A report for:

Vertical Farming

Can it change the global food production landscape?

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Executive Summary

It is a known fact that the world’s population is rapidly increasing and becoming ever more urbanized. At the same time, people have never been so disconnected from their food sources. Agriculture uses a great deal of the water resources available and effluent runoff is a major problem. Vertical Farming means producing food in vertically stacked growing layers, and it seems to be a solution to address some of those problems we currently face.

Vertical Farms apply Controlled Environment Agriculture (CEA) techniques to some extent. CEA allows farmers to control many variables that influence crop growth and development, such as lighting, air and temperature control, and nutrient supply. Vertical Farms are closed production facilities that share a lot with manufacturing industries, which are constantly optimizing their processes.

The main advantages of Vertical Farms are year-round crop production, irrespective of external weather, predictable and stable yields, considerably shorter crop cycles, a highly diminished water consumption, minimal usage of pesticides or fungicides, a decreased growing area and the repurposing of urban buildings and unproductive spaces. Hydroponic, aeroponic or even aquaponic systems favour a clean and quick crop development while maintaining the resource usage to a minimum.

These advantages are clear; however, profitability is still difficult to achieve. Many new businesses suffer once their seed money dries up. Vertical Farming is still farming; therefore, the produce must be sold at the same price levels as products grown in an open field where the light, air, soil and water are almost free. Controlling each and every variable comes at a cost. The high capital and operational costs (electricity and labour) force companies to scale up in order to achieve profitability or focus on higher margin crops.

The possibility of being close to the point of consumption is another huge point in favour of Vertical Farms. There is a clear market tendency towards foods with a lower “mileage”, as well as organic produce. The lesser distance travelled not only guarantees freshness but is also a “green” selling point, saving CO_2 emissions from shipping. In the US, for example, most of the greens consumed in New York City must cross the whole country, as they are produced in sunny California.

The Brazilian market does not share all the drivers that are strong in countries which have already adopted Vertical Farming commercially. Weather in Brazil allows year-round production, and the main producing areas are near to the huge cities like São Paulo or Rio de Janeiro. Trying to sell leafy greens in the open market at the same price level as open-field produce can be hard. However, business models that focus on scarcity, high value crops or medicinal compounds offer a huge opportunity which is yet to be explored.

As technologies keep evolving (like LED lighting did in recent years), costs will go down and efficiency will increase even further. This will allow Vertical Farms to be more profitable as they lower their production costs, and also diversify the crops produced. It is hard to predict whether Vertical Farms will help feed the world someday; however, the necessity for fresh, safe, dependable food will always exist. The Vertical Farming industry has a bright future ahead. This is just the start.

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Foreword

My family has been involved in agriculture for generations. Since the Dutch colonizers arrived in Brazil after WWII, in the 1950s, producing food has motivated each and every family who arrived in this vast, still unexplored country (at the time).

My path was different. As I moved out to study, I decided to follow my love for technology and new ideas and became an Electrical Engineer. My engineering mind makes me constantly rethink how processes could work more efficiently.

Being raised inside agriculture, I also have farming in my soul. My father is an agronomist and dedicated most of his life to research; I love to hear of new ideas that come to solve everyday problems. In summary, my appreciation for both topics has led me to work with high-tech products specifically developed for agriculture, which allow farmers to be more productive, basing their decisions on real data from their fields.

Thinking about how we can be more efficient, innovative, break old paradigms and create a new future has led me to become interested in a fresh topic – Vertical Farming.

The Nuffield Scholarship gave me the opportunity to travel around the world and gather knowledge from multiple sources, understanding if and how these new production techniques can change the way we produce food on an increasingly urban and more densely populated planet.

Acknowledgments

Thanks to TIAA-CREF for having invested in me and believing in my work. This opportunity opened the doors of the world for me to explore, and to develop this research on such an innovative a topic – I look forward to repaying your generosity.

This report is a compilation of countless conversations, visits and interviews which have given me the knowledge and understanding of this beautiful new industry. Thanks to you all of you – farmers, consultants, enthusiasts who have generously shared their time, knowledge and experience with me!

My sincere thanks to all the fellow Nuffielders, both in Brazil and internationally, who have supported me during my research, and all the scholars with whom I have talked and interacted. You all have broadened my view about the world's agriculture, filling my mind with interesting ideas and possibilities. To the GFP Africa team: thanks for being a part of this experience which I will cherish forever! A special huge thank you to Sally Thompson and Jim Geltch for the wise advice I have received since this journey began.

Ivana Pantarotto, my love: you have truly exercised the meaning of partnership supporting me each and every day during this long journey which often took me so far away around the world! Professionally, I thank you for having dedicated yourself to our business brilliantly in a very busy time. Personally, I am forever grateful for the encouragement you always gave me when I needed, for believing in my work, for your great ideas and conversations, and for always supporting me to follow my dreams and travels.

Of course, nothing of this would have been possible without the education, principles and values my parents have taught me. Eltje and Catharina Loman, thanks to you, since I was a small kid I knew the importance of a life full of curiosity, learning, dreaming and dedication. And Camilla, my sister: If you had not sent me that e-mail about the Nuffield application process, I would have never had this life changing experience! Thanks!

My friends at Metos Brasil: thanks a lot for keeping the positive momentum and our company running during my absences! You are an amazing team and I am really proud to be part of it.

Abbreviations

AAO: Organic Farmers Association
BNDES: National Bank for Economic and Social Development
BPA: Bisphenol A
Capex: Capital Expenditures
CEA: Controlled Environment Agriculture
CFL: Compact Fluorescent Lamp
CLASP: The Collaborative Labelling and Appliance Standards Program
CO_2: Carbon Dioxide
DFT: Deep Flow Technique
EC: Electrical Conductivity
EIA: U.S. Energy Information Administration
GAP: Good Agricultural Practices
GHG: Greenhouse Gas
HID: High-Intensity Discharge
HVAC: Heating, Ventilation and Air Conditioning
HPS: High Pressure Sodium
kWh: kilowatt-hour
ICE: Institute of Culinary Education
ICMS: Merchandise and Service Circulation Tax
IEA: Agricultural Economy Institute of São Paulo
IPI: Industrialized Product Tax
LED: Light-Emitting Diode
LEED: Leadership in Energy and Environmental Design
MIT: Massachusetts Institute of Technology
NASA: National Aeronautics and Space Administration
NFT: Nutrient Flow Technique
NYC: New York City
PAR: Photosynthetic Active Radiation
PFAL: Plant Factory with Artificial Lighting
PVC: Polyvinyl Chloride
RH: Relative Humidity
UN: United Nations
USDA: United States Department of Agriculture
VF: Vertical Farming
WHO: World Health Organization

Objectives

This study aims to:

- Develop an understanding of the concept of Vertical Farming and compile the best production practices adopted by this flourishing industry.
- Clarify the economics behind the Vertical Farms and the reasons behind the successful initiatives.
- Ultimately, to understand the potential present and future fit of Vertical Farms and related technologies and processes in the Brazilian scenario.

Introduction

In the 21st century, we face a rapidly growing population with a declining amount of available arable land. In a world where 815 million people go to bed hungry every night [1], 1.9 billion people are overweight [2], arable land, fresh water and fertilizers are scarce, innovative solutions for food production, distribution and access are necessary.

Earth's population will have an additional billion people within ten years, 2.5 billion over the next 35 years, and nearly two-thirds of this global population is expected to live in a city during this time [3, 4]. Estimates predict that feeding these new generations will require humanity to increase food production by 70% over our current levels of production [5].

Due to limited natural resources, 90% of this growth in global crop production is expected from higher yields and increased cropping intensity, with the remaining 10% from expansion of productive land [6]. Almost all of the land expansion in developing countries will take place in Sub-Saharan Africa and Latin America. The availability of freshwater resources is also a serious issue: globally, there is more than sufficient fresh water; however, it is unevenly distributed. Food production and consumption already accounts for 19%-29% of global greenhouse gas (GHG) emissions, larger than emissions from the energy or transportation sectors [7, 8].

Our present agricultural footprint is already the size of South America. It feeds (although not in the most efficient way), our seven billion people. To feed the coming three billion people in the next few decades using conventional agriculture, would need an additional landmass of the size of Brazil. As a Brazilian, I can safely state that our country is not willing to lose its 61% of its still preserved land including its native rainforests.

To tackle these and many of the current food production challenges, a new form of agricultural cultivation is becoming more important and attracting much attention and research: Indoor Vertical Farming, based on a plant-factory system with artificial lighting and controlled environment, for a super-efficient production of food crops.

One solution to our need for more space and more food might be found in the abandoned warehouses in our cities, or in new buildings built on environmentally damaged lands and even in used shipping containers from ocean transports.

Vertical Farming involves growing crops stacked vertically in controlled indoor environments, with precise light, nutrients, and temperatures. The growing plants are stacked in layers that may reach several stories tall. The term "Vertical Farm" was first created by Prof. Dickson Despommier, who envisaged that high urban buildings could start producing food and change this scenario. While the "food-producing skyscrapers" are still far away from reality, Vertical Farming is definitely becoming part of the urban scenario in many Asian countries, in the US and in a few countries in Europe.

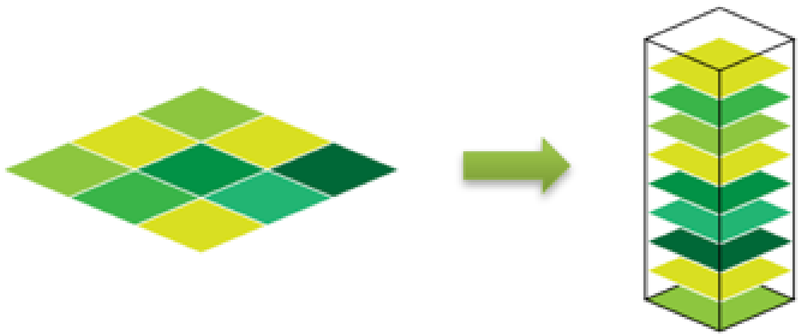

Figure 1 - Stacked productive layers greatly increase productivity

The main advantage of this high-density production is that control over many variables not only drastically reduces the amount of inputs but also allows for control of insects and pathogens. Vertical Farming also allows significantly shorter crop cycles and year-round production, with no need for many fungicides and pesticides. The result is not only faster growing plants but also food that is almost organic due to this lack of pesticides and other additives. Interest in these new farming techniques is growing rapidly, and several entrepreneurs are taking a serious look at this innovative farming system, especially in mature markets and in high-density populated areas.

Basically, a plant growing in these artificially-lit environments lives in a perfect sunny day every single day, which results in very good crop development. The lighting usually comes from efficient LEDs, which in some cases even emit only the light frequencies that the plants are able to absorb. The fact that Vertical Farms stack these growing beds many layers high, with LED lighting and a good hydroponic system, results in a productivity that is dozens of times higher per square meter when compared to open field agriculture, especially if you compare the output per area per year. In many countries, conventional agriculture is not able to produce food year-round, due to the weather conditions, which clearly gives an advantage to Vertical Farming in the market.

Vertical Farms are not a replacement for conventional greenhouses or open-field production. Rather, the rapid development of Vertical Farms (or PFALs – Plant Factory with Artificial Lighting) has created new markets and business opportunities. Vertical Farms are being used in the US, Japan and other Asian countries and some countries in Europe, for production of leafy greens, herbs, transplants and seeds to feed urban populations with local and fresh food.

The high level of possible control in these farms allows tweaking environmental variables (e.g. forcing a certain stress), which may induce plants to metabolize certain desired components: an interesting possibility when producing medicinal plants and extracts, which is an industry that still has a lot to benefit from Vertical Farming. Vertical Farms are uniquely suited to overcome the most common challenges associated with the phyto-pharmaceutical industry, which include focusing growth on specific plant parts, providing sufficient supply when wild habitats are endangered and biodiversity loss is a key threat, mitigating contamination risk of genetically engineered organisms in the natural environment, and increasing yields of specific chemical compounds dependent upon specific environmental conditions.

As a Nuffield Scholar, my mission is to understand the growth of Vertical and Urban Farming, its techniques, business models, challenges, and whether it can be part of a global sustainable food production system. Ultimately, my aim is to understand if these innovative businesses are viable in Brazil.

Chapter 1: Concepts and technologies

1.1 Controlled environment agriculture and vertical farming

The definition of Vertical Farming is the practice of producing food in vertically stacked layers, vertically inclined surfaces and/or integrated into buildings. The modern idea of Vertical Farming uses Controlled Environment Agriculture (CEA) concepts and technologies. CEA facilities use environmental control (humidity, temperature, gases, etc.), fertigation, and artificial control of light (as a supplement in the case of a rooftop greenhouse, or as a unique light source in Vertical Farms).

Environmental factors that affect plant growth

Major and well-studied environmental factors that affect plant growth include temperature, light intensity, light quality, humidity, CO_2 concentration in the air, air-current speed, nutrient and root-zone environments.

One of the great advantages of Controlled Environment Agriculture and consequently of Vertical Farming is the possibility to tweak and adjust each environmental factor to maximize the productivity and desired results for each crop. Understanding these key factors is crucial to maximizing the biomass production in Vertical Farms.

Of course, controlling each of these components comes at a cost, and each level of control brings different outcomes. Each grower needs to determine whether a control system (usually automated) will make sense case-by-case, comparing the expected gain in production and control versus the investments involved. This type of cost-benefit analysis is crucial when growers are determining if they will build a Vertical Farm instead of a greenhouse, which would rely on natural sunlight.

1.2 Components of a Vertical Farm

Vertical Farms can be very diverse, both structurally and technologically. Some farms rely solely on artificial lighting for plant growth, whereas others grow plants vertically, still utilizing some of the sun's light. Also, plants can either be grown in soil (potted) or using hydroponic methods, which are much more common. Usually, a commercial Vertical Farm relies on an artificial, warehouse-like structure, thermally insulated, in which ventilation is kept at a minimum, and artificial light is used as the sole light source for plant growth [9]. In such Vertical Farms, the environment for plant growth can be controlled as precisely as desired, regardless of the outside weather. In addition to the recirculating nutrient solution in a hydroponic or aeroponic system, the water transpired by plants can be condensed and collected at the cooling panel of the air conditioners and then recycled for irrigation.

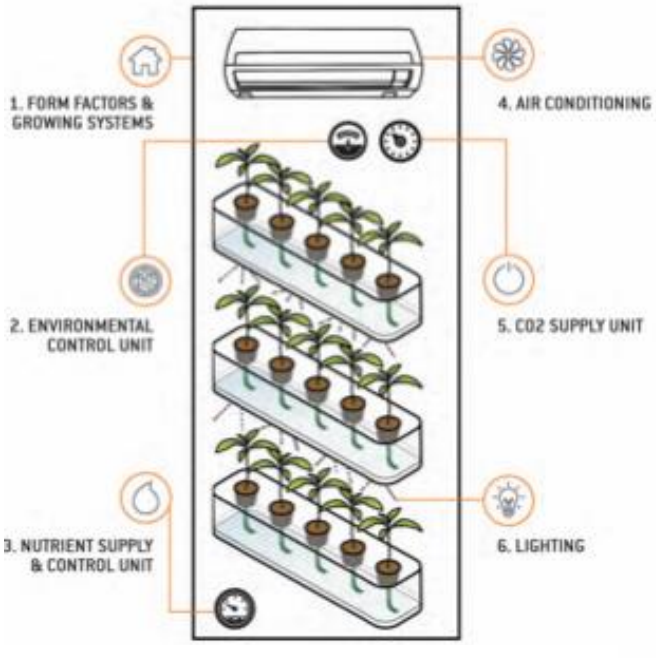

Figure 2 - Typical Vertical Farm components

Structures and growing systems

Vertical Farms are housed in controlled environments, and these are generally insulated and isolated from the outside world via air locks, or by operating in entirely clean-room conditions. They are in a variety of settings, from purpose-built warehouses to re-purposed semiconductor factories. Growing systems comprise a series of up to 20 vertical layers of grower racks, with troughs that contain the nutrient-rich water in which plant roots grow. Each layer incorporates its own lighting. Historically, growers have mostly chosen to build their own growing systems – using everything from basic PVC pipes to professionally engineered racking systems. A plethora of firms now offer turnkey solutions.

Environmental control units

Environmental Control Units (ECU) monitor, and sometimes adjust, a range of indoor farm factors, for instance, pH, nutrient and humidity levels. Companies such as Argus Controls, Autogrow and Priva offer many products, from the simplest pH monitors to sophisticated systems that track worker productivity. Several have cloud-based options that allow users to remotely access and control their farms. Thanks to the advent of big data – vast data sets that can be analysed to identify patterns, trends, and associations – control systems are one of the most promising areas for further development, as market commentators anticipate better crop yields from the application of results from big data analytics.

Nutrient supply & control

In hydroponic systems, a plant's nutrient needs are supplied through the root solution and differ according to plant type and life stage. Some growers use commercially available nutrient mixes, while others choose to create their own custom mixes and view these as part of their unique approach to growing plants.

Hydroponic nutrient solutions are composed of many essential elements, essential for crop growth. These nutrients are generally taken into plants in various ionic forms, such as NO_3^-, $H_2PO_4^-$ or HPO_4^{2-}, and K^+. Since the reserves of nutrients for the plants are limited in hydroponic cultivation, an inaccurately balanced nutrient solution may result in an unbalanced nutrient composition in the root environment. In closed systems that re-use the drainage solution, like hydroponics or aeroponics (roots suspended in the air being misted with nutrients), the build-up of salts in the solution is managed by dramatically reducing the amount of fertilizers which are added to replenish the drainage solution. Each nutrient has a suitable concentration and relative ratios for an optimal plant growth and these are the target values of a nutrient control system.

Due to the fact that the plant nutrient uptake, and reused solutions, changes ion concentrations in the nutrient solutions with time, causing a nutrient imbalance, the ideal scenario is to have control systems which allow real-time measurements of all individual nutrients that are required (however these systems are still not commercially available). As a second-best choice, the measurements and adjustments of nutrient ratios are mostly based on Ion Electrical Conductivity (EC) – however this technique can also suffer from nutrient imbalance, since only the total ion concentration is measured. Therefore, periodic analysis of nutrient solutions and adjustments of nutrient ratios must be performed. Some other, more advanced, options like ion-selective electrodes, can be a choice to estimate the concentrations of each ion.

Air conditioning

Creating optimal temperature and humidity conditions is vital for plant health, so growers devote a good deal of attention to selecting air conditioning equipment. A large range of options are commercially available, and the grower's selection is generally determined by a combination of initial capital cost, unit capacity and operating costs, as air conditioning typically comprises 20-30% of electricity costs. There are substantial economies of scale in air conditioning, so that larger farms have lower capital and operating costs per square meter of planted space.

CO_2 supply unit

Carbon dioxide, or CO_2, supplies essential elements to plants. It is common to enrich the CO_2 available in plant factories above ambient levels (to between 800 – 1200 ppm), as studies as far back as the mid-1980s have established a correlation with better yields - especially when used at certain plant life stages - and with more efficient plant water use. CO_2 is generally piped directly into the facility to reach the required level, though ventilation systems and local regulations may preclude some farms reaching the level that is theoretically optimal for the plants. There are two main techniques to supplement CO_2 - first is injecting pure CO_2 from canisters, other is to use a generator run on natural gas or propane.

Lighting

Lighting design is a vital component for Vertical Farms, as it provides the only source of illumination for plant growth in a closed system. It is also an important financial decision for the grower, typically comprising around half of the build-cost of a farm when LEDs are used, and a substantial part of the electricity costs of a Vertical Farm.

Recent developments and technologies have brought LED lighting closer to the market, as the technologies have been advancing rapidly, with projections for further improvements, resulting in lower cost, increased reliability, and reduced energy consumption. Until just a decade ago LED lighting was restricted to laboratory research on plant cultivation, and most of the light sources in Vertical Farms were fluorescent lamps and High-Intensity Discharge (HID) lamps. Fluorescent lighting is still widely used in this industry, mainly in earlier-built projects. The newer projects are almost exclusively using LEDs rather than fluorescent lighting.

LEDs emit a relatively low level of thermal radiation, have no hot electrodes, and have no high-voltage ballasts. LEDs also have a long operating life, which makes them a practical alternative for long-term usage involving plant production. One of the most appealing features of LEDs is that it is possible to modify the radiant output frequency to approximate the peak absorption zone of chlorophyll. Some LED lamp arrays allow for fine-tuning of the individual wavelengths, so the grower can adjust the frequency distribution of the emitted light according to the most efficient light absorption for each crop. A few companies have even developed 'light recipes' that are intended to deliver the optimal light spectrum required by a plant through its lifecycle without grower intervention or adjustment.

The greatest disadvantage of LED lighting in Vertical Farms is the high initial cost for a set of LED light sources compared to conventional lamps – however the prices are greatly decreasing each year. There was a huge price drop in LED lamps in the past years, with a global decline of 67% between 2012 and 2015, and the price in several European countries has dropped at least 80% over the last four to five years. [10]

1.3 Hydroponic systems

Hydroponic production systems are not a new concept. They have been widely used in food production facilities for years; the biggest benefits are higher yields, shorter crop cycles, usually higher plant densities and a significant reduction of water usage.

Hydroponic systems are essential tools for any indoor farming system, and most commercial Vertical Farms rely on this soil-less cultivation method. A hydroponic system, simply put, consists of a technique of growing plants using mineral nutrient solutions in water without soil.

There are many variations of the techniques used, and among these, the most common and with best results for commercial purposes are Nutrient Film Technique (NFT), Deep Flow Technique (DFT), Aeroponics, and Aquaponic symbiotic systems. All these systems are widely used with re-circulated nutrient solutions.

Nutrient film technique

In the Nutrient Film Technique (NFT), a thin film of water continuously flows through the pipe/gutter, so it is always in contact with the roots. This ensures constant availability of nutrients to the plants. NFT also supplies ample oxygen to the plants, since the roots are exposed above the thin film.

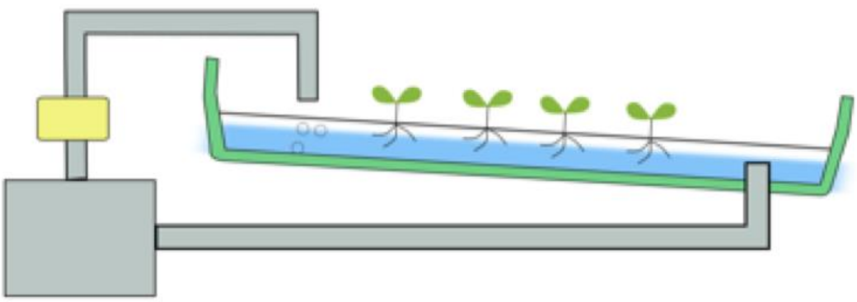

Figure 3 - Nutrient Film Technique Hydroponic System

This system requires the nutrient solution to be continuously in circulation, which results in no stagnant water in any point of the system. This translates to the pump being always on, and as observed by some Vertical Farms that were visited, like Farm.One, the NFT systems are more sensitive and prone to problems with clogging and power cuts. If the pump fails, the system immediately runs dry, and if a particular section clogs, plants suffer immediately.

Figure 4 - NFT racks at Farm.One

Deep Flow Technique (DFT)

Deep Flow Technique (or Deep Water Culture), as opposed to NFT, always has some amount of nutrient solution at some depth. More nutrient is periodically pumped in and through the overflow pipe and the excess nutrient solution goes back to the reservoir and is recycled.

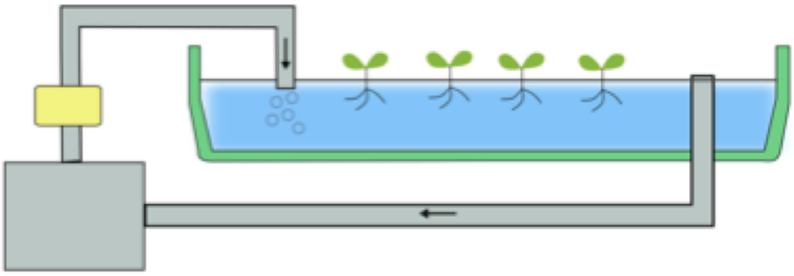

Figure 5 - Deep Flow Technique Hydroponic System

Even when there is a power outage, or other problem preventing the pump operating properly, there is always some water to keep the plants alive. This system allows more control over water temperature when compared to NFT.

Most commercial Vertical Farms that have scaled up their operation prefer to use DFT systems since they have a lower risk, being easier to maintain and less prone to errors and problems. They also present a labour benefit, since the roots are easily accessible. [11]

Figure 6 - Healthy roots on DFT system - Blue Planet Consulting

Aeroponics

Aeroponics is a method of growing plants that works by suspending the roots in air and applying nutrients and water with a fine mist. There are numerous benefits that come with growing with aeroponics. Plant roots are in full contact with oxygen at all times and roots thrive on oxygen. Also, the nutrients dissolved in the water are being directly applied to the roots, making them readily available for plant uptake.

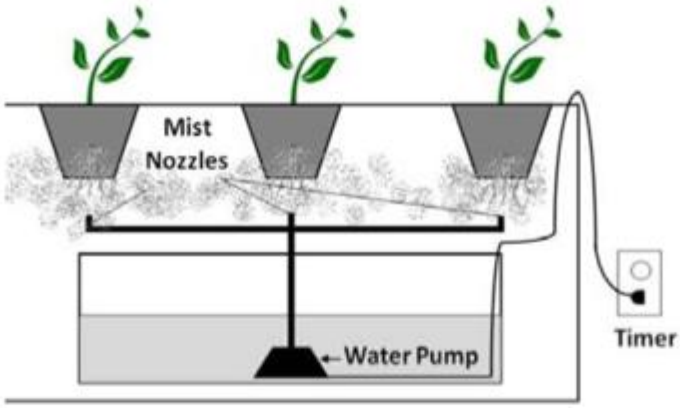

Figure 7 – Aeroponic System

According to NASA's website, which developed and tested Aeroponic setups in zero-gravity conditions, "*Aeroponics systems can reduce water usage by 98 percent, fertilizer usage by 60 percent, and pesticide usage by 100 percent, all while maximizing crop yields. Plants grown in the aeroponic systems have also been shown to uptake more minerals and vitamins, making the plants healthier and potentially more nutritious*." [12]

Since aeroponic growing systems are based on a continual application of mist to the roots, it requires that the system stays active at all times. Systems must be in place to alert the grower of failures and someone should be on hand to repair the issues presented, making aeroponics generally a costly method of hydroponic production. Additional hurdles include mould in the planter box and knowing when and how to properly feed the plants.

As stated by Henry Gordon-Smith, an Indoor Farming consultant and founder of Blue Planet Consulting (which designs and develops Vertical and Urban Farming projects), aeroponic systems will speed up plant growth and deliver excellent production levels, but these systems are risky to operate. Power outages, broken pumps, clogged nozzles, and empty reservoirs can all derail the crop. Roots without moisture will start dying within the hour.

One major player in the Vertical Farming scenario is Aero Farms, which has developed its own, proprietary aeroponics technology, which consists on a recycled, reusable "plastic fabric" as a growing medium. The seeds are planted at high density on the fabric, which is stretched according to the growth stage of the plants, allowing them to achieve an ideal space usage and solving the plant density problem that can be faced when using other techniques.

Aeroponic techniques are a good tool for the production of seed crop. For instance: *"they offer the potential to improve potato seed production and reduce costs compared to conventional methods or to the other soil-less method of hydroponics (growth in water). Aeroponics effectively exploit the vertical space of the greenhouse and air-humidity balance to optimize the development of roots, tubers, and foliage. The basic difference is the sequential seed harvests in aeroponic plants. In the conventional system, there is only one final harvest. Depending on the potato cultivar, with aeroponics we can have up to 10 or more harvests*" [13].

An innovative Brazilian initiative in this segment is CBA Sementes do Futuro, which produces aeroponic seed potatoes inside a greenhouse in Divinópolis -MG.

Figure 8 - Tuber development of Peruvian cv "Canchan" grown in aeroponic conditions at CIP Huancayo Station, Peru.

Aquaponics

Aquaponics refers to any system that combines hydroponics (DFT or NFT) with conventional aquaculture (raising aquatic animals such as fish, crayfish or prawns in tanks) in a symbiotic environment. In normal aquaculture, excretions from the animals being raised can accumulate in the water, increasing toxicity. In an aquaponic system, water from an aquaculture system is fed to a hydroponic system, where the animal by-products are broken down by nitrifying bacteria initially into nitrites and subsequently into nitrates. These are utilized by the plants as nutrients, and the water is then re-circulated back to the aquaculture system.

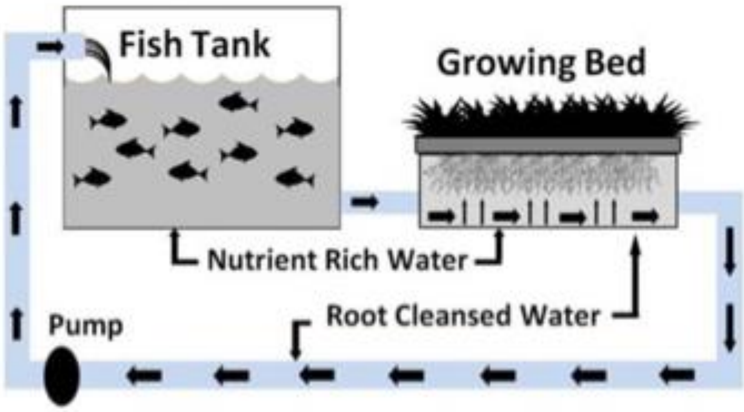

Figure 9 - An aquaponic system

As existing hydroponic and aquaculture farming techniques form the basis for all aquaponics systems, the size, complexity, and types of foods grown in an aquaponics system can vary as much as any system found in either distinct farming discipline.

Aquaponics methods allow Vertical Farms to profit not only from the plant production, but also from fish commercialization. Examples are VertiCulture and Edenworks, both located in New

York City, which develop and operate vertical indoor aquaponic farms, growing salad greens and fish. Edenwork's microgreen personal salads are allegedly up to 40 times more nutrient dense than traditional salads.

1.4 Structures – buildings or shipping containers?

In the past few years, with the increased interest on Vertical Farming and the technologic advances, a few companies started to manufacture and sell complete turnkey systems for small Vertical Farms – inside rebuilt shipping containers. Typically, a "farm in a box" is a modified shipping container with approximately 30 square meters of growing space, fitted with a custom hydroponic kit utilizing vertical growing systems. The investment ranges anywhere from $70,000 – $125,000 for a single container farm.

Based on conversations had with Vertical Farming consultants, and other players in this industry, the author found out that the general consensus is that growing in warehouses and abandoned buildings is a better method of implementing a Vertical Farm, for the following reasons:

1. *Freight containers are too small.* Every business needs room to operate effectively and the space inside a container is very restricted. Also, there is not much room for improvement and optimization, since the grower is buying a pre-designed system, which lacks flexibility. Without room to grow, experiment and even expand, the container farmer is limited. The biggest issue, however, is that growers cannot benefit from economies of scale and taking production to the "next level" (even though a grower could buy more containers, they are designed to be self-sufficient and therefore buying more containers does not necessarily result in economies of scale). Scale is a key factor in successful businesses, with a possible exception for the business models which focus on diversity and rarity (crops grown-to-order), like Farm.One.
2. *Depreciation.* Shipping containers depreciate very quickly compared to most other structures and warehouses are typically more valuable after years of growing/occupancy than they were beforehand. Therefore, shipping containers can be a questionable investment.

Chapter 2: Plants and crops suited to vertical and indoor farming

Plants and crops suitable for Vertical Farms are plants that develop well in relatively low light intensity, have a short cycle, and thrive at a high planting density. These plants are usually 30cm or shorter, such as leafy greens, herbs, medicinal plants or transplants, because the distance between vertical tiers usually is around 40cm (the optimum height for maximizing space usage).

Mushrooms are arguably the longest standing commercial indoor crop, having been cultivated commercially in countries like the US since at least the late 19th century. Newer Vertical Farms – those that have been established since 2013 – are primarily growing leafy greens, such as lettuces, kale, arugula, rainbow chard, and spinach, along with culinary herbs, especially basil, and microgreens (such as basil, beets, radish, mustard, arugula and spinach). These have the benefit of being fast growing, often having crop cycles of under a month.

Other staple food crops, consumed mainly for calories, such as wheat, rice, and potatoes, or even soybeans are not currently suitable for a Vertical Farm because their monetary value per kilogram of yield is generally much lower and they require more time to grow than leafy greens.

In Japan, small Vertical Farms with a floor area of 15-100m^2 have been widely used for commercial production of seedlings, because the seedlings can be produced in a short time, at a high planting density and often without any pesticides or fungicides, which makes the seedlings suitable for organic producers as well. Grafted and non-grafted seedlings of tomato, cucumber, eggplant, seedlings of spinach and lettuce for hydroponic culture, and seedlings and cuttings of high-value ornamental plants are produced commercially in these small Japanese Vertical Farms.

AeroFarms developed their own branding, called "Dream Greens". They focus on baby (not fully developed) standardized "Salad mix" products, including lettuce, arugula, kale, and baby watercress. It is a good example of a business model focusing on a low product variety grown in a big volume, with the accompanying scale benefits. On the other hand, Farm.One grows special crops, grown-to-order, in smaller volumes, directly for chefs and high-end restaurants, such as Siam Queen basil, Tabasco Green Leaf, Tooth-numbing plant, edible flowers, and Morenga leaves. In total over 150 species are grown.

Figure 10 - AeroFarms own `Dream Greens` brand of Salad mix products

Figure 11 - Farm.One focuses on rarity

2.1 Producing medical plants and herbal compounds using Vertical Farming

Medicinal herbs were the primary health care agents for many centuries before the advances of modem medicine and are still used worldwide as a significant part of the healthcare system. In a recent report of the World Health Organization, the percentage of the population which has used plant-based medicine at least once is 48% in Australia, 70% in Canada and 75% in France. Currently, up to 80% of the population in Africa and 40% in China use traditional medicines to meet their health care needs [14].

As a result, international trade in medicinal plants has become a major part of the global economy and demand is increasing in both developing and industrialized nations. According to a recent report by Global Industry Analysts, the global herbal supplements market will reach $107 billion by 2017 [15]. However, this explosive growth in the consumption of plant-based medicines has been accompanied by issues of quality and consistency, compromising the safety and efficacy of these products and leading to serious health issues [16]. However, there is virtually no cultivation of medicinal plants on any significant scale worldwide and the current procedure for preparing medicinal plant agents mainly involves harvesting wild plants. A vast majority of the plant species currently sold for use in traditional medicine in Africa, for example, originate from wild sources. Therefore, it is necessary to develop new technologies to ensure the efficacy and safety of medicines based on plants and to maximize the biomass and metabolite contents in plants.

Environmental factors such as temperature, relative humidity, light intensity, light quality, water content, minerals, and $C0_2$ concentration in the air influence the growth of a plant and production of medicinal metabolites. Recent research indicates that growing medicinal plants under controlled environments with artificial light can ensure the efficacy and safety of the medicinal plant products, ensure year-round harvesting of products, and maximize biomass production by optimizing nutrient uptake and environmental factors such as temperature and $C0_2$ concentration. A number of studies have been conducted in recent years to manipulate environmental factors to optimize medicinal components while growing under controlled environments.

The Vertical Farming growing systems may facilitate the development of safe, consistent, and high-quality phyto-pharmaceutical products of many medicinal plants. These often-minute changes in growth conditions are facilitated by the increased levels of control available to producers working in CEA systems. This is especially important for medical plants because of how plants produce phyto-chemicals. Phyto-chemicals targeted for medicinal purposes are often secondary metabolites in plants and frequently serve as adaptations to abiotic stresses like antioxidant production in response to changing temperature, or flavonoid production as a response to infection [17]. For example, cool-grown *Papaver somniferum* (poppy) contains more morphine than the same plant grown in warmer conditions [18]. By using the controls inherent in CEA, growers can potentially tweak environmental stresses to increase phyto-chemical concentration.

Chapter 3: Economics and business models

The technical aspects of food production under controlled environments are clear. There are proven “recipes” for high yields, short crop cycles, and desirable aspects of plants can be enhanced using the multiple hydroponic systems, lighting schedules, etc.

However, in the author’s opinion, the most challenging factor for a successful business is still the choice of a correct business model to be followed in each different scenario, its size and scalability and the technologies and capital expenditures involved. Other factors which control the business profits are the markets to which the product will be sold and the correct product mix. After all, Vertical Farming is still farming, and therefore the products will be sold into the open market, competing with all the produce grown in conventional agriculture (that can already suffer from very low margins).

For all of their many benefits, indoor farms are hampered by higher initial capital costs per area than outdoor farms, and the need for funding is accelerating as the industry transitions from a niche activity to a commonplace companion to outdoor farming. In the U.S., Vertical Farms raised $56 million during the record-breaking 2015, and $141 million in 2016. In the first half of 2017, the category raised $198 million across 17 deals, a 560% increase year-on-year. With the inclusion of Plenty’s $200m financing in July by Softbank, a record invested value was achieved during 2017[19].

Growers and operators of Vertical Farming projects pursue very different objectives. The farm facility may be built and operated for research, lifestyle, social, educational or commercial purposes. The main objective of the farm, as well as the choice of structures for either open-air or CEA, will have a deep impact on its size and profitability, which can range from a few square meters dedicated to educational activities, to large indoor Vertical Farms with commercial objectives.

The financial key to any farming project is the capital expenditure (capex) required to build and operate the site. Depending on the growing system, techniques and building adaptation or construction, Capex may range from approximately US$1,000/$m^2$ and up to US$ 4,000/m^2, however the average cost is around US$ 2,800/m^2 for four levels of production [20]. Conversations with multiple commercial growers indicate that starting a Vertical Farm is still risky and is not quick money. For instance, only a quarter of Japan’s plant factories are profitable, and half break-even. [21]

Typically, the first few years for indoor farming entrepreneurs will be very difficult. At first, farmers will have product they cannot sell. Once they figure out how to grow crops, they have to figure out how to sell them. In fact, they need to do these things at the same time. That is why a comprehensive pilot project is very important.

Produce sale contracts are an essential part in a successful farm, as the output of the fresh produce is key. One successful example which has established a stable output of produce is AeroFarms, which is selling to major grocers, such as Whole Foods, ShopRite and Fresh Direct, as well as to dining halls at businesses like Goldman Sachs and The New York Times.

Of course, Vertical Farms can achieve a higher margin on their product if they sell it directly to the customer; however, pursuing this higher margin means investing in a strong sales team, backed up by marketing, distribution, logistics and inventory management.

It is crucial to avoid costly mistakes early. Although the technology is ready, there are still significant risks with entering this industry. Vertical Farming, though profitable, is a capitalintensive business with a lot of variables specific to the markets that growers hope to operate in. There are many hidden costs associated with setting up a Vertical Farm and becoming an independent operation, such as:

1. Overcoming regulatory barriers.
2. Understanding all input costs (power, fertilizer, waste, etc.)
3. Matching different pieces of equipment.
4. Selecting profitable crops to support the initial capital costs.
5. Knowing whether to diversify or focus on the low hanging fruit (i.e. microgreens.)
6. Going into the right market.
7. Evaluating a particular equipment vendor's promises for yield and turnaround time on harvests.
8. Maintaining equipment.
9. Understanding and meeting legal expenses.
10. Hiring and maintaining high quality staff.

Working with industry consultants who can account for these costs up-front is one way for entrepreneurs to avoid critical errors that can hamstring a business during execution.

3.1 Production and running costs

A study by Ohyama (Japan, 2015) [22], showed the component costs for electricity, labour, depreciation and others in an artificially lit Vertical Farm, as displayed in the graph below:

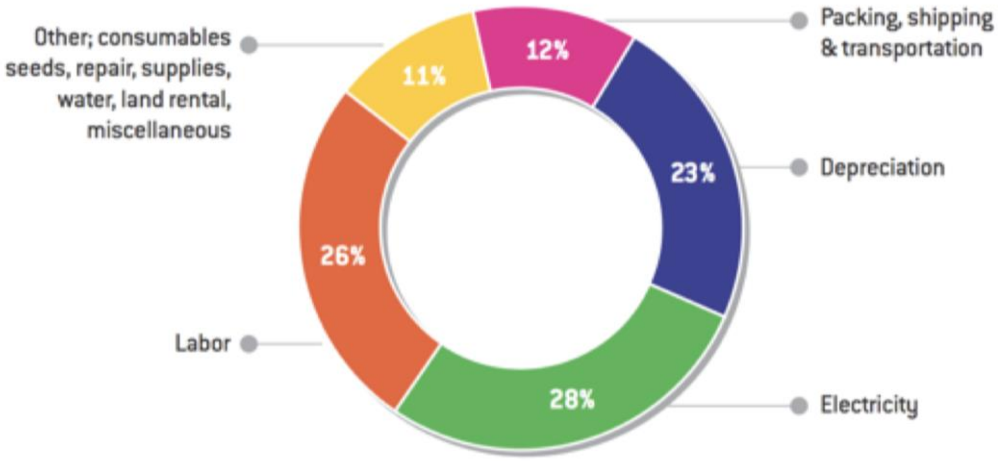

Figure 12 - Production costs in a Japanese Vertical Farm [23]

Electricity, labour and depreciation are the three major components of the production costs. However, a few aspects should be noted: taxable write-down times for capital equipment differ from country to country (in Japan, it is 15 years for the Vertical Farm building, 10 years for the facilities and 5 years for the LED lighting). Also, this specific example was not located near the biggest consuming cities, so the packing and delivery costs account for 12% of the production costs. These costs could go as low as 6-8% if the location was closer to consumption point.

In the US, the cost structure is similar, however the labour costs are higher and are the main component in the production costs. Labour costs are typically 35-40% of total costs, and energy 30%, usually split between lighting and HVAC (Heating, ventilation and air-conditioning). One important point to consider in the US is the cost of urban labour: some operations are quite labour-intensive and cost considerably more than in the countryside. In the urban environments, the employees hired are permanently employed, compared to conventional agriculture which, in the Americas, can be influenced by the lower costs of an illegal immigrant workforce.

3.2 Market Analysis – Drivers & Maturity

To understand the Vertical Farming business models and successes, it is important to know what drives indoor agriculture growth in the countries in which these innovative farms have been established.

The primary driver of the indoor agriculture industry is consumer demand for affordable, high quality, local produce. Distribution options have expanded for farmers, as chefs embrace 'farm to table' concepts, grocery chains seek more local suppliers and online delivery platforms have gained traction. Combined, these factors have provided the opportunity for high-margin indoor crops and also “salad-mix” standardized crops (low margin) to establish a foothold in the market.

The local foods category has been gaining market share in the produce industry, and the trend appears to be accelerating. Local foods are defined in several ways, such as those traveling less than a few hundred kilometres to the point of sale or sourced within the state where they are sold. By 2014, the U.S. local food market had a value of nearly US$12bn [23], up from just under US$5bn in 2008 [24]. Yet, the unmet demand is still large. In the U.S., the big majority of states grow fewer fruits and vegetables than they consume.

The desire to “eat local” is driven by health and taste concerns and is accelerating as 'Millennials' become a larger share of the first-world countries’ consumer base. Edelman Digital found that 40% of Millennials prefer to shop locally, even if it costs more [25]. In a 2016 study, market researcher the Hartman Group found that “*local sourcing conveys both the delivery of freshness and the building of community*” [26].

Indoor agriculture is well suited to meeting this need, as it offers a decentralized solution. Decentralizing the supply chain and bringing production closer to the consumer results in produce with a longer shelf-life and potentially better taste. Produce traditionally bred for resilience and the ability to withstand long-distance transport can instead be cultivated for their texture and flavour profiles.

Growth has been seen across direct-to-consumer channels (farmers' markets, community supported agriculture) and intermediated marketing channels (grocers, restaurants, regional distributors) alike. In the US, the number of farmers' markets has nearly doubled over the past decade, providing increased opportunities for consumers to “buy local” [27]. Small farms tend to favour direct-to-consumer channels as they offer logistic simplicity and higher per-unit margins. Large farms tend towards intermediated channels, contributing to “local food” sections in grocery stores.

Demand for clean, local food is soaring and "Hyper-Local Sourcing" is the top trend for 2017 according to the National Restaurant Association [28]. From data provided by the Organic Trade Association, sales of organic produce are expected to grow 70% between 2016 and 2021 [29].

Most of U.S. baby greens are grown in irrigated fields in the Salinas Valley, in California. During the winter months, some production moves to similar fields in Arizona or goes even farther south, into Mexico. If you look at the shelves of baby greens in a store, you may find plastic clamshells holding 140 grams of greens for $3.99 (Organic girl, from Salinas), or for $3.29 (Earthbound Farm, from near Salinas), or for $2.99 (Fresh Attitude, from Quebec and Florida).

“Almost all consumers (93%) associate local with 'fresh', which is the primary purchasing factor for grocery consumers” - AT Kearney (2015) [30].

Figure 13- The author proudly holding organic beans bought in St. Petersburg/FL Farmer's Market

Commercial food buyers are keen to embrace consumer demand for local foods. For retailers, distributors, and food service professionals, the local category represents an opportunity to meet consumer demand, and simultaneously decrease food waste, increase unit margins and ultimately drive bottom lines. In the U.S., 92% of fine-dining restaurateurs said they planned to add a locally sourced item to their menus in 2016 [31].

The supermarkets lose a significant amount of money annually in unsold fruits and vegetables (the USDA estimates that this loss is US$15bn annually in the US [32]). A large portion of this loss is attributable to shrinkage (produce damaged during transport) and spoilage, which typically increases proportionately to food miles – the distance food travels between farm and the end customer. Local produce offers an opportunity to mitigate shrinkage, as food is no longer required to travel hundreds, or thousands of miles in transport between farm and store. Shelf life is simultaneously increased as the time between harvest and customer drops.

Successive studies have shown that, in common with parts of the organic category, local produce can generally demand a price premium and increase per unit margins. For example, management consultant AT Kearney found that shoppers were willing to pay 13% more for local than for regular strawberries [33].

As a result, many grocers have added or expanded 'local' category shelf space and have developed local sourcing initiatives. Sourcing locally enables regional grocery chains to differentiate themselves from 'big-box' competitors, and it allows larger players to meet corporate social responsibility targets. Meanwhile, local delivery and 'meal kit' services are seeking to secure reliable supply as their operations expand.

In reality, most food buyers struggle to source any portion of their produce locally on a consistent basis. Seasonality makes year-round sourcing difficult, if not impossible for many locations where climate conditions, soil conditions and access to land limit the growth of high-quality produce for many months of the year. Small farms frequently cannot meet delivery schedules, volume demands, regulatory requirements, or other food safety certifications imposed by large produce buyers. Instead they turn to direct-to-consumer channels where they sell at prices too high for much of the population.

Figure 14 - Gotham Greens installed a rooftop greenhouse on top of a Whole Foods Market store in NYC.

Indoor growing techniques are uniquely situated to meet this market need, as they enable year-round crop production irrespective of location. Businesses use indoor agriculture technologies to drive profits and grow indoor crops in a cost-competitive manner, whether it is growing leafy greens during the winter when local produce would be otherwise unavailable, or to grow a high value herb crop with specific flavour characteristics.

The most enduring criticism of the industry is that it cannot compete with field grown produce and this criticism still holds in some cases; for instance, few indoor farms can claim to produce lettuce at the same price as California's famed farming area, Salinas Valley, in summer months. But 'field parity' is coming closer as the costs of indoor farming equipment fall every season.

Moreover, this trend is just beginning. Indoor growers have an increasingly plentiful range of options when it comes to the technologies that they can employ to attain cost competitiveness.

Chapter 4: Case studies

4.1 Sky Greens

The wealthy island city of Singapore is one of the most densely populated cities in the world, with an area of 710 square km and a population of five million inhabitants. The majority of the island's land is utilized for urban development, and there are only a few acres of farmland, which are insufficient to feed the current (and growing) population. Therefore, the majority of the food consumed in Singapore is imported from over 30 countries – which makes the country highly vulnerable to turbulence in food supply and prices. The only way out of this problem is to maximize the use of land for food production. For the island of Singapore, where real estate is at a premium and the land rates are exceptionally high, the only viable option is to go vertical to make the island more self-sufficient in food.

One of the world's first commercial Vertical Farms, Sky Greens, was built 22.5 km from the city's central business district. This soil-based, naturally-lit, Vertical Farm produces one ton of vegetables every other day and is five to ten times more productive than a regular farm. Their produce varies over 10 types of high quality, flavourful and safe vegetables, at a higher yield than traditional methods. Large varieties of tropical vegetables are grown, such as Chinese cabbage, spinach, lettuce, xia bai cai, bayam, kang kong, cai xin, gai lan and nai bai.

This Vertical Farm is one of the few commercial initiatives that rely on natural sunlight for its plants. The Farm uses its proprietary hydraulic system called "A Go-Gro", consisting of 6m tall hydraulic water-driven *A-shaped* towers that only need approximately $6m^2$ floor space to be installed (Figure 15). These modular A-frames are quick to install and easy to maintain. Each tower consists of 22 to 26 tiers of growing troughs, which are rotated around the aluminium tower frame at a rate of 1mm per second to ensure uniform distribution of sunlight, good air flow and irrigation for all the 2,500 plants growing in each tower. The rotation system does not need an electrical generator. It is powered by a unique gravity-aided water-pulley system that uses only one litre of water per 16-hour cycle, which is collected in a rainwater-fed overhead reservoir. This method also boasts a very low carbon footprint, as the energy needed to power one A-frame is the equivalent of illuminating just one 60-watt light bulb. The water powering the frames is recycled and filtered before returning to the plants. All organic waste on the farm is composted and reused.

A total of 120 such towers have been erected, with plans for 300 more, which would allow the farm to produce two tons of vegetables per day. Sky Greens wants to build over 2,000 towers in the next few years. The company also has plans to sell this technology to other countries with a price tag of $10,000 for each tower.

The vegetables are harvested every day and delivered almost immediately to retail outlets. Although Sky Green's vegetables cost about ten percent more than the imported vegetables, sales numbers are high, with consumers happy to buy Singapore-grown produce.

There are a few factors that are making Sky Greens successful. First, the business venture is supported by the Singapore government. An additional advantage is the region's weather conditions; the country benefits from year-round natural heating and sunlight, convenient temperature and the farm is set in an open area designated by the government as an agro-technology park, miles away from the shadow of city skyscrapers. Even with these positive factors, return on investment is not quick, with payback being estimated around 7-10 years.

Official Sky Greens advertisements claim their farms have up to 10 times more output per ha. than average farm output in Singapore (90ton/ha/year), using 95% less water (only 12 litres to produce 1kg of vegetables, and no wastage due to run-off), and five cents (US) is the cost of electricity per kg of vegetables produced. This method uses less than half the labour needed by traditional farming to produce the same output in Singapore.

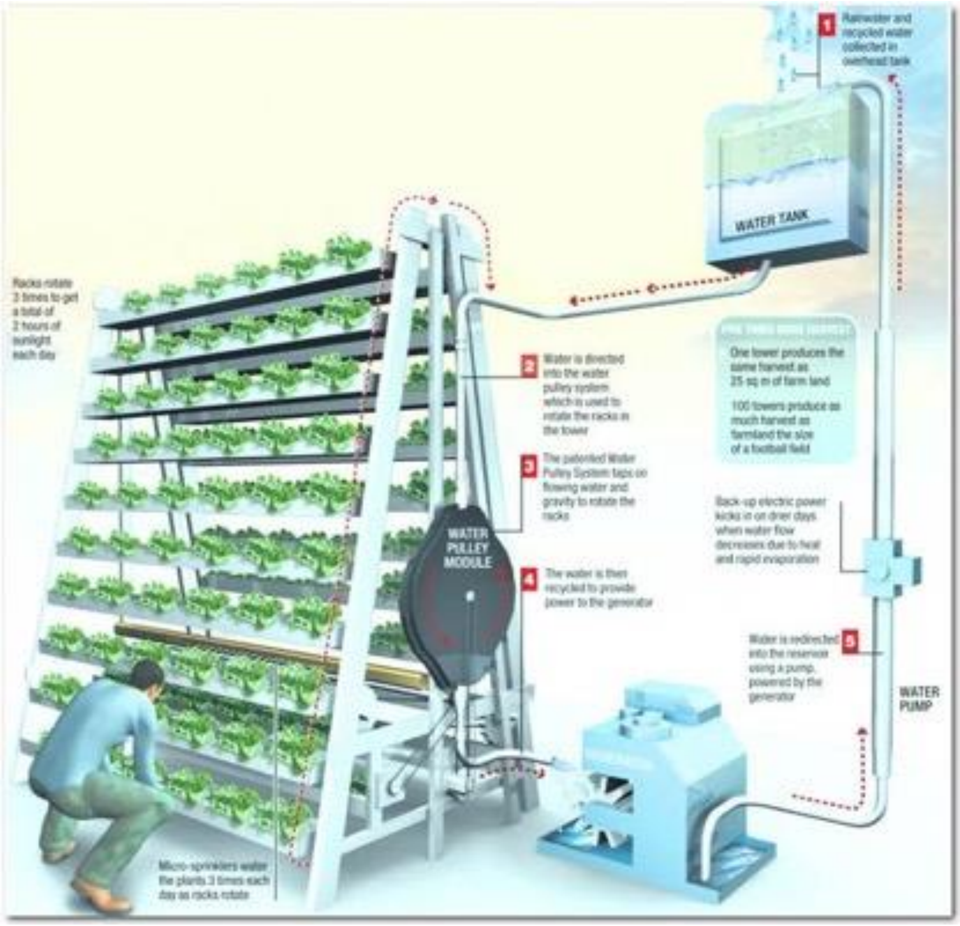

Figure 15: A-Go-Gro growing tower uses almost no electrical energy due to an ingenious hydraulic system which reutilizes evaporated water and collected rainwater

4.2 Farm.One

Farm.One was founded in 2016 by CEO Rob Laing with the idea of growing rare, hard-to-find produce for high-end chefs and restaurants in the middle of New York City. The first farm was installed at the Institute of Culinary Education (ICE) in downtown Manhattan, and the second, larger farm is now in Tribeca, underneath the restaurant Atera. Using hydroponics and LED lights, Farm.One grows rare produce year-round, just minutes away from customers. The company, which has 10 employees, supplies rare herbs, edible flowers and microgreens to some of the best chefs in New York, with 14 Michelin stars already among its customers.

The first location chosen resulted in an interesting way to initiate business, allowing the “prototype” farm to have multiple income streams. Apart from selling the produce itself, it time it generates interest from all the chefs, students and restaurants attending ICE - the farm has big glass windows which open on to a full-time display inside the Institute and organizes guided visits, urban farming courses (which the author attended).

Figure 16: Some of the products produced by Farm.One.

Using a mix between NFT and DWC hydroponic systems, Farm.One grows over 500 different products, mostly on demand, including sour, tangy wood sorrel flowers, spicy red Mizuna microgreens, Pluto basil, purple oxalis, Tabasco green leaf, the Brazilian tooth numbing plant, Morenga leaves, Siam queen basil and a nutty “dragon’s tongue” arugula. The farm is filling a supply gap for such herbs and edible flowers, which could not be found regularly and at the desired freshness by the highly demanding NYC restaurants.

As explained by Rob Laing, around 75% of the produce is grown on customer request, whereas a few more common products (like basil) are continuously maintained in the farm. The new 112 m^2 farm is capable of growing over 450kg of produce per month and serving up to 50 restaurant customers. A discount is offered when buyers pay upfront, to get commitment from chefs to buy the produce ordered. Free samples for chefs is crucial to gain momentum and attract new customers.

Their produce is grown completely pesticide-free, using beneficial insects to control pests (ladybugs and lacewings), and delivered only to restaurants in Manhattan and Brooklyn, via bike and subway - eliminating food miles and keeping costs down. Their delivery time can be so short that bacterial growth in the delivery chain can be almost eliminated (this is a significant reason for bacteria on plants that travel long distances over many days to a supermarket).

Farm.One CEO Rob Laing explains *"Farming indoors in Manhattan allows us to deliver a huge range of rare produce for the most demanding chefs within a few hours of harvest, year-round. Our location eliminates waste and provides a fresher, better product. High-tech Vertical Farming does not have to be about the same old leafy greens; it can be about excitement and delight."*

Unlike most urban Vertical Farming start-ups, which are focused on mass-market leafy greens for supermarket use, Farm.One is the only Vertical Farm business growing a large number of rare, premium ingredients. Henry Gordon-Smith, a Vertical Farming industry expert, says *"Farm.One produces on-demand products for chefs that are rare, unique and consistent year-round, giving it a very interesting business case that helps it stand out from the rest of the competition in Vertical Farming".*

Figure 16 - Farm.One's newly installed operation, in Tribeca - NYC

4.3 AeroFarms

"*An unprecedented intersection between engineering, horticulture and data analytics*" – David Rosenberg, AeroFarms Co-Founder and CEO.

Figure 17 - AeroFarms has been one of the pioneers in large-scale Vertical Farming

AeroFarms has constructed and operates nine Vertical Farms, of which four are in New Jersey, including its state-of-the-art 6,410m^2 flagship production facility in Newark. It is claimed that the renovated former steel mill will be the world's most productive indoor farm once it reaches full capacity.

AeroFarms employs 120 people and has raised more than $130 million to date [34].

Its main products are high-end baby greens, which it sells to grocers on the East Coast including Whole Foods, ShopRite, and Fresh Direct, as well as to dining halls at businesses like Goldman Sachs and The New York Times. Currently, AeroFarms' greens retail for around the same price as similar gourmet baby greens.

By growing locally year-round, the company hopes it will be able to provide fresher produce at a lower price point, since transportation will be kept to a minimum (currently, about 90% of the leafy greens consumed in the U.S. between November and March come from the Southwest, according to Bloomberg) [34].

According to AeroFarms, their growing method is 130-390 times more productive per square meter annually than a field farm, from a crop-yield per area perspective. An AeroFarm uses 95% less water than a field farm, 40% less fertilizer than traditional farming, and no pesticides. Crops that usually take 30 to 45 days to grow, like the leafy gourmet greens that make up most of the company's output, take as little as 12 days.

AeroFarms sees its growing method as especially useful in areas where the climate might not be friendly to growing plants, or where water or land is sparse. Besides the US farms, the company currently has operations in Saudi Arabia and China. It plans to reach 25 farms within five years.

The company uses Aeroponics to mist the roots of the greens with nutrients, water, and oxygen. They have developed a patented, reusable cloth medium for seeding, germinating, growing, and harvesting. The growing cloth medium is made out of Bisphenol A-free (BPA), post-consumer recycled plastic, each taking 350 water bottles (500ml) out of the waste stream. The cloth can be fully sanitized after harvest and reseeded with no risk of contamination.

The fabric is a thin white fleece that holds the seeds as they germinate, then keeps the plants upright as they mature. The roots extend below the cloth, where they are accessible to the water-and-nutrients spray.

Figure 18 - AeroFarms proprietary aeroponic system has been key to the company's success

AeroFarms uses LED lights to create a specific light recipe for each plant, giving the greens exactly the spectrum, intensity and frequency they need for photosynthesis in the most energy-efficient way possible. At different growth stages, the plants require light in different intensities, and algorithms controlling the LED arrays adjust for that. This engineered lighting allows AeroFarms to control size, shape, texture, colour, flavour and nutrition with great precision and also to increase productivity. The LED lights are in plastic tubing above each level of the grow tower - their radiance has been stripped of the heat-producing part of the spectrum, the most expensive part of it from an energy point of view.

With remote monitoring and controls in place, AeroFarms has minimized the typical risks associated with traditional agriculture. The temperature, humidity and CO_2 content of the air; the nutrient solution, pH, and electro-conductivity of the water; the plant growth rate, the shape and size and complexion of the leaves and many other factors are tracked on a second-by-second basis. AeroFarms' biologists and other plant scientists overseeing the operation receive alerts on their phones if anything goes awry. A few even have phone apps through which they can adjust the functioning of the Vertical Farm remotely. At the Newark Farm, 24 million measurements are taken per day, with 160.000 data points captured per harvested tray. More data points, if well understood and utilized, can optimize plant yields, thus lowering their cost of goods sold.

According to AeroFarms, their growing process has been optimized to minimize and mitigate pest proliferation. In addition to their controlled indoor environment, the growing methods disrupt the normal life cycle of common indoor pests so that they never get started.

Chapter 5: Analysis of the Brazilian market and opportunities

Vertical Farms have proven to be a possible profitable business in USA, a few places in Europe and specially in Asian countries like Singapore, Taiwan and Japan. However, it is a known fact across the industry that no Vertical Farm has high margins or quick return on investment.

Therefore, in order to assess the viability of Vertical Farms in Brazil, this study will analyse three important aspects: production, market (which ultimately sets the products needs and pricing), and the Vertical Farm operating costs (specially energy, labour and depreciation, which are the biggest cost factors).

5.1 - Production

Big cities like São Paulo and Rio de Janeiro are served with fresh leafy green vegetables cultivated in the surrounding cities, called the “Cinturão Verde” (Green Belt). The “Green Belt” in São Paulo state, for example, produces vegetables and leafy greens all year round, mainly in the cities of Suzano, Mogi das Cruzes, Biritiba Mirim, Salesópolis and also in the Ibiúna region.

Figure 19 - Green Belt: Leafy Greens produced year-round in Mogi das Cruzes

In São Paulo state, the cultivation of four types of leafy greens and flowers occupied 23,300 hectares in 2015, according to data released by the Agricultural Economy Institute (IEA). Most of the area, 11,100 hectares, was devoted to lettuce [36]. Price has a small influence in size of the lettuce planted area; what changes the market and price levels are supply fluctuations due to excess rain or intense cold weather.

During the past years, the planted area of most leafy greens has increased in Brazil. While lettuce and coriander still represent a huge part of the cultivated area, some varieties are being more demanded by the market and therefore presenting a substantial growth, like cress (a 92% expansion from 2013-2016).

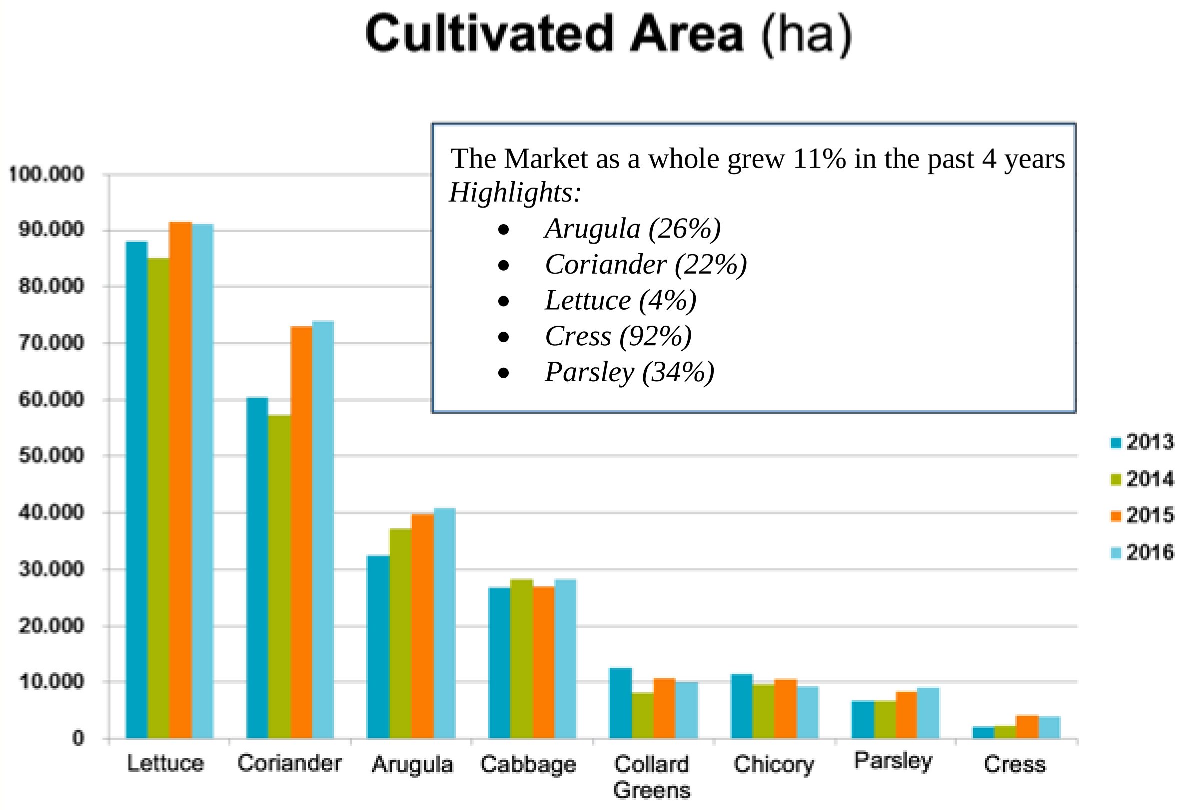

Figure 20 - Leafy Greens cultivated area in Brazil, 2013-2016

The fresh and mild climate, due to the high altitude, favours the development of vegetables in the Green Belt and guarantees a higher quality of the products. However, there is a problem that the region has been facing recently, since it is a river spring protection area: the construction of reservoirs is increasing the relative humidity of the air, which results in a proliferation of fungi and bacteria in the plantations. The climate is becoming more favourable to the manifestation of diseases and producers are having to face this problem. [37]

In January 2017, due to intense rainfall in the first three weeks of the year, producers lost 60% of the crops in São Paulo's Green Belt [38]. The consumption of leafy greens tends to rise in the summer with a positive impact upon farmers' income. However, the high temperatures and sometimes excessive precipitation in the summer are a risk factor: when it is too hot, plants need irrigation to lower the leaf temperatures. The high humidity, caused by irrigation or excessive precipitation, allied to high temperatures, favours the proliferation of diseases. Scarce rainfall also adversely affects the production of leafy greens, as happened in some regions in the state of São Paulo in 2014 and 2015, when some producers in São Paulo even reduced their planted areas because there was not enough water for irrigation. To overcome these weather-related problems, there has been an increasing adoption of hydroponic systems and protected cropping lately, and this trend will most probably continue.

The prices paid to the farmers can fluctuate over 100% during the course of a year. In general, farmers will have a strong few months; during half of the year the cost of production is almost the same as the price they sell their produce.

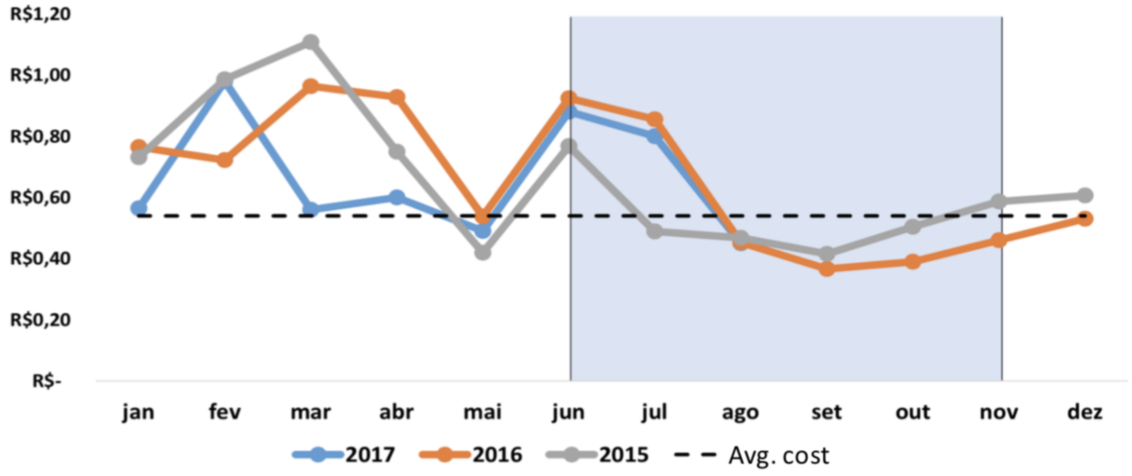

Figure 21 - Price levels for a head of lettuce in Mogi das Cruzes (Sao Paulo) – R$/unit [CEPEA/HF Brazil]

Due to low initial investments and short-term returns, the traditional soil-based cultivation of leafy green vegetables is strategic and important for family farming. A great proportion of the properties is family-run and with only a handful of employees. One difficulty that the "Green Belt" growers face is the lack of an agricultural and agrarian policy. There is no security for the producers and therefore they end up suffering many financial losses.

5.2 - Market

Brazilian eating habits are getting healthier. For this reason, it is believed that the habit of consuming leafy green vegetables is on a rising trend across the country. At the same time, the production and quality of these vegetables oscillate quite a lot, as they depend a lot on weather conditions. The so-called mini-vegetables and "baby-leaf salads" are gaining momentum (even though still not comparable to more mature markets), through a visual, taste and practicality combination, pleasing children very much. The materials used in mini-products come from abroad, a fact that calls for research into new cultivars and cultivation in tropical open-field conditions.

Figure 22 - Hydroponic baby spinach sold in supermarkets in São Paulo

There is a firm and growing tendency in the market towards minimally-processed vegetables, which are practical and convenient for the consumer, with longer shelf life, increased added value, lower shipping volume and less product loss. However, in the short term, due to the Brazilian economic recession, the market for cheaper and simpler products will prevail, while minimally-processed products will have a limited demand until the economy grows again.

In general, the Brazilian market does not strongly recognize the branding of vegetables, and the key value drivers of successful Vertical Farms in the US or Japan are not so strongly sought after, such as local, organic, sustainable and social. However, these drivers get more important as the income level of consumers rises. Higher income consumers also demand a richer variety of greens apart from the usual lettuce, coriander and arugula.

5.3 - Cost Comparison

To analyse the viability of installing and operating a Vertical Farm in Brazil, it is crucial to understand how the major costs compare themselves against prices in the USA, Europe or Asia.

Electricity costs

Electricity in Brazil is not cheap. Even though a majority of the electricity comes from renewable sources, the costs are 72% higher than in the US, but still 36% lower than in Japan. Brazil relies mainly on renewable energy sources: 68% Hydroelectric, 9% Biomass, 6,5% Eolic, while others as coal, gas, oil and nuclear account for roughly 16% of energy generation [39]. This means that a Vertical Farm operating in Brazil would be considerably 'greener' than its counterpart operating in the US, which relies mainly on fossil fuels for energy generation.

Labour costs

Estimates from The Conference Board and the US Bureau of Statistics indicate that labour in Brazil is much cheaper than in the US, Japan and Netherlands, and is comparable to Taiwanese wages, which is a positive factor when analysing the possibility of operating a Vertical Farm in Brazil. However, the workforce can be less skilled than in those countries, therefore there might exist a necessity to hire more workers, or costlier workers.

Table 1: Hourly compensation costs according to two sources

Country	**Hourly Compensation costs (US$) – 2013 [1]**	**Hourly Compensation costs (US$) – 2016 [2]**
USA	35.70	37.70
Japan	35.34	23.60
Taiwan	9.46	9.51
Netherlands	39.62	36.50
Brazil	11.20	7.97

[1] US Bureau of Labour Statistics, International Labour Comparisons, August 2013

[2] The Conference Board, International Labour Comparisons program, April 2016

Capex and depreciation costs

Imports are subject to a number of taxes and fees in Brazil, which are usually paid during the customs clearance process. The Brazilian taxation system is complex and cumbersome. Three taxes account for the bulk of import costs: the Import Duty (II), the Industrialized Product tax (IPI) and the Merchandise and Service Circulation tax (ICMS). In addition to these taxes, several smaller taxes and fees apply to imports, and most of them are calculated on a cumulative basis.

Each product will have different taxation levels. However, on average, imported goods will have taxes that account for around 40–70% of the value of the goods. As most of the equipment required to construct a Vertical Farm are imported (LED lighting, automation and control systems, etc.), this will certainly have a huge impact in the final cost of the farm setup.

It is also worth mentioning the high interest rates when applying for financing. Interest rates in Brazil averaged 15.45% from 1999 until 2017, reaching an all-time high of 45% in March of 1999 and a record low of 7.25% in October of 2012. At the moment, the rate is 7.50%.

The volatility of Brazil's national currency (BRL – Brazilian Real) can also impact investments, since the liabilities of Brazilian firms with foreign currency debts can increase dramatically with the devaluation of the Brazilian Real against US dollars over a short period of time (from 2012 to 2017, BRL has devaluated over 40% compared to US dollars).

Funding is, however, available at below-market interest rates (even negative in real terms) from the National Bank for Economic and Social Development (BNDES). BNDES is Brazil's main government development bank and is the leading source of long-term financing for Brazilian companies. The interest rates charged are subsidized by the government and are well below the rates charged in the market.

All of the factors described will lead to a higher capex, therefore contributing to higher depreciation costs, estimated to be at least 50% above the level of USA or Europe.

5.4 Comparison between possible Business Models

"Large-scale": low margin / commodity produces

Such companies would compete with open field, regular vegetable farmers.

A large-scale operation, inspired by AeroFarms business model, seems to be difficult to make financially viable at this moment. The very high depreciation costs, allied to a market that has plenty of greens produced cheaply during most of the year, give rise to a less-than-favourable scenario. Compared to the US, where the market is willing to pay a premium on local, organic leafy greens, the Brazilian market does not seem willing to pay this extra. Also, Brazilian vegetable production is nearly year-round, and the vegetables do not travel as much as in the US, since the producing areas are surrounding the major cities.

"Small-scale": high margin / specialty crops

Inspired by Farm.One business model, this approach could work well in big centres like São Paulo or Rio de Janeiro, which have plenty of fine-dining restaurants, and a wealthy public willing to pay for fresh ingredients in their plates. A higher margin guarantees a profit, the controlled climate guarantees year-round rare herbs and the lack of competition with local producers make this model seem viable. The lower capex investment, which is a big burden in any Vertical Farming business, contributes to this favourable scenario.

"Niche": Medical compounds/ seed production / high value crops / medical cannabis

Producing medical compounds is a big opportunity. Even with higher capex, due to a more precise level of control and automation, the products grown can be of incredible value. Those high-value crops can make a Vertical Farm profitable irrespective of the investment costs, as does the production of native medicinal species and other compounds needed by the pharmaceutical industry. Seed and seedlings production can also be a profitable niche to be explored.

The possibilities of cultivating innovative and high-value crop in Vertical Farms, like vanilla, should be further explored. While hard to grow, vanilla is a highly profitable crop with some of the key characteristics that make it valuable for vertical farming cultivation. If more people experiment with this type of cultivation, it is fair to assume that knowledge will increase and costs will come down, making it even more competitive. Like saffron, because of the high labour costs, it is unlikely that cultivation of this crop will move primarily to the countries that are leading the way in vertical farming any time soon, but this poses an opportunity for countries with lower labour costs like Brazil. As changing weather patterns affect agriculture around the world, the adaptability of Vertical Farming may prove beneficial for continuing to produce vanilla and other expensive plants.

More recently, a new and highly profitable market has arisen. This is the medicinal cannabis industry, which is flourishing in Canada and a few U.S. states for example. In the State of Colorado, legalizing, regulating, and taxing marijuana for adult use has generated over US$ 500 million in tax revenue so far and the demand is increasing rapidly, generating a good profit for growers. Whenever Brazil regulates the production of medical cannabis, it will be a huge opportunity for anyone entering the market.

All the above-mentioned models share a common feature. In general, more automation means increased capex, which is already high due to import costs. Therefore, one strategy could be to lower initial investments and rely more on manual labour, since labour is a cheaper cost component in Brazil.

Conclusion

This study started with reasonable doubts that crops grown in Vertical Farms might be too expensive to ever become financially viable. This work has shown, however, that it is a possibility which needs to be further investigated.

Farmers, researchers, equipment companies and industry consultants agree that '*the technology is already here.*' There are successful and profitable companies in Vertical Farming today, unlike a few years ago when Vertical Farming was an unreliable business and mainly operating on a research and development scale. Today, it is both a technical and business reality due to the emergence of higher efficiency LED lighting, low-cost sensing and data collection, along with a growing knowledge base of applied hydroponics technology for food production. In addition, the current global market drivers are very closely aligned with the value propositions of Vertical and local grown produce.

The key advantages of Vertical Farming are to grow healthy crops anywhere, all year round, with very high and very predictable yields.

Indoor agriculture is at an exciting point in its development, with technology advances changing the economics of the industry, and enabling new business models, at a rapid clip. At present, developments in LED lighting and in 'big data' usage, are being commercialized, bringing better yields and lower resource-usage to plant factories. Examples include the exploration of adjusted light spectrums for LED lighting. Further out is an expansion of the crops that can be grown in indoor systems; research ranges from staple crops such as rice, to highly specialized medicinal crops.

The author anticipates that there will be better economics and more international expansion from Vertical Farms over the next few years, driven by rapid technology development. Asia's plant factory companies are leaders in exporting their technologies to establish new farms in other countries. To date, this expansion has been contained to a limited number of Asian markets, but these companies will eventually look to Europe, Africa and the United States as export destinations.

A sometimes-reasonable criticism of the indoor agriculture industry is that it is unprofitable; small-scale operations and a focus on commodity crops (such as lettuce) being two reasons for this pessimism. Consequently, a major industry focus going forward is likely to be better profitability; the most obvious way of achieving this being by investing in newer technologies, and in the expansion of existing operations. Lighting, automation and control systems are likely to be the main areas of technical upgrades, as growers seek to contain the energy and labour costs that each typically take up more than a quarter of operating costs.

Care needs to be taken when analysing the Vertical Farming "green" allegations. It is important to remember that, even though the production techniques are efficient, there are no CO_2 emissions from machinery and the food miles are greatly reduced, all the energy utilized in Vertical Farms needs to be generated somewhere – most electricity generated in the US for example comes from fossil-based fuel power plants like coal and natural gas. Therefore, Vertical Farming in this situation would be merely transferring the emission of greenhouse gases to the electricity generation point (power plants) as opposed to generating greenhouse gases during production and transport, like open field agriculture. The Brazilian scenario would be greatly different, since almost 90% of the energy generated in Brazil comes from clean, renewable sources.

Even if most facilities do generate some electricity via renewable sources (solar, wind, etc.), the energy generated is not nearly enough to meet all the demands of a Vertical Farm (especially those running on 100% artificial lighting). Taking solar panels as examples, they take up too much space to deliver the amount of energy needed by the same area of the producing layers. In addition, solar availability may not synchronize with need, leading to energy losses and the need for supplemental energy at other times.

There is quite some controversy over organic certification. It is unclear if or when there will be agreement on whether crops produced in a Vertical Farm can be certified organic. Many agricultural specialists feel that a certified organic crop involves an entire soil ecosystem and natural system, not just the lack of pesticides and herbicides.

At this point in time, it might be hard to reach break-even prices when farming indoors and relying on artificial lighting. Nevertheless, one has to consider that this price would be independent from seasonal effects, independent from unpredictable events such as droughts, floods or insects plagues, and Vertical Farms could produce fresh crops in any place in the world. This last point is interesting for three regions on our planet, where traditional agriculture is largely not feasible. The first regions would be desert countries, like Saudi Arabia and Dubai. These countries are trying to gain food independency for their population, while being located in extremely arid regions, with almost no fertile land. A second potential group can be seen within Taiga states, like Siberia, Canada, Sweden and Iceland, where agriculture is limited by a short summer and a long winter. The last group lie within mega-cities, where no agriculture land is present at all, but a huge number of consumers are living. Here, Vertical Farms can provide in-situ fresh food for the population. The target mega-cities should be seen within high income industrial areas like Northern America, Europe and Asia.

A Vertical Farm may not always be the answer for local food production. Sometimes a better solution would be installing more traditional horizontal greenhouses around the perimeter of urban areas. These “peri-urban” greenhouses would still reap many of the benefits of urban infrastructure – such as water, power, high-speed roads and other transportation options – while avoiding the phytotoxic effects of urban air pollution, and they would capture the most effective, cost-efficient source of energy for plants: the sun.

As for the specific Brazilian scenario, commercial Vertical Farms focused on a lower variety of leafy greens, or microgreens, would struggle to be sustainable as a business and would only be viable if they could rely on natural lighting or be scaled up enough to overcome the low margins caused by the high energy, capex and labour costs. But the main problem for this business model in Brazil is the lack of market maturity and associated demands for high return crops. As opposed to the US, Europe and some Asian countries, the Brazilian market is still not paying much of a premium on organic foods (even though the market is growing), let alone local foods, which is one of the key selling points of Indoor Farming produce.

A model that could work in Brazil, however, is the implementation of small-scale farm aiming at high margin rare crops (herbs, edible flowers, etc.) that could be sold directly to high-end restaurants which exist in large numbers in São Paulo or Rio de Janeiro. These restaurants demand freshness, rarity and constant availability of herbs and spices and are willing to pay extra for it.

Technologies adopted and perfected by the Vertical Farming industry have opened doors for other industries that are not necessarily food production, such as the production of seeds and medicinal crops. Creating more efficient stratification processes, enhancing targeted phytochemical production, supplying new urban markets, increasing yields, and decreasing contamination risks are all unique advantages which Vertical Farming can bring to these industries. With few companies competing in these spaces, even compared to the relatively small number of all Vertical Farms globally, there is a large opportunity to create and test new markets.

Recommendations

1. When considering building and operating an Indoor or Vertical Farm, one should first focus on the Product:

- What do you want to sell?
- At what price point?
- What market are you targeting?
- Where will you sell it?

The technology and processes that will allow for a profit should only be developed after those first questions are answered. There needs to be care not to focus on technology and leave the process behind!

2. When choosing a location for a Vertical Farm, more important than being close to the point of consumption is being close to the distribution point.

3. A small-scale Vertical Farm focusing on specialty and rare crops could work well in big centres like São Paulo or Rio de Janeiro. A higher margin guarantees the profit, the controlled climate guarantees year-round rare herbs and the reduced competition with local producers make this model seem viable.

4. Apart from food production, Vertical Farming techniques and technologies can be used in two very promising markets: seed production (e.g. potato seeds) and phyto-pharmaceutical (medical plants) production.

5. Whenever Brazil regulates the production of medical cannabis, it will be a huge opportunity for anyone entering the market. Vertical Farming techniques are especially suited for this type of cultivation, and this already multi-billion dollar market is developing and specializing at an astonishing pace in countries that have regulated cannabis production.

6. Remember, Big Data is different from Right Data! Vertical Farming is a mix between manufacturing and futuristic food production, therefore lean manufacturing techniques can and should be used. Farmers need to map and understand each process involved in the business, then collect data and understand it, to be used in a productive way to optimize production and profit.

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Plain English Compendium Summary

Project Title:	Vertical Farming: Can it change the global food production landscape?
Nuffield International Project No.:	1601
Scholar: Organisation:	Luciano Jan Loman Nuffield International Telephone: (03) 54800755 Facsimile: (03) 54800233 Mobile: 0412696076 Email: enquiries@nuffield.com.au 586 Moama NSW 2731
Objectives	Develop an understanding of the concept of Vertical Farming and compile the best production practices adopted by this flourishing industry; Clarify the economics behind the Vertical Farms and the reasons behind the successful initiatives; Understand the potential present and future fit of Vertical Farms and related technologies and processes in the Brazilian scenario.
Background	It is becoming necessary to find new ways of producing food for an increasingly big and urban population. Food needs to be local, fresh, and have a reliable and stable output.
Research	Many professionals from the Vertical Farming industry, farmers, consultants were interviewed. Vertical Farm initiatives were visited. The author also participated in a two-day training course on the topic. The literature available and pertinent to the topic was reviewed.
Outcomes	Even though Vertical Farming techniques are very efficient for food production, the economics are still difficult to balance, and therefore Vertical Farms have mainly had success in developed markets which pay a premium for fresh/local/organic produce. Adopting "commodity-producing" strategies in Brazil does not seem to make sense at the present moment especially considering the favourable climate for food production, the proximity to consumer areas and the lack of customers willing to pay a premium price. Other strategies can be successful, like specialised rare herbs production, medical compounds farming and seed/seedlings production.
Implications	Vertical Farming will become ever more present in the future global food production scenarios, especially once there is universal access to cheaper and more sustainable energy sources.