factors that has been pushing the annual growth of the commercial greenhouse market to almost 9%. It is expected to reach \$29.64 billion by 2020 (Markets and Markets 2016). The idea behind a greenhouse is to create a space to keep heat in so that farmers can grow crops throughout the year. Greenhouses serve as a shield between nature and the crops, allowing growing seasons to be extended and possibly improved. They play a role as a shelter from excess cold or heat as well as pests. A greenhouse can be constructed relatively cost-effectively or more expensively, depending on the materials, functions, and techniques it requires. There are professional greenhouses that are built for lab finding research, commercial greenhouses built for agricultural business, and also hobby greenhouses that people can simply build in their backyard.

Figure 5. Combined heat and power for commercial greenhouse (picture from



<https://power.cummins.com/greenhouse-growers>

Compared to a greenhouse, the requirements for building a vertical farm are much more strict (site). Every single detail needs to be designed by professionals which makes it more difficult to achieve. With these comes the ability to increase the yield dramatically in vertical farms. In addition, investors do not need to spend money on pesticides or on insecticides, meaning there will be less agricultural waste and little to no impact on the water quality. The advanced CEA technology protects crops from extreme weather conditions such as hurricanes, droughts and snap freezes. As the global temperature becomes unpredictable, this method can assure profit for investors. There is little spoilage of produce and people won't need to bear as much transportation costs of the produce from one place to another, as all crops would be utilized within the city.

However, with the high return comes the high cost associated with vertical farms. Because the cost is so high, crops in vertical farms must be valuable to keep the

ecosystem economically sustainable, which makes only a few varieties of crops viable to be produced in this controlled environment, such as lettuce, flowers or herbs. The dependence on technology is another shortcoming of vertical farming. A vertical farming system will not be sustainable without a reliable and consistent power supply. If the power cuts off, all the growing crops will not survive, since they are dependent on the artificial atmosphere, which provides its necessary requirements for the crops and to maintain the environmental factors at a stable temperature of 40 degrees Celsius and constant humidity(site).



Figure 6. Comparison between the greenhouse system and vertical farming (picture from <https://amhydro.com/horizontal-vs-vertical-hydroponic-farming/>)

The location of a vertical farm is critical because it is related to the demand of the local market. As an ecosystem, vertical farms need to be sustainable to continue to exist. Vertical farms require consistent investment for producing crops. However, because the technology and techniques exist to grow food anywhere, the aspiring vertical farmer still has many questions to answer in order to get the location recipe just right. In addition, greenhouse operations might be done by a single person but vertical farming requires a team. To make the labor equation work, local farmers need a reliable, capable workforce to help them with daily tasks like planting, harvesting, and packaging to provide a healthy working environment in a vertical farm. Farms need to know more than just experience, they need to learn more about what they are growing and how to monitor the plants by using advanced tools. Last but not least, pricing the produce reasonably is another challenge in vertical farms, making the produce affordable yet profitable can ensure the development of the farm. For example, a vertical farm in Vancouver announced bankruptcy in 2014 because the company could not make enough revenue to cover their cost (site 23).

	Advantages	Disadvantages
Greenhouse	<ol style="list-style-type: none"> 1. Suitable for many types of crops (fresh greens, vegetable and fruit). 2. Fresh food all year long. 3. Safety from pests. 4. Easy to achieve. Adds beauty and visual appeal to a landscape. 	<ol style="list-style-type: none"> 1. Can be expensive to build. 2. Usually takes a large space (large footprint). 3. Can be expensive to heat. 4. Requires constant monitoring, maintenance and care. 5. Requires high energy use and water use.
Vertical Farming	<ol style="list-style-type: none"> 1. Efficient Growing Method. 2. Protection from Harsh Weather Conditions. 3. Reduces water usage and waste. 4. No spoilage of produce. 	<ol style="list-style-type: none"> 1. High Cost (land, technology) 2. Limited varieties of vegetables and Fruits. 3. Dependence on technology.

Table 1. Comparison Between Greenhouse Systems with Vertical Farms

4.1 Comparison of Greenhouse vs. Vertical farming

The debate in the agriculture industry regarding whether greenhouses or vertical farming will be more profitable for growing plants is divided. Some research has been done in order to compare the aspects of greenhouses and vertical farming. Studies of the economics associated with operating greenhouses in various locations (eg., Kessler 2016), the investigation of the economic dynamics underlying the operation of a vertical farm (eg., Mok et al 2014; Eigenbrod and Gruda 2015). People in the industry commonly believe that vertical farming is not compatible with greenhouses because of the high cost of the artificial lighting (Shackford 2014). The policy paper *Comparing the Profitability of a Greenhouse to a Vertical Farm in Quebec* from James Eaves and Stephen Eaves provide a comparison between the two models when holding production variability and yield equal(cite).

5. Discussion

While organic food is becoming more and more popular in our society, most people have realized that using agrichemicals in farming has all sorts of numerous negative impacts on the ecosystem, therefore organic farming has been touted as an environmental solution. However, organic farming does not generate as much yield per unit as non-organic farming, therefore in order to produce enough food for the

increasing population, such systems have to use more land to achieve the production, which is a problem in itself.

To solve this problem, the answer is to grow upwards instead of growing outwards. As a closed stacked system, vertical farming is a promising solution to the drawbacks of traditional agriculture. Compared to traditional farming, it is able to produce healthier and higher yields in a relatively short amount of time, and the quality of the produce can almost be guaranteed because the system is resilient to climate change.

Depending on the use, size and main techniques that are used in a vertical farm, vertical farms can be categorized into different types, however the common goal of most vertical farms is to increase the yield in a sustainable way. Table 2 is the estimated yield of a vertical farm compared to traditional agriculture for 10 different crops. As expected, yields in vertical farms are usually higher. A good example would be potatoes; yield of potatoes in traditional farms is 28 tons/ha while in vertical farm is 150 tons/ha, which is almost 5 times more. The average yield of a vertical farm is about 2.5 times more than traditional farms. These increases in yield of the vertical farming are the result of the protected environment, additional numbers of growing cycles and harvests, as well as area utilization optimization.

Crops	Yield in VF due to Tech (tons/ha)	Field Yield (tons/ha)	Factor increase due to Tech	Factor increase due to Tech and Stacking
Carrots	58	30	1,9	347
Radish	23	15	1,5	829
Potatoes	150	28	5,4	552
Tomatoes	155	45	3,4	548
Pepper	133	30	4,4	704
Strawberry	69	30	2,3	368
Peas	9	6	1,5	283
Cabbage	67	50	1,3	215
Lettuce	37	25	1,5	709
Spinach	22	12	1,8	820
Total (average)	71	28	2,5	516

Table 2. Estimated yield of a vertical farm compared to traditional agriculture (source: Designed in a CE Study by the author at DLR Bremen)

Despite the high cost of building a vertical farm, higher yields mean more revenue for investors, as long as there is a market for it. Markets for vertical farming are found mainly in resource-constrained nations and mega-cities with substantially high purchasing power (site 24). Figure 6 displays the market value of vertical farming worldwide in 2015 by region in million U.S. dollars. In 2015, Asia-Pacific had the largest market for vertical farming and the market valued was estimated to be approximately

355 million U.S. dollars. As populations continue to grow and land becomes extremely precious, the idea of vertical farming will become more accepted and understood, which will help to increase the demand and market of vertical farming.



Figure 6. Market Value of Vertical Farming Worldwide in 2015

Anyone that has been paying attention to the vertical farming industry over the last few years knows that it's just starting to take off. There are new agricultural companies emerging every day, promising to deliver new solutions in every aspect from growing equipment, lighting, climate controls, data, sensors, automation, consulting, and even machine learning. Vertical farming is happening today in several U.S. cities, Canada, Sweden, Japan and shortly in Shanghai and Singapore. As the cost of energy continues to decrease, produce from vertical farming will become more affordable and the market is promising.

6. Recommendations

The expected result of this project is to determine if vertical farming is a good way to supply food to cities in an energy efficient and sustainable manner from both a quantitative and qualitative approach, and also to provide useful information for vertical farm stakeholders to help them achieve a sustainable vertical farming system. There are 8 major principles for vertical farming to access its sustainability:

- Food safety and quality assurance of the produce
- Strict pest management
- Nutrient management

- Water conservation, recycle and management
- Community education
- Waste management
- Energy and climate control
- Site and facility characteristics

In order to meet the principles and set the standards, four basic recommendations are made to help achieve a sustainable vertical farm.

- Pick the right location:** Choosing the right location is critical. Because after all, the reason of building a vertical farm is to grow crops closer to market and meet the demand for fresher food.
- Quality farm laborers are required:** Requirements to maintain a clean environment in a vertical farm are very strict, therefore employees need to be well educated on this subject to keep the environment suitable for plants to grow and therefore achieve the max harvest rate.
- Trustworthy technology and power resources:** Vertical farms cannot survive without consistent energy supply and water supply. Because vertical farms are soilless farming and are highly dependent on technologies to create an artificial environment for plants. Out of power for too long will make the environment out of control, when plants don't get enough sunlight, nutrition and water, they will soon become dehydrated and won't last for too long in a soil-less environment.
- Accessible data platform:** The average age is 6 years old for vertical farms, which means most of them are fairly new. Investors tend not to reveal their costs because it's a competitive industry, however, it would be much more valuable if more people can have access to those data. Make the industry more transparent can also help the industry to grow. Having consistent data would also be helpful for farmers to learn from the previous examples and find out the best practice possible.

7. Conclusions

Vertical farming is at an early stage of development. It is still on its way to its mission of bringing local produce to people and communities everywhere by growing the freshest, best tasting crops, all while using one percent of the water that a traditional farm would. Vertical farms also use less than one percent of the land, and none of the pesticides, synthetic fertilizers, or GMOs of conventional agriculture. The integration of vertical farming into the urban areas has also been seen as a connection to the city

and its residents. It simultaneously helps to reduce poverty, contribute to food safety, and increase contextual sustainability as well as human well-being.

It is still unclear how competitive vertical farming will be. It may not be able to compete with other suppliers in a global market unless people are willing to pay a premium for fresh and local produce. However, with the rapid advancement of technology and new research focused on improving indoor crop production, vertical farming can become more affordable, through overcoming hefty electric bills, improving food safety, expanding crop range, and increasing people's knowledge of the industry. To sum it up, despite its challenges, this industry is looking up.

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