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Vertical Farming: Under Climate Change Effect

A. Teoman Naskali, Ozgun Pinarer, and A. Cagri Tolga

Abstract The daily life of people is changing due to the increase in climate change effects. In the times of historic Covid-19 pandemic event, by the precautions like stay at home, people tried to obey those cautions. This kind of protections decreased the CO₂ gas emissions by 17%, obtaining the world returned to 2006 gas emissions values. The air became more breathable and the nature began to repair itself without the touch of people. As the population grows, feeding this population became a separate problem. People started to destroy forest areas because more agriculture was needed for more nutrition. Of course, this destruction also had a direct impact on climate change. Humanity once again saw that it had to develop with nature, not against nature. This eye-opening process will force people to act quickly on what needs to be done for climate change. Even though the relatively less emission comes from the agriculture, this sector has to transform itself by new technologies due to its strategic position. Vertical farming alternative is a candidate for this conversion process. Many methods in vertical farming are handled in this chapter. Some cultivation methods as hydroponic, aeroponic and aquaponic systems are dealt also. Energy and water consumption, yield, and scalability criteria are examined for the vertical farming under climate effects. In addition, some newly technologies like artificial intelligence applied to vertical farming are presented in this study. To see the benefit of this agricultural method a feasibility and economic analysis had to be made, so it's done with real data. Interesting results and inferences have been obtained and presented at the end of the study.

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1 Introduction

By 2000s, the world population was around 6 billion and the number of people per km^2 was 41. Today the population has increased to 7.8 billion and the number of people per km^2 has reached 52. The U.N. predicts world population to reach nine point eight million by 2050 with an increasing demand for food in the developing world and an increased demand for meat in particular. Besides, according to the FAA, we will need a 70 percent increase in global food production by 2050. World is facing major problems: limited sources, water problem, species loss, climate change. Meanwhile, land allocated to agriculture is decreasing to critical levels. Researchers have started searching alternative solutions to overcome these global problems. Since agriculture is one of the important domains, alternative solutions are extremely crucial for the future of agriculture. In this context, vertical farming is proposed as a concrete solution to these listed challenges.

Traditional agriculture is one of humans oldest and most important innovations, a practice over several millennia old. Studies on urbanisation prove that a majority of the world population were involved in farming several decades ago, however recently, it is only 1% [1]. This immense loss of farmers clearly causes a problem feeding people. The amount of food acquired from agriculture will not be sufficient soon to feed the world population. The growth of the world population unfortunately does not provide high agriculture productivity, in contrast, size of agricultural fields are decreasing and the current fields lose their productivity and sustainability [2] due to land degradation. Besides, increased residential population, increase of non-farm business and industry cause a social problem: urbanization and increased urbanization causes a decrease in agricultural productivity [3].

There exists another threat for current agriculture systems: biofuel. Biofuels are basically liquid transportation fuels that include ethanol and biodiesel. Biodiesel is indeed a vegetable oil product. It is made from agricultural crops and residues. To obtain biofuels, new crops may be grown. Some agriculture fields can be reserved for biofuel production. Today, a profitable market for biofuels exists and is expected to increase by 2050. The global bio materials market is also expected to grow significantly. To fulfill these requirements, current agricultural fields should be increase up to 21%. On the other hand, due to the urbanization, existing farm lands are decreasing. Farmable land is set to be turned into an urban environment, with the global urban footprint expanding by 33 percent. Thus, an important question is arises: Does arable land to sustain this growth even exist? It is estimated that arable land can be created for food production in 2050 at the expense of consuming forests leaving almost no natural habitats for wildlife. [4].

Due to the reallocation of land for agriculture animals are losing their natural habitats and becoming extinct. This extinction process is accelerating rapidly, the World Wildlife Foundation estimates that 38% of land animals have gone extinct in the last 4 decades primarily because of habitat destruction. [5]. Besides, global deforestation is another big problem that needs to be overcome. Global deforestation in 2018 was 180000 km^2 . Freshwater animal populations have seen an alarming 81% reduction since 1970. Agriculture is the main contributor to this, primarily draining

wetlands to create cropland. 50% of the world's wetlands have disappeared since 1910. Water consumption for irrigation further depletes local water levels, damaging habitats. Agricultural runoff, such as pesticides, finds its way into local water systems, poisoning wildlife. Runoff fertilizer from the fields is a nutrient and some species can take advantage of this such as algae which over reproduce in blooms, draining the water of oxygen and creating dead zones, this upsets the balance of the ecosystem. More critically, to prevent mass starvation, there does not exist enough capacity in hand. Land requirements to keep the global population sustained points us to our next global challenge.

Growing food, sustainability and the productivity of current agricultural system is crucial for every country. 40 years ago, China was a net exporter of food. Yet now it's the world's biggest importer of food by far [6]. All of the countries in the world, with the exception of the United States, have agreed to the Paris climate accords. The aim is to limit the global average temperature rise to one point five degrees Celsius this century against a baseline of pre-industrial levels. Preventing the temperature rise essentially focuses on reducing emissions of greenhouse gases [7].

All this data leads us to believe that we will run out of land in the near future. It appears that in the very near future forests and natural habitats will be converted to farming land and to cities. This will have a very negative effect on the environment and will accelerate global warming which in turn is expected to cause a rise in sea levels further decreasing the available land. The planet will also become more hostile from a crop growing perspective because of global warming and climate instability. If new technologies and techniques are not invented famine appears to be inevitable. To solve such crucial and highly important global challenges, vertical farming has recently become one of the hottest topics.

The remainder of this chapter is organized as follows: vertical farming systems will be deeply investigated in the second section. The third section presents the alternative soil-less cultivation methods for vertical farming. The evaluation criteria are provided in section four. The subsequent fifth section puts forward the new technologies applied in traditional and also vertical farming. The sixth section consists of future, feasibility and economic analysis of vertical farming. Section seven gives example of Japanese vertical farms. Then conclusion and future remarks are given at the last section.

2 Vertical Farming

A vertical farm is essentially an indoor farming method. It provides an unusual farming environment to grow food rather than being restricted to two dimensions. Plants are put on a grow tracks and they are stacked in levels on top of each other and make use of artificial lighting. Using artificial light and world conditions provides the ability to grow any plant independently from time and season. The combination of highly controlled growing conditions and optimal light provide a very predictable

amount of output for a given area of land. The major advantage of such systems is to be independent of time and location.

When the global challenges are examined, vertical farming is considered as a future style of agriculture that claim to solve one of the most critical aspects i.e the lack of land. To clarify the ambiguity, in some researches, it is confused with urban agriculture where food is not grown in farms but in cities. In fact, urban agriculture handles the problem of transportation of the food to the cities. Hence, researches on the urban agriculture focus on moving the production fields close to the cities.

2.1 Vertical Farming as a Factory

The scale of a vertical farming may vary to different dimensions: a small corner in a house to sustain a single family or a whole building as a farming factory to mass produce crops. There are few city skyscraper examples that are built to realize vertical farming. Such environments require a huge investment [8]. Figure 1 indicates the growth and the investment all around the world on vertical farming.

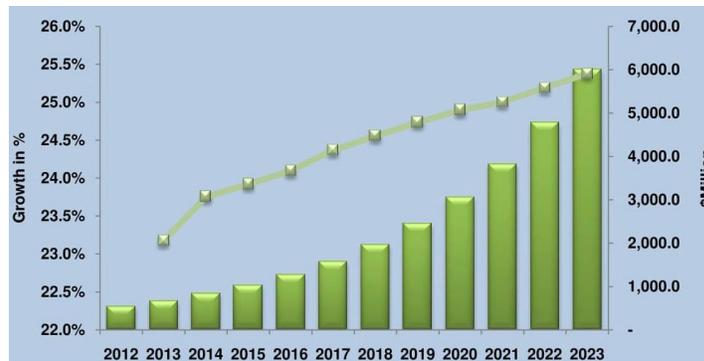


Fig. 1: Investment and Growth of Vertical Farming Market [9]

On the other hand, since growing requires water and is used as a transport medium for major nutrients, vertical farming environments the installation of a pumped water system is required. From an economical point of view, every cost is important and should be considered. Besides the deployed system, an energy saving approach can help to improve the cost of growing plants in such environments especially for farming factories that contain hundreds of stacked layers.

Farming in living environments has started as roof farming and commenced as a hobby. However, these rooftop surfaces are limited. Researches prove that for a densely populated city such as New York, the rooftop farming utilized to the maximum capacity may supply only 2% of 2015 New York's population [10].

Besides, even if all the roofs in the world participated in rooftop farming, it can be equivalent to 1% of global land [11, 12].

Although there are several building designs intended for vertical farming, until now there are very few skyscrapers that are built for farming. For instance, a skyscraper vertical farming building is under construction in Linköping, Sweden (See Figure 2). It is estimated that its initial cost has reached 40 million dollars and 550 tons of vegetables can be produced in a single year. The main problematic of stacking vertically is providing enough light which is one of the primary necessities of plant growth and avoiding shadowing issues since a layered structure is utilized.

2.2 Use Case Japanese Vertical Farms

Market researches prove that Japan has the most mature vertical farming industry [14, 15]. Japan has a possibility to be installed over almost everywhere in any kind of size with any kind of producing crops.

Based on the researches, there exists 165 vertical farms in Japan. When economical states of these factories are analyzed, only 25% of them are profitable and 25% of them can not profit and are in danger of bankruptcy. Although economical states of these factories are not so eye-opening, it is expected that the vertical farming industry will increase 1.15 billion dollars in 5 years and reach 13 billion dollars.

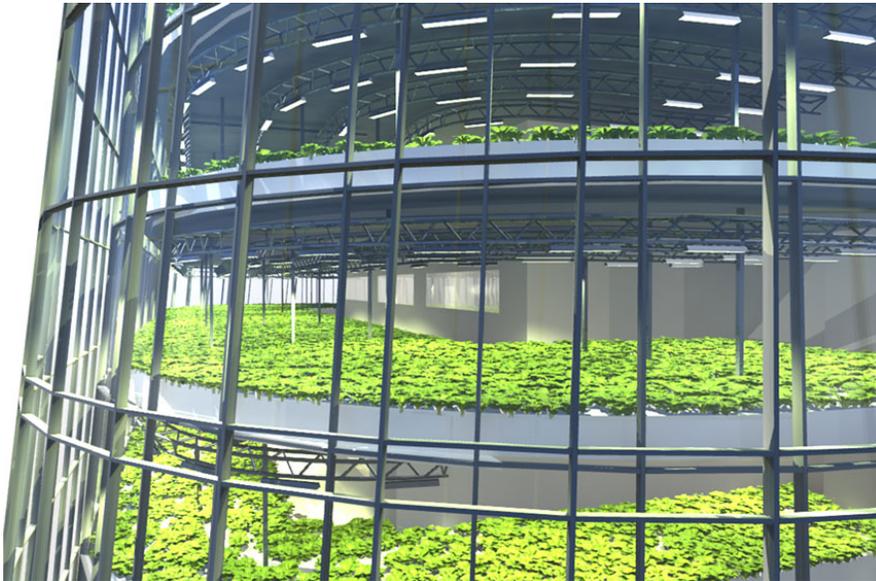
2.3 Vertical Farming in a Container System

Besides plant factories, for less scale alternatives container system is provided in vertical farming system. This system provides 21 m² area for cultivating, however vertical design ensures more space. By its modularity the system could be expanded, and could be moved to everywhere on the plant, all you need is electricity and some water. Electricity could be generated from solar panel even in desert, so this is why this system alternative could be preferred among others. In addition, to gather the advantage of being close to the market this container system also could be utilized. This system could be utilized for cultivating fresh plants for restaurants, and even could be used for farming micro-greens and fodder for feeding the live-stocks.

A container system alternative is presented in Figure 3 which is the basic one; furthermore solar panel systems could be added to the system. Despite all cited advantages, the first investment cost of this alternative is very high due to it is hard to get the short payback period.



(a) Swedish Vertical Farming Building in Linköping



(b) Inside View of the Building

Fig. 2: The World Food Building Plantagon in Linköping, Sweden [13]

2.4 Micro-based Vertical Farming System

As healthy lifestyles became popular among people, they began seeking a better way for their nourishment. Cultivating the greens, tomatoes or strawberries in their own indoors became for them not only a hobby but also a requirement. Micro-based vertical farming alternatives like seen in Figure 4 gained popularity among healthy



Fig. 3: Container Vertical Farming

life seekers. The system assures climate controlled cultivation process, moreover it provides whole year production cycle. By these advantages growing period diminishes and per meter square yield doubles in that case. Due to the relatively low initial investment cost, the system is mostly affordable for everyone.



Fig. 4: Micro Based Vertical Farming

One of the effects of the climate change is drinking water decrease, so this alternative farming system utilization of 95% less water than outdoor agriculture may provide a little bit improvement in this direction. While the unit cost is calculated with the costly electricity consumption and LEDs of the micro-based agriculture system alternative, the system provides profit all year due to crop cycle and growth rate. Only one disadvantage of the system might be; you cannot cultivate whatever you want due to space limit for the system in houses, balconies or gardens.

3 Soil-less Cultivation Methods in Vertical farming

Vertical farming concept usually implies a hydroponic cultivation system however two other techniques called aeroponic and aquaponic systems also could alternatively be utilized in this context. In addition, basically from the meaning of the word vertical, traditional agriculture methods can be used in vertical farming, yet conventional techniques in cultivation are inefficient in every dimension of the vertical farming concept. Traditional farming techniques are only economically viable at the moment due to the lower price of land and water. When the initial investment costs of vertical farming are taken in to consideration, the inefficiencies and lower crop yields of traditional farming techniques in vertical environments are not economically viable.

3.1 Hydroponic Systems

Hydroponic agriculture is a method of growing plants in a water based system where a nutrient rich solution is used. Studies show that plants can get the nutrients and minerals they need from the water solution and plants use mainly as a support medium relying on rainwater to transport the needed substances. In this way, hydroponic systems emerge as the systems that provide the nutrients that plants need by means of water, without the need for soil [16, 17].

Although the plants do not need soil and absorb all of the nutrients through the water solution, they still do need a medium that can mechanically support the plant also called grow medium. Some of the mediums also act like a sponge and or wick temporarily storing a small part of the nutrient solution or transporting the solution short distances.

There are several types of hydroponics systems which differ mainly by the method nutrients and water is delivered to the plants. Drip hydroponics systems, as the name implies are simple systems that drip the nutrient solution on to the plants, the runoff is collected in the reservoir that is kept away from plants. A pump pumps the solution through drip irrigation pipes to the individual plants. The timing of the pump can be automated. On Flood and drain systems, the plants are placed on trays or tubs, and the tub is flooded by means of a pump up to the root line of the plants. Then the nutrient solution is slowly drained off by gravity back to the reservoir and cycle is

repeated. The frequency and duration of flooding is tuned according to temperature, humidity and the water holding capacity of the grow medium that is used. In wicks hydroponics systems a good wicking grow medium such as vermiculite, rock wool, perlite or coco coir is used. Some more conventional materials such as propylene felt strips, fibrous rope, polyurethane yarn, nylon or cotton rope can be utilized. This system is not suited for larger plants due to the transport capacity of the wicking media. The other disadvantage of this system is that the wick can get a buildup of nutrients that can reach toxic levels around the roots, therefore it requires frequent flushing. In water culture hydroponics systems the plants are directly suspended in to the reservoir tank, usually the plants are setup on a float made of a buoyant material such as Styrofoam so that the roots are submerged in to the reservoir and the leaves grow on top of the float. Stagnation of the nutrient solution is not desired and plants benefit from aeration or oxygenation of the roots, therefore a pump is used to pump air in to the solution under the roots which also mixes the solution.

The nutrient film technique system has a slightly inclined horizontal growtray. The plant is placed in the holes on the reservoir and the roots of the plant are released into the water at the bottom. The reservoir is placed with a slight slope so that the aqueous solution circulates like in fish aquariums. Figure 5 shows a basic hydroponic system architecture and nourishing film technique. As shown in architecture, a water pump delivers water and other nutrients from a reservoir system to this room. This water circulation is set to deliver water and other nutrients at the most convenient time to maximize growth [18, 19]. Figure 5 illustrates the hydroponic farming mechanism.

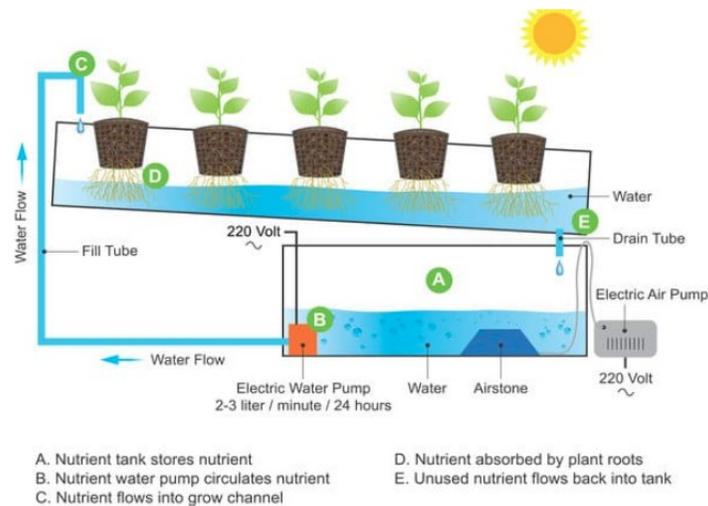


Fig. 5: Mechanism of Hydroponic System [20]

The biggest advantage of water-based systems is the increase in growth rate. Because plants do not need to expend energy to obtain nutrients and do not need to

invest energy growing larger root structures, based on an optimal experimental setup, plants can mature 25% faster, besides provide 30% more production than traditional farming [21]. In order to ensure efficiency in water-based systems, the ambient conditions and pH level of the aqueous solution should be constantly monitored and intervened quickly when necessary. Also, since hydroponic systems carry out soil-less agriculture, no weed problems, pests or plant diseases that we encounter in traditional agriculture can occur. Apart from algae that may occur in the water tank, a negative impact from the outside is minimized. For this reason, it is not necessary to use any pesticides [22].

However, the biggest problem of hydroponic systems that stands out as an alternative to traditional agriculture is cost. Since the vitamins and minerals that the plant should take from the soil under normal conditions are given through an aqueous solution, the chemical and physical values of the established environment and solution should be constantly monitored. The aqueous solution should be constantly monitored and the necessary settings should be made according to the type of plant and the growing phase. This causes the necessity to establish a special monitoring and emergency response system as well as the system's own cost. For example, in the event of a pump failure, all plants can die within a few hours as plants need a constant water supply. Therefore, environment monitoring systems are of great importance in these systems [23, 24].

3.2 Aeroponic Systems

Aeroponic systems are also water-based much like hydroponic systems, and are based on the spraying of the aqueous solution to the plant roots at regular intervals. In these systems, the aqueous solution is sprayed into the plant roots in the form of mist or steam with the help of a pump. An ultrasonic fogger can also be utilized to generate a mist in the environment where the roots reside. The roots of plants also require oxygen. In traditional agriculture soil is modified to be more permeable to air for this reason. In nature worms help with the soils aeration problem. The architecture of the aeroponic system is shown in Figure 6. Since it is water based and does not require soil and fertilizer, it is offered as a strong alternative to traditional agriculture such as hydroponic systems. In traditional farming, the plants establish a developed root structure to obtain nutrients from a broader region compared to hydroponics or aeroponics. Also soil is relatively stable with regards to temperature and humidity. Since during their growth of crops optimize themselves to the new environment and since a problem in the water supply can have such a drastic impact on the environment of the plant, the values of the aqueous solution must be constantly monitored and rapid intervention is required when necessary.

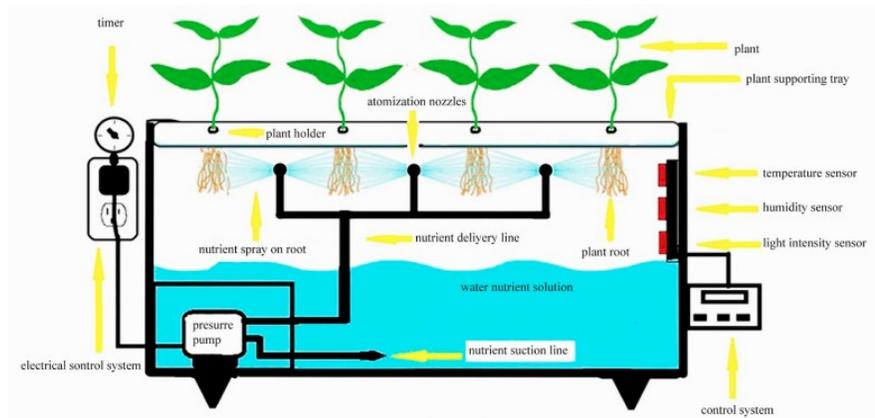


Fig. 6: Mechanism of Aeroponic System [25]

3.3 Aquaponic Systems

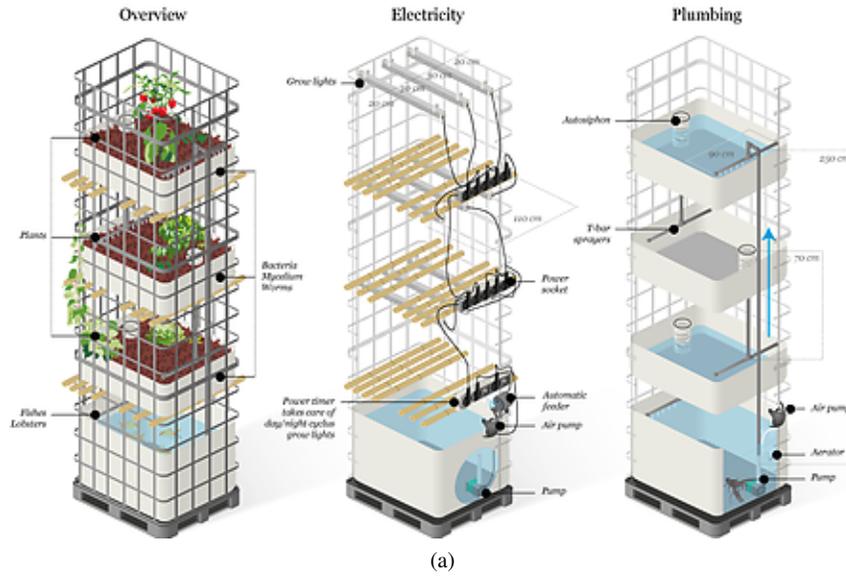
Basically, an aquaponic farming system is the combination of aquaculture (way of raising fish) and hydroponics system [26]. In this sort of farming, fish and plants are grown together in one integrated system. Fish eat their nutrition and excrete ammonia. Bacteria converts ammonia into nutrients that plants can absorb. Aquaponics farming system builds an integrated relationship between the animal and the plant environment. These two species share the same environment and maintain stable farming [27, 28]. Figure 7 illustrates the mechanism of aquaponic farming system.

4 Evaluation Metrics for Vertical Farming

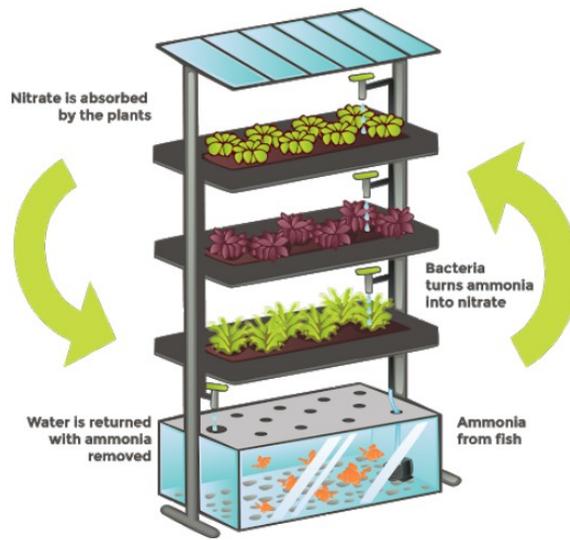
To be economically viable in the foreseeable future, plants growing in vertical farms ideally need the following characteristics: high edible mass percentage, low plant height to make better use of the vertical axis and fast growing cycles.

4.1 Energy Consumption

While there are several factors that are a good measures for determining the current profitability of a crop, there is one fundamental barrier to being able to grow every crop type which is energy. Leafy greens do not require much light to grow as they are made of around 95% water, and they are entirely edible. Mass makes up most of the crop. Compared to rice, which provides the most calories worldwide, supplying 90% of global human calories. It is just 15% water that has a much lower edible mass



(a)



(b)

Fig. 7: Mechanism of Aquaponic System [29]

percentage. Unfortunately, growing rice using artificial lighting would require about 30 times more energy than lettuce. Rice, grown in a vertical farm using current

technology, will produce extremely expensive rice and have a significant energy demand.

As seen from many researches on this domain, energy is the major constraint for plant factories and the overwhelming factor that dictates what plants can be grown economically. For this reason, energy constraint is the major challenge for vertical farms.

In fact, each plant has its own luminous requirements. Crop types can be classified into three broad categories based on their approximate energy requirements:

- Group 1: Leafy greens and herbs
- Group 2: Vegetables, roots, pulses and ground fruits
- Group 3: Staple crops, nuts and tree fruits

When we compare these groups, Group 1 is considered as a starting point (base). Group 2 requires 2.5 times more energy per kilo than Group 1 and Group 3 requires 30 times more energy per kilo than Group 1.

4.2 Water Consumption

Water is another important challenge for vertical farming systems. These 3 groups indicated above are highly water intensive. Pulses in particular have a relatively high demand for water. Growing this category in vertical farms would save a significant 23% of global fresh water consumption. This change alone could have a profound impact. Hydroponic systems employed in vertical farms can save 95% of the water if traditional farming techniques were used. In addition, as the nutrient loaded water is a financially valuable resource that is closely monitored and kept in reservoirs it is not wasted or dumped in to the environment causing problems.

For these systems, it's essential to apply enhance energy saving approaches. There are many studies on reducing the energy costs of vertical farms by understanding more about yield and how it relates to energy efficiency.

4.3 Nutrient Consumption

As vertical farms re-utilize their feeding solutions there is very little waste. One of the important nutrients for plants and all living organisms is phosphorus. It is utilized in cell structures as well as DNA. Currently phosphorus is being mined and it is currently not a renewable resource. In conventional farming only 15% to 30% of the phosphorus is absorbed by the plants as they are only capable of absorbing nutrients in 1 mm proximity to the roots. A majority of phosphorus contaminates underground and fresh water supplies. As modern farming techniques have broken the phosphorus cycle, the phosphorus used to create the plants and then feed people and animals is not returned to the soil. Estimates show that phosphorus reserves will

be depleted within several decades at current consumption rates. Vertical farming can slow down the depletion rate of this non-renewable resource. [30]

4.4 Yield

Yield is one of the most significant indicators of a farm's operational efficiency. While it's relatively simple for traditional agriculture, there are numerous ways to measure yield in vertical farms. An outdoor field only has one level, so the land and surface area are the same for traditional agriculture. For a vertical farm, things are different. Doubling a five layer farm to a 10 layer farm, doubles the footprint yield, because it produces twice the amount for the same building footprint. Absolute yield remains the same however, because doubling the layers doubles the surface area.

The numerical results of vertical farming appear impressive. As doubling the layers of a vertical farm, doubles the land saved from displacing field production. However, it's important to remember that doing so would double the energy requirement. If solar panels are used to provide the energy for the farm, then doubling the energy would double the solar footprint. This should be factored in when comparing footprint yields.

For most crop types, the area of additional solar panels is very small when we compared with the vast land. Plant factories can have an arbitrarily high footprint yield, because they can grow as with as many levels as are economically viable. Future vertical farms will likely have a footprint yield hundreds of times greater than the best outdoor farms, such farming environment with high footprint will allow them to leverage a significant economy of scale.

While footprint yield is a valuable measure for farming, it's not necessarily the best indicator of the operational efficiency for a vertical farm. After all, skyscraper farms would boast very impressive footprint yields. Yet would not be profitable. As stated before, the biggest challenge for plant factories is energy. If doubling the surface area doubles the energy requirement, then it makes more sense to use a measure that is independent of the number of levels in a farm.

Due to the high investment cost, studies focused on how plant factories may increase the yield at a given level. Plant factories that grow produce faster, get more harvest per year and increase yield as a result. They can also grow plants close together in the horizontal dimension. This greater density increases absolute yield. Increasing the edible mass per plant also increases the yield that is achieved by growing a higher percent edible mass plants or by growing larger plants. Increases in absolute yield for given energy input leads to a higher energy efficiency as such, improvements in absolute yield vital for plant factories. Energy efficiency can be thought of as the most critical metric in vertical farms. The higher the kilos of edible mass per watt hour, the higher for energy efficiency. This metric can be considered the fundamental determinant of what crops can be grown in a plant factory. Not only is it essential for the profitability of current farms, improving this number has

a direct result on how much they positively affect the global challenges like climate change.

4.5 Scalability of Vertical Farming

Technology in this area is improving quickly. But what can plant factories do to reduce their energy overhead? The key is to maximize the kilos of edible mass per watts of light and also reduce the dollar per watt of electricity. So what changes can be made to improve this. Vertical farms can increase the yield of any given plant beyond what is seen in hydroponic greenhouses. And it's not just because of their additional growing layers. They have much greater temperature, atmospheric and light control than greenhouses. This allows for superior growing conditions and waste elimination. Plants only absorb certain wavelengths of light. Using LED grow lights allows plant factories to use specific light recipes tailored to each plant, enhancing the energy efficiency. While a vertical farms, atmosphere, nutrient and light control already far surpass current growing methods.

There are many opportunities to increase it further. Plant growth is complex and affected by many parameters. There is still a considerable amount of work to be undertaken to understand the optimal conditions for plants. Outdoor plants use changes in sunlight to determine when to grow and flower. Normally this is dictated by the environment but LED's can emit different recipes of light at different growth phases of the plant. These light recipes can alter many of their characteristics. They can be tailored to increase the flowering portion, reduce the root growing phase and even control how the plant tastes. This allows plant factories to increase the edible mass percentage significantly. Energy a plant uses building none-edible structure is waste energy. This is inconsequential for sun grown plants but is critical to vertical farms. Field grown lettuce has about 40% edible mass when considering root systems and inedible outer leaves, while vertical farms have managed to achieve 92% edible mass. But that's not the only advantage of light recipes. Since they can be used to trigger growing cycles, they can accelerate plant growth considerably. While field grown lettuce can be harvested twice per year, vertical farms can harvest up to 12 times per year. Even rice can be harvested about four times more often than when grown in a paddy field. While the edible mass percentage for lettuce is approaching its limit, that's not necessarily true for other plants. Despite being a new industry, yield improvements are happening quickly.

5 Enabled Technologies in Vertical Farming

To provide sustainability, vertical farms require a real time monitoring system with deployed IoT based wireless sensors and actuators: temperature, humidity, nutrient levels, luminosity, ventilation level etc. Because plant factories control the environ-

ment so effectively, it's considerably easier to actively run experiments and interpret the data. Maximizing yield by the fine tuning of variables such as CO₂ and humidity levels. Not only that, but due to having considerably more harvests per year, they have a lot more opportunities to experiment, collect data and learn. This allows for a learning rate that is a number of magnitudes higher than other growing methods. Hence, sensor data analysis and data engineering domains are also involved in vertical farming researches.

Machine learning has also involved in proposed approaches. Despite this, it's still at an early stage. A number of plants are poorly suited to vertical farms, due to low edible mass percentage, being ill suited to hydroponics, or being a tall crop. Since, current commercial outdoor crops have no need to consider these parameters they breed plant varieties that thrive outdoors and are often incompatible with vertical farms. Plant factories have different priorities and require different seed types as a result. There are many dwarf varieties of existing crops, that could be utilized. If they can match existing crop quality with a seed optimized for short height, hydroponics and high edible mass percentage, then the energy requirement for replacing existing crops could shrink significantly.

Additionally, seeds can be bred for faster harvest cycles, not a requirement for most current crops. Many current crops sacrifice breeding for peak yield so as to breed for viral resistances. This isn't necessary in vertical farms because of their sealed conditions. Unlike greenhouses, they don't need to vent and are run like a clean room environment. These yield improvements alone can significantly reduce the energy gap for future crop types, but it's not the only improvement available. This area has a huge potential for improvement, especially for plant factories that utilize genetically engineered seeds. Gene editing techniques are getting much cheaper and easier to implement. This has a lot of potential for both indoor and outdoor farming in the future. In the last few years LED lights have improved considerably. Special units are being developed specifically for indoor growing and their efficiency is anticipated to improve by 50% in the next decade. Efficient LED's run colder, not only does this save electricity but allows them to be placed closer to the plant without risking heat damage. This allows plant factories to fit more levels into a fixed building height, increasing footprint yield. Closer positioning increases light penetration into the canopy allowing plants to be grown closer together and increasing absolute yield. It also reduces light bleed and increases light absorption efficiency, reducing energy requirements. Greater use of reflective bay materials, deeper penetrating green wavelength light and mid level bay lighting can further reduce the total energy requirements. It's not just efficiency though. LED's are increasingly capable of delivering a broader spectrum of light, allowing for greater control and yields. The cost of the units are also falling quickly, while the unit lifespan continues to improve. This will reduce the the depreciation costs for future vertical farms, and is essential for improving their cost competitiveness.

5.1 Renewable Energy Technologies

If there is one technology that could transform the potential of vertical farming, it's renewable energy. It has the potential to solve the environmental and economic outlook simultaneously. Solar for instance is projected to half in cost over the next decade. This will bring its cost below traditional production methods in many areas of the world. Reducing the cost of electricity will be the final step, enabling vertical farms to grow a broader range of products. The future of energy production is looking very promising and is of critical importance to many global challenges, not just those related to vertical farming. If vertical farming can realize the extent of these improvements, their future energy demand can be dramatically lower and will be able to supply much cheaper produce than we see today. If renewable energy sources prove not to be as cost effective and environmentally beneficial as predicted, and nuclear energy proves to be a much cleaner alternative, then vertical farms have the option of shifting their lighting periods to the night. This will help with load balancing the power stations where at night power stations are seeing lower loads and are generally more inefficient.

5.2 Machine Learning and Artificial Intelligence

Vertical farming shares a lot of aspects with modern farming techniques such as hydroponics, aeroponics, aquaponics, and smart farming. Farming technology and techniques have taken millennia to mature to their current state and most would argue that we still have a lot to learn. In today's ever growing population and financial stresses on farmers, time is not a luxury that can be afforded. Plants have evolved over millions of years and are well adapted to their environments.

Improving farm productivity is one of the main aims of farming applications and systems. Using machine learning (ML) techniques and improved artificial intelligence techniques may provide significant solutions to increase productivity and crop harvest.

Although monitoring many aspects of the agricultural process is important to give an immediate response to problems or detect nutrient-deficient areas there is too much data to be analyzed. With machine learning and artificial intelligence, it is becoming possible to detect problems, infections or nutrient deficiencies with much greater speed and accuracy.

As more data on the environment and plant growth is gathered, machine learning algorithms may be used in the modeling of plant growth, and feedback loops can be utilized to monitor and provide for the plants. This is especially important in vertical farming applications where the plants are grown in indoor environments and their entire interaction from feeding to lighting to CO₂ levels to humidity to pollination are controlled by the farmer. For example, plants can tolerate only a certain concentration of nutrition in their feeding solution, and for optimal growth they need a certain nutrient uptake. The amount of uptake is closely related to the

amount the plant can excrete from its stomatas which depends on the environmental temperature and the environmental humidity. Therefore, the nutrient concentrations must be strictly regulated according to temperature and humidity. What concentration and composition of nutrients at what stage of growth is another area that is being investigated. There has been a lot of progress made on determining the optimal conditions for plant growth but a unified system that also creates a model of the plant and determines the optimal parameters that have not been created as of yet.

Machine learning can also be utilized to determine and predict the optimal harvesting times of crops. In vertical farms, the plants reside in very dense populations all sharing common resources passing through all of the plants or plant groups. This can amplify any problems such as bacterial, viral, and fungal problems. In vertical farms, it is vital to track the plants and immediately react to any problems.

In such machine learning applications, support vector machine (SVM) and neural network (NN) are two well-known approaches. SVM approach uses a discrimination function to obtain classes. In these approaches, an unsupervised clustering algorithm such as k-mean is mostly preferred ML algorithm [31]. Moreover, artificial neural network (ANN) approaches can also be applicable on farming data.

In literature, these various machine learning and deep learning models are applied in the farming domain for crop and yield management, disease, weed detection, species recognition, soil, and water management. Table 1 summarizes the existing machine learning applications in the farming domain. For the time being, all of these studies can be merged with decision making systems. Meanwhile, machine learning applications in farming have started to cover data analysis and big data studies since acquired data from the real time monitoring system is required to process and store.

6 The Future of Vertical Farming

Researches on vertical farming identified that energy consumption as the primary barrier to plant factories having a big impact on the world and presented how vital improving absolute yield is to improving their energy efficiency. Besides, several methods are proposed to optimize and to boost yield, lower their energy consumption, and take advantage of cheaper, cleaner electricity. Current LED's achieve about an efficiency of approximately 200 lumens/watt. The theoretical maximum lumens / watt is 670 which indicates that there is room for improvement. One interesting research performed at MIT university achieved over unity efficiency in LED's meaning more luminous power output than electrical power input was achieved, it was observed that the LED was capable of absorbing thermal energy and converting it to lumens. The LED's were powered with 30 picowatts and produced 70 picowatts of light. Although promising the setup works in the pico-watt ranges but has the potential to completely transform the vertical farming industry [48].

Table 1: Usage of Machine Learning Techniques in Smart Farming

Study	Methodology	Application
Jhuria et al. (2013) [32], Moshou et al. (2014) [33], Bhange et al. (2015) [34], Chung et al. (2016) [35], Ebrahimi et al. (2017) [36], Kim et al. (2018) [37]	prediction model, neural Network, SVM classifier and image processing	disease detection
Geipel et al. (2014) [38]	image processing and re- gression	managing corn grain yield
Coopersmith et al. (2014) [39], Morellos et al. (2016) [40], Nahvi et al. (2016) [41]	multivariate regression models	soil management
Lottes et al. (2017) [42]	machine learning tech- niques	distribution of weeds and classifi- cation of crops
Sa et al. (2017) [43]	CNN-based dense semantic classification	crop health
Grinblat et al. (2016) [44]	CNN	plant identification
Maione et al. (2016) [45]	classification	geographic origin prediction
Pantazi et al. (2016, 2017) [46, 47]	hyperspectral imaging	weed detection
Moshou et al. (2014) [33]	LSSVM	plant stress

6.1 Vertical Farming Industry

There are several research directions in this domain. One of them is to realize the proposed improvements. The question to be asked is when, where and how far these improvement can be achieved. Based on the currently employed technologies, it is hard to define a time interval. Although in theory, it is possible to grow everything everywhere, in practice, as seen from the previous sections, there are many factors that affect the yield and management. The economic viability of the industry will vary by crop and location at any given time. When we recall the groups indicated in Section 4.1, crops in Group 1 are already well underway in Japan for instance. However, it does not signify that these crops although they are basic, can grow in everywhere. There are specific environmental, physical and chemical conditions to obtain for every type of plant.

With some research, by looking at what percent of vegetables a country produces as a ratio of it's total vegetable consumption, it is possible to estimate where vertical farming industry may make the most economic sense. Commonly, countries that import high percentages of their vegetables, probably prefer, since producing it locally is difficult and expensive. Thus, it results in high market prices. Besides, the local cost of electricity should be considered, as it's one of the fundamental costs for plant factories. High electricity prices would make food produced in vertical farms prohibitively expensive.

From the crop types, crops of Group 1 is relatively small scale and energy requirements this carbon cost is low. To recall, Group 2 would require approximately

2.5 times the energy of Group 1. Based on the current economical status, Group 2 crops are more or less viable, although profits on non premium products will be very slim. Especially in Asia, vertical farming is very common. The emergence of Group 2 crops such as cucumbers, tomatoes, and even strawberries being produced commercially in these regions. Based on the current trend, if Group 2 continues its course and becomes ubiquitous worldwide, we will start to see significant global freshwater savings in the next 10 years. Thus, the global benefits of vertical farms become a lot more tangible. However, the energy problem remains important. Energy problem may become bigger if Group 2 farms reach a global scale. Besides, carbon cost may become prohibitive if renewable sources aren't used in these systems.

Compared to the Group 1-2 Group 3 has the greatest global impact but it's also the hardest to achieve for this technology. A significant part of this group would be staple crops such as rice and wheat. Current production of these crops already benefit from a massive economy of scale and have small profit margins. Staple crops store well, thus neutralizing the freshness value that vertical farms provide. Additionally, staple crops are generally tall, which hurts the growing density advantage of plant factories. However, the biggest barrier of all is the 30 times greater energy requirement compared to leafy greens.

6.2 Feasibility Analysis - Ways to Reduce Costs

Plant density and large energy costs are much bigger problems. To make Group 3 profitable, the energy cost per kilo must be greatly reduced. Wheat is the staple food in Turkey and the Mesopotamian region. Currently edible radiation use efficiency (ERUE) of wheat has been measured as 0.33 g/mol of light [49]. In order to grow 1 kg of wheat, 3030 moles of light are needed. Current CREE brand LED's have been reported to have $2.2 \mu\text{mol} * \text{s}^{-1} \text{W}^{-1}$. This equates to $7.92 \text{ mol}/\text{kWh}$. From these values we can compute that 382.5 kWh of energy is required to produce 1 kg of wheat. With today's electricity prices that equates to 275.5 Turkish Liras or 40.3 USD. These numbers are clearly not feasible. For the production of staple foods to be feasible the price has to drop by an order of magnitude. Currently wheat retails for 2 Turkish Liras/kg.

In order to lower these prices several things can be done. First of all, grains can be stored for longer periods of time and their freshness usually does not equate in to their prices. Therefore relocation of production to a location where cheap energy is available has the potential to lower prices. Iran for example has 1/9 the electricity price of Turkey.

As growing wheat in closed environments makes no financial sense, it has not been done and not much expertise or data is available on it. Although there are some studies performed for NASA, optimization of light cycles, nutrients, light intensities and various other conditions have not been performed. Optimizing the conditions for wheat growth could substantially decrease the energy requirements to grow them. Furthermore, growing and harvesting times can also be accelerated

again reducing the energy requirements. For example, for same amount of consumed energy, 33% yield increase signifies 25% energy saving [50, 51]. Dwarf wheat varieties can be utilized to reduce energy requirements. In addition, crops can be genetically engineered to further enhance yield and shorten the harvesting time. As vertical farms are closed systems, environmental changes are much easier to perform. Increasing the CO₂ concentration in the growing environment will further provide gains. The advances in LED technology will again reduce the amount of energy needed to produce the crops. The price of renewable energy sources is decreasing constantly. A dedicated solar or wind farm could provide the necessary energy for the vertical farm. Furthermore, as the energy required is luminous energy, solar panels that absorb the non-photosynthetic region of light and reflect the rest can be utilized, reflecting or transporting the light through fiber-optic cables or light tunnels to the vertical farm. With these changes the energy consumption of vertical farms can decrease to almost competitive prices.

In the perfect conditions indicated below, near 2030s, our world has a chance to have a highly resilient food production system. That scales easily to produce more food and not be vulnerable to climate, flooding, and pest damage. A system that will make food cheaper than it's ever been before. It's not the only change required to eliminate world hunger, but it will help significantly. Reducing agriculture's global fresh water consumption by 91%, will have an even greater effect, both in terms of global water security and environmental impact. Hence, it may be possible to halt and reverse desertification, and drastically reduce most of agriculture's large greenhouse gas footprint. We could further help reduce atmospheric CO₂ by reforesting the 15% of the global land we are able to displace. And this will finally reverse the trend of mass wildlife depopulation we see today. For the global issues, the news coming all around the world is promising but more changes and technological improvements will need to happen to solve them entirely.

Grown products are consumed by people but also are used for biofuel and livestock feed (respectively 9% and 36%). Meat takes a huge amount of water to produce, as the crops grown for the animals require a lot of water. Producing one kilo of beef requires seven kilos of crops to produce. This makes meat production extremely water inefficient. Meat production is also extremely land inefficient. 70% of all agricultural land is considered grazing land. Currently, foods such as soy and hay are used to supplement livestock feed. Meat production contributes a considerable amount of the global challenges but it's largely due to its food import. Sprouted barley fodder is considered as an revolution in animal feeding. It can supplement a significant percentage of livestock's feed and can improve the health of the animals. It can be grown extremely cheaply in plant factories, with minimal labor, water, and electricity costs. In fact, the energy costs are so low, that it can be grown profitably right now, all across the world. While data for this market is limited, it appears to be growing quickly. If this opportunity is realized by businesses globally, it is highly possible to see an impact on the global challenges sooner than expected.

6.3 Economic Comparison of Agricultural Systems

Feasibility analysis requires economic analysis at first. Then, to perform a decision analysis additional criteria could be found. As discussed before vertical farming system is a powerful alternative for traditional farming systems in case of climate change conditions. Besides it may repair the effects of climate change conditions due to less usage of scarce resources. For this recovery process vertical farming system has to be used mostly. So, it is necessary to make an economic analysis for all kinds of agricultural systems in yield performance to decide which one will be preferred by a majority in the next decades. All prices are accounted in Turkish Lira. Rates and other considerations are derived from the literature.

Here we compare the prices of food production on what is available in the market during seasonal harvesting times. In completely controlled environments with artificial lighting there are no more seasons regarding the production of the plant or fruit. For example strawberries that are a summer fruit can be produced year round in fully closed vertical farms and they can be sold in the winter for a higher price. In vertical farms that utilize ambient light without significant light supplementation, i.e. those that resemble greenhouses rather than factories, the seasonality of the produce remains relevant. However, changes in nutrient composition and temperature can shift the cycle of the plant by a few weeks landing the harvest time in to a much more profitable market. In our calculations we do not take these considerations in to account.

Here, we compared the conventional outdoor, greenhouse, and micro-based indoor vertical farming alternatives per 1 meter square. All the costs are reduced to a 1 m² space to be able to compare the apples to apples. First investment costs are presented as capital expenditure (CAPEX) for both alternatives in Table 2. Five years investment period would be sufficient for this analysis, and in addition due to less costs, no interest rate is taken into account. Financing through own equities are considered, and of course if one thinks to finance this investment via credit all the calculations could indeed change. In Table 3 monthly operating expenditures (OPEX) for all alternatives are introduced. As in CAPEX, here all costs are calculated in a monthly basis.

Table 2: Capital Expenditures (CAPEX) for Alternative Farming Systems

CAPEX		Outdoor		Greenhouse		Vertical Farming	
Items	Unit Cost (₺)	Quantity	Costs (₺)	Quantity	Costs (₺)	Quantity	Costs (₺)
LED 10 W	58.31	0	-	0	-	8	466.49
Air Pump	25.71	0	-	4	102.85	4	102.85
Controller ESP8266	28.78	0	-	0	-	8	230.24
Container	68.20	0	-	4	272.80	4	272.80
Container Top PU	40.92	0	-	4	163.68	4	163.68
		Subtotal	0.00	Subtotal	539.33	Subtotal	1236.06

Water costs ₺4.00 for greenhouse and vertical farming systems, however in an outdoor area it costs ₺1,00. Sprout, solution for plants, and water costs are computed according to growth cycles. Costs of electricity for LEDs, and for the other electronics / sensors are calculated in monthly based. As said before, investment period is 60 months, so we transformed this CAPEX into monthly based by dividing it to sixty months. And then we supplemented it to the OPEX to find the unit cost as presented in Table 4.

Table 3: Operational Expenditures (OPEX) for Alternative Farming Systems

OPEX-Monthly		Outdoor		Greenhouse		Vertical Farming	
Items	Unit Cost (₺)	Quantity	Costs (₺)	Quantity	Costs (₺)	Quantity	Costs (₺)
Sprout	0.25	18	1.93	25	4.17	30	10.71
Electricity-LED	0.71	0	-	0	-	0.16	13.64
Electricity-The Others	0.71	0	-	0.04	3.27	0.11	9.24
Solution (in L.)	31.98	0	-	1.00	21.32	1.20	54.82
Water m ³	4	7.20	3.09	0.50	1.33	0.6	3.43
		Subtotal	5.01	Subtotal	30.09	Subtotal	91.84

In Table 4, the major differences between the farming methods are presented and the crucial impact of vertical farming is underlined. In May 31, 2020 the market clearing price of a lettuce is 4.75. Though this study is just for to show the differences among farming alternatives we just took the market price, in practice the seasonal average price and whole year average price should be taken.

Table 4: Benefits of vertical factory farms versus other methods [52]

	Outdoor	Greenhouse	Vertical Farming
Growth cycle (days)	70	45	21
Water consumption per crop (L.)	35 lt	15 lt	1.5 lt
Number of crops per m²	18	25	30
Waste rate	20 %	10 %	5 %
Unit Cost (₺)	0.65	2.34	2.62
Crop cycles (days)	140	225	365
Pesticides/herbicides	Often	Less often	None
Location	Open field	Open field	Anywhere
Post harvest handling	High	Medium	Low
Market Clearing Price (₺)	4.75	4.75	4.75
Yield / per m² / year (₺)	118.08	270.58	1053.32

To compute the footprint yield the net revenue value has been accomplished and we took account the crop cycles to calculate the whole profit, and we considered also waste rates to reach the exact data. At last, as can be seen from the Table 4 we

achieved that the vertical indoor micro-based framing alternative provides the best profit. Of course short maturing process, low waste rate and possibility of whole year planting assured this result. Pesticides/herbicides non usage ensured more healthy benefits.

7 Conclusion

It is expected that by 2050 world population will exceed 10 billion people with 68 percent of us living in urban city centers. This will generate various global challenges such as providing enough food for everyone in a sustainable, efficient and cost-effective way. Due to the climate change, restrictions of seasonal weather patterns force researchers to find alternative solutions for agriculture. In this context, vertical farming has become one of the hottest topics. With vertical farming, studies aim to enhance yields for the future of food production.

Vertical farms are modular and can be adjusted to fit in almost any building, for instance in an old laser tag area in New Jersey, USA. When the plant layers are stacked and with the special growing methods can lead to 75 times more products per square foot than a traditional farm. Controlled indoor environments disrupt the normal life cycle of pests. Thus, it does not need pesticides, herbicides, or fungicides. In these environments, energy-efficient LED lights are used to help crops grow indoors. A nutrient mist is sprayed on the plant's roots, using 95% less water than traditional agriculture. As said before, for market-clearing price seasonality effect should be calculated to access exact data for the future studies. Renewable energy or smart farming cost computations could be performed as well. Although much development is still needed for vertical farming technologies to mature, vertical farming has the potential to solve the world food problem and become a major tool for fighting climate change.

References

1. M.N. Hodges, M.L. McKinney, *Urban Ecosystems* **21**(4), 721 (2018)
2. P. Hazell, *Agriculture and food systems to 2050*, 137 (2018)
3. O.R. Iheke, U. Ihuoma, *International Journal of Agricultural Science, Research and Technology in Extension and Education Systems* **5**(2), 83 (2016)
4. C.L. Huang, S. Qu, B. Gao, Y. Huang, H. Fang, X. Yan, S. Cui, M. Xu, *Journal of cleaner production* **214**, 803 (2019)
5. M.J. Labrum, R. Gomulkiewicz, *Journal of Mathematical Biology* **80**(1), 93 (2020)
6. J. Huang, G. Yang, *Global Food Security* **12**, 119 (2017)
7. H. Long, D. Ge, Y. Zhang, S. Tu, Y. Qu, L. Ma, *Journal of environmental management* **209**, 440 (2018)
8. A.M. Beacham, L.H. Vickers, J.M. Monaghan, *The Journal of Horticultural Science and Biotechnology* **94**(3), 277 (2019)
9. Vertical farming market to grow at significant rate of around 25% in coming years forecasts acumen research and consulting. Tech. rep., Acumen Research and Consulting (2020). URL

- <https://www.acumenresearchandconsulting.com/vertical-farming-market>. Accessed: 2020-05-05
10. D. Despommier, Trends in biotechnology **31**(7), 388 (2013)
 11. B.J.P. Grard, C. Chenu, N. Manouchehri, S. Houot, N. Frascaria-Lacoste, C. Aubry, Agronomy for sustainable development **38**(1), 2 (2018)
 12. D. Despommier, Journal für Verbraucherschutz und Lebensmittelsicherheit **6**(2), 233 (2011)
 13. A. Lauri, The companization organizational model: managerial challenges and responses in a peculiar hybrid organization: a case study on plantagon international. Master's thesis, LUISS Guido Carli, Viale Romania, 32, 00197 Roma RM, Italy (2017)
 14. K. Benke, B. Tomkins, Sustainability: Science, Practice and Policy **13**(1), 13 (2017)
 15. F. Kalantari, O.M. Tahir, R.A. Joni, E. Fatemi, Journal of Landscape Ecology **11**(1), 35 (2018)
 16. H.M. Resh, *Hydroponic food production: a definitive guidebook for the advanced home gardener and the commercial hydroponic grower* (CRC Press, 2016)
 17. R. Singh, S.K. Upadhyay, D. Aggarwal, I. Sharma, N. Prasad, Bio Science Research Bulletin **35**(2), 59 (2019)
 18. R.R. Kumar, J.Y. Cho, Environmental Science and Pollution Research **21**(16), 9569 (2014)
 19. T. Sayara, B. Amarnah, T. Saleh, K. Aslan, R. Abuhanish, A. Jawabreh, International Journal of Plant Science and Ecology **2**(3), 23 (2016)
 20. H.T. Gardening, Hydroponic system basics. Tech. rep., High Tech Gardening (2019). URL <https://www.hightechgardening.com/hydroponic-system-basics-the-ultimate-guide/>. Accessed: 2020-05-04
 21. G. Marques, D. Aleixo, R. Pitarma, in *International Conference on Computational Science* (Springer, 2019), pp. 658–669
 22. S.D. Ferguson, R.P. Saliga III, S.T. Omaye, International Journal of Agricultural Extension **2**(3), 227 (2014)
 23. P. Sambo, C. Nicoletto, A. Giro, Y. Pii, F. Valentinuzzi, T. Mimmo, P. Lugli, G. Orzes, F. Mazzetto, S. Astolfi, et al., Frontiers in plant science **10**, 923 (2019)
 24. C. Cambra, S. Sendra, J. Lloret, R. Lacuesta, Sensors **18**(5), 1333 (2018)
 25. I.A. Lakhari, J. Gao, T.N. Syed, F.A. Chandio, N.A. Buttar, Journal of plant interactions **13**(1), 338 (2018)
 26. A. AlShrouf, et al., American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS) **27**(1), 247 (2017)
 27. R.V. Tyson, D.D. Treadwell, E.H. Simonne, HortTechnology **21**(1), 6 (2011)
 28. H.W. Palm, U. Knaus, S. Appelbaum, S. Goddek, S.M. Strauch, T. Vermeulen, M.H. Jijakli, B. Kotzen, Aquaculture International **26**(3), 813 (2018)
 29. H.J.A. Sánchez, Aquaponics and its potential aquaculture wastewater treatment and human urine treatment. Ph.D. thesis, Universidade NOVA de Lisboa, 1099-085 Lisbon, Portugal (2014)
 30. D.L. Childers, J. Corman, M. Edwards, J.J. Elser, BioScience **61**(2), 117 (2011). DOI 10.1525/bio.2011.61.2.6. URL <https://doi.org/10.1525/bio.2011.61.2.6>
 31. J. Behmann, A.K. Mahlein, T. Rumpf, C. Römer, L. Plümer, Precision Agriculture **16**(3), 239 (2015)
 32. M. Jhuria, A. Kumar, R. Borse, in *2013 IEEE Second International Conference on Image Information Processing (ICIIP-2013)* (IEEE, 2013), pp. 521–526
 33. D. Moshou, X.E. Pantazi, D. Kateris, I. Gravalos, Biosystems engineering **117**, 15 (2014)
 34. M. Bhanghe, H. Hingoliwala, Procedia Computer Science **58**, 280 (2015)
 35. C.L. Chung, K.J. Huang, S.Y. Chen, M.H. Lai, Y.C. Chen, Y.F. Kuo, Computers and electronics in agriculture **121**, 404 (2016)
 36. M. Ebrahimi, M. Khoshtaghaza, S. Minaei, B. Jamshidi, Computers and Electronics in Agriculture **137**, 52 (2017)
 37. S. Kim, M. Lee, C. Shin, Sensors **18**(11), 4051 (2018)
 38. J. Geipel, J. Link, W. Claupein, Remote Sensing **6**(11), 10335 (2014)
 39. E.J. Coopersmith, B.S. Minsker, C.E. Wenzel, B.J. Gilmore, Computers and electronics in agriculture **104**, 93 (2014)

40. A. Morellos, X.E. Pantazi, D. Moshou, T. Alexandridis, R. Whetton, G. Tziotzios, J. Wiebensohn, R. Bill, A.M. Mouazen, *Biosystems Engineering* **152**, 104 (2016)
41. B. Nahvi, J. Habibi, K. Mohammadi, S. Shamsirband, O.S. Al Razgan, *Computers and Electronics in Agriculture* **124**, 150 (2016)
42. P. Lottes, R. Khanna, J. Pfeifer, R. Siegwart, C. Stachniss, in *2017 IEEE International Conference on Robotics and Automation (ICRA)* (IEEE, 2017), pp. 3024–3031
43. I. Sa, Z. Chen, M. Popović, R. Khanna, F. Liebisch, J. Nieto, R. Siegwart, *IEEE Robotics and Automation Letters* **3**(1), 588 (2017)
44. G.L. Grinblat, L.C. Uzal, M.G. Larese, P.M. Granitto, *Computers and Electronics in Agriculture* **127**, 418 (2016)
45. C. Maione, B.L. Batista, A.D. Campiglia, F. Barbosa Jr, R.M. Barbosa, *Computers and Electronics in Agriculture* **121**, 101 (2016)
46. X.E. Pantazi, D. Moshou, C. Bravo, *Biosystems Engineering* **146**, 193 (2016)
47. X.E. Pantazi, D. Moshou, R. Oberti, J. West, A.M. Mouazen, D. Bochtis, *Precision Agriculture* **18**(3), 383 (2017)
48. P. Santhanam, D.J. Gray Jr, R.J. Ram, *Physical Review Letters* **108**(9), 097403 (2012)
49. J. Li, N. Zhang, J. Luo, Q. Yu, W. Ai, L. Zhang, Y. Tang, *Acta Astronautica* **162**, 336 (2019). DOI <https://doi.org/10.1016/j.actaastro.2019.06.028>. URL <http://www.sciencedirect.com/science/article/pii/S0094576518313870>
50. C. Banerjee, L. Adenaeuer, *Journal of Agricultural Studies* **2**(1), 40 (2014)
51. T. Kozai, G. Niu, M. Takagaki, *Plant factory: an indoor vertical farming system for efficient quality food production* (Academic press, 2019)
52. T.D. Maarten Vandecruys, Frederic Bulcaen, Urban crop solutions. Tech. rep., Urban Crop Solutions, Grote heerweg 67, 8791 Waregem, Belgium (2020). URL <https://urbancropsolutions.com/>. Accessed: 2020-05-05