

Article

Implementing Vertical Farming at University Scale to Promote Sustainable Communities: A Feasibility Analysis

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Abstract: The issue of food security has affected the well-being of the people for centuries. Academic and industry experts have been constantly developing alternate and better ways to address this issue. One of such innovations is the concept of vertical and zero acreage farming for providing food security and ensuring environmental sustainability. However, this concept has been in its nascent stage, and its development has been sporadic for many years. This paper uses a comprehensive framework to conduct a feasibility analysis of initiating vertical farming on university campuses, which could set an example for using this technique on a large scale. A case study was conducted on a set of 24 canteens across a university in Wuhan, China for accessing the return on investment and food sufficiency using this technique. By using the central limit theorem, a model was developed after investing in 24 canteens in the university, and various scenarios were analyzed. The breakeven on implementing these farms was about 10 to 20 years, with annual profits reaching \$92,000 (592,000 RMB).

Keywords: vertical farming; zero acreage farming; university; sustainability; economics; climate change

1. Introduction

The issue of food and nutrition security is at crux, which we are experiencing on Earth today. A recent study shows that over 815 million people are facing food insecurity, which is an increase of 38 million due to climate change and the proliferation of vicious conflicts [1]. According to these numbers in our current scenario, we must take the responsibility for mitigating this problem and chase the Sustainable Development Goals 2030 of the United Nations in order to eradicate hunger and poverty. At present, the global food system is subjected to pressure in delivering food to the ever-growing population. The consumer behavior and food production practices play important roles in the inefficiency of every type of food system [2]. By 2050, almost 80% of the population will reside in urban areas. According to traditional food production practices, an extra one billion hectares of land will be required in order to feed the growing population in the meanwhile [3]. The scarcity of land and depletion of natural resources have been a driving factor to find smart solutions in this fast-moving world. There have been many successful attempts in research and innovative solutions to fight this issue in our built environment. One such innovation is the integration of farming into building structures, which is called “vertical farming”. This is an alternate method where the food supply chain is shifted directly from the producer to the consumer. This results in a significantly lower carbon footprint and is environmentally sustainable [4]. Although this concept has remained in its nascent state, there are real-time examples that have proven that vertical farming is a sustainable way

to supply the best-quality produce while spending less energy. Countries such as the United States, Japan, and Singapore have shown significant results in applying vertical farming to their buildings. This study provides a framework that encourages institutions such as universities into adopting this system for their students. This study also investigates food data from the Huazhong University of Science and Technology (HUST) in China, which has over 24 canteens and compares the production and financial outcome using vertical farming. This could lead the institution into producing their own food on site and use the financial benefits to something more valuable. Additionally, this could also be a chance for all the commercial and residential sectors to take the initiative to mankind and create environmental responsibility. This study looks at the approach to vertical farming and how it could contribute to saving fossil fuels and reducing resource wastage.

2. Materials and Methods

2.1. Definitions

There are various definitions of vertical farming but to put into simple words, it is a method of urban farming of fruits, vegetables, and grains inside a building in a city or urban center, in which floors are designed to lodge crops with the absence of soil (hydroponics and aeroponics) [5]. Using large multistory buildings to cultivate agricultural produce was an incredible idea by Gilbert E. Bailey, who was an American geologist. His book simply titled “Vertical Farming” was revolutionary in the field of modern agriculture [6]. In the early 1980s, Dr. Yeang, who was a Malaysian-born architect, advanced the ideas of Mr. Gilbert into the subset of architectural design. He believed that the way agricultural products were grown, and all human activity, must be based upon “eco-mimicry”, which means that in order to be deeply sustainable, all built or devised human environments must mimic the patterns, characteristics, attributes, and cycles of natural ecosystems [7]. Another definition states that vertical farming is a system of commercial farming whereby plants, animals, fungi and other life forms are cultivated for food, fuel, fiber or other products or services by artificially stacking them vertically above each other [8]. The concept of supplying food using the city is not modern, but the idea of dedicating an entire building/skyscraper to cultivate produce, which is the concept of vertical farming, is a large-scale extension of urban agriculture within a building [9]. Another concept that has been recently coined is known as “zero-acreage farming”. It implies farming that is carried without using any additional farmland such as using rooftop gardens, indoor farming, or rooftop greenhouses. These are categorized as a subset of urban farming that is sustainable and decentralized [10]. This concept has been introduced in cities such as Berlin (Germany), and encourages other cities to incorporate these practices while recognizing its benefits and challenges [10]. This could also be one of the trends that could give the common people control of their produce quality and quantity.

2.2. Causes of Vertical Farming

According to the United Nations (U.N.), the population of the world through mid-2017 was 7.6 billion, and it is projected to reach 9.8 billion by 2050 and 11.2 billion by 2100 [11]. It is estimated that 19.5 million hectares of agriculture land are annually converted to urban centers and industrial developments [12]. This is because cities are the hubs of ideas, science, jobs, productivity, social development, prosperity, and more. Due to rapid urbanization, resources such as water supplies, sewage, biodiversity, land and soil resources, and public health are under pressure. The sustainable development of urban and rural areas requires addressing the demands for social, economic, and environmental land use in an integrated approach. Over two billion hectares of cultivable land has been degraded, and more than 1.5 billion people are living off the degraded land. Severe droughts have led to starvation and famine, which affected more than 25 million people in 2017 [13].

A study done by the Crawford School of Public Policy and Australian National University estimated that 4.3 to 20.2 trillion dollars is lost annually in global land-use change [14]. The direct

costs of the degradation of land amount to approximately USD 66 billion per year [15]. The world needs an increase of 70% in food production to feed the 9.5 billion people who are expected to live by 2050 [16]. At present, China has a population of 1,382,710,000, which is a rise of 8,090,000 compared to 2015. With 145 people/square km, China ranked 138th for national density in 2016 [17]. Interestingly, out of 130 million square kilometers of ice-free land, about 46% is currently being used for farming and forestry, and 7% is considered urban/pre-urban [18]. The Food and Agricultural Organization (FAO) estimates that up to 25% of the land is currently highly degraded and 36% is moderately degraded, while 10% is merely improving [19]. Two of the most populated nations in the world have almost 42% of their population facing chronic hunger [20]. The unprecedented explosion of megacities may lead to unsustainable and ecological disaster. In the year 2000, the megacities of the world took up to 2% of the Earth's land, which accounted for approximately 75% of the industrial use of wood, 60% of water use, and 80% of carbon emissions [21]. By these observations, it is valuable to implement techniques such as vertical farming into our built environment to protect natural and economic resources.

2.2.1. Food and Nutrition Security

Over 8.7 million species are thought to have been living on the planet, out of which 8% are extinct, and 22% are at risk of extinction due to habitat destruction [22]. There are numerous studies that have indicated the impacts of climate change on food security [23]. The sustainable management of land can minimize the impacts of conventional farming. By introducing vertical farming, external independents such as pesticides, heavy machinery, and other elements that are destructive to the environment can be significantly reduced. It will also minimize the use of resources such as water and energy and help improve soil nutrient availability [24]. Fortunately, there are many ways to achieve benefits such as afforestation, pest management, soil erosion control, vegetation management, and others.

2.2.2. Climate Change

The average global temperature has risen by 0.85 °C. For every increase in one degree, grain yield declines by about 5%. The carbon emission grew rapidly in the last three previous decades from 2000 to 2010 [25]. The figures below demonstrate these increments through recent years, which prove that climate change is real. Since 2001, annual trends have shown the warmest temperatures of the 136-year record (Figure 1). The consumption of food with low energy profiles has had a substantial effect on serious health issues such as obesity reduction and the mitigation of climate change. Also, an increase in active transport (i.e., walking and cycling), with public transport for longer journeys, could have a substantial role in meeting targets for greenhouse gas (GHG) emissions, and would result in major public health benefits [26]. The increase in greenhouse emissions is a major contributor to climate change, and the data from some of the largest economies can be observed in Figure 2.

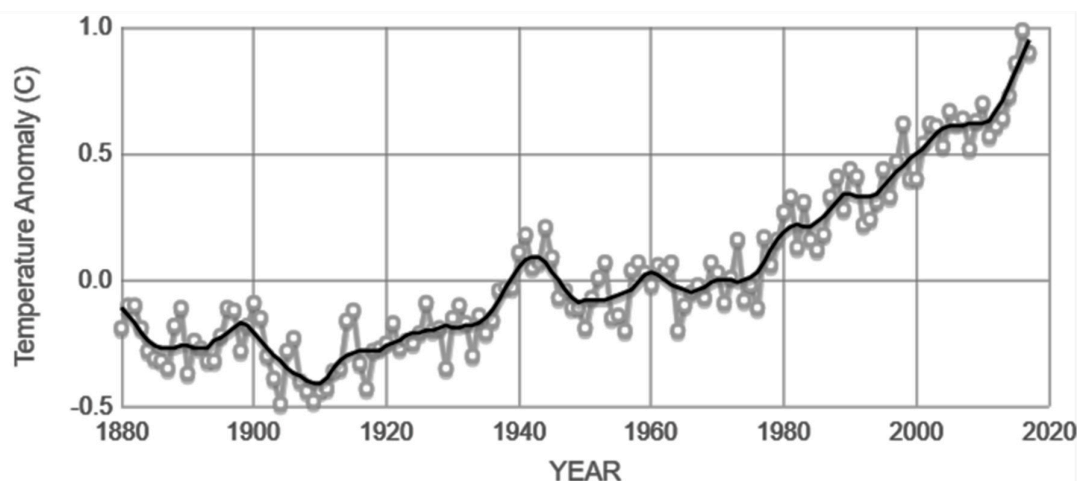


Figure 1. Global land–ocean temperature index.

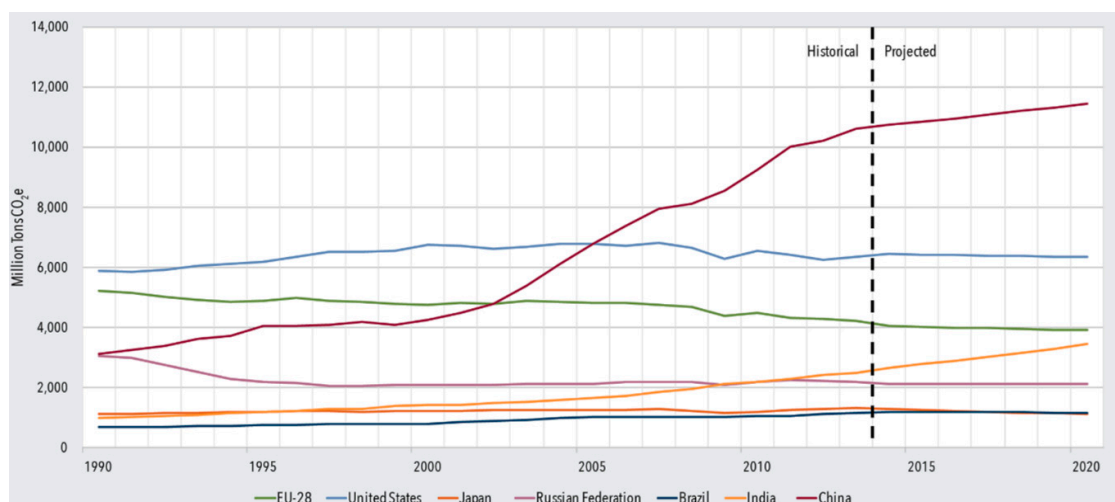


Figure 2. Greenhouse gas emissions for major economies.

2.2.3. Energy Crisis

Energy is the leading contributor to climate change, accounting for almost 60% of total global greenhouse gas emissions. The rapid scaling up of low-carbon, clean and renewable energy sources is a key solution in long-term climate goals. It is a keen factor to consider in the sector of farming. Research shows that almost 1.4 billion people lack access to electricity and 2.7 billion people rely on traditional use of biomass cooking. By 2030, 1.2 billion people will still lack access to electricity out of which 87% reside in rural areas [27]. The figure below shows the energy consumption.

The energy-use pattern across various industries with respect to different available sources is shown in Figure 3. This indicates that there is an urgent need for shifting from non-renewables to renewables. Also, 92% of the petroleum (fossil fuels) is used in the transportation industry, which can be saved by using techniques such as vertical farming.

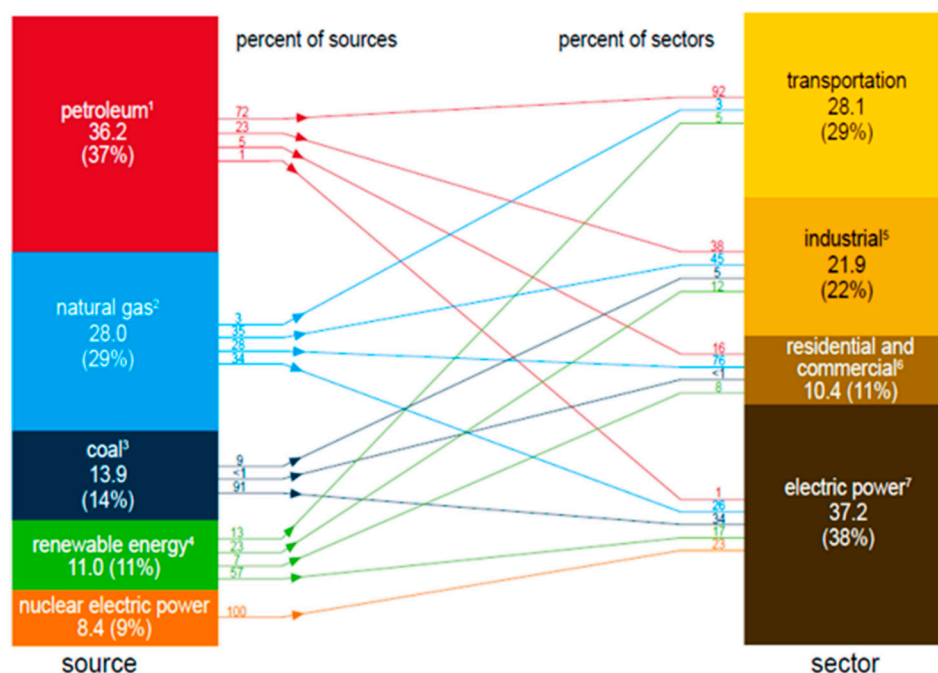


Figure 3. Energy consumption patterns across industries and their sources.

2.2.4. Water

Land development is associated with a water decision, and water management is very essential. Sustainable land practices must include the improvement of water efficiency and quality in a cost-effective way, as well as the restoration of ecosystems, which are intended to mitigate water scarcity. In the case of vertical farming, the issue of water scarcity is significantly minimized. Water scarcity affects almost 40% of the global population, and with 1.7 billion people living on river basins where recharge is minimal compared to usage, it can be dangerous for survival. Additionally, the water discharge for irrigation peaks at 70% of the total consumption of the world's water and 80% of the wastewater is simultaneously put free into the environment [28]. A study at the James Hutton Institute found that up to GBP 10 million could be saved over 25 years of implementing sustainable land management measures in a large drinking water catchment [29]. Vertical farming has large potential to save energy regarding consumption and food production, and the system can be designed to go off-grid (municipal supply).

2.2.5. Supply Chain Logistics

Regarding the industries contributing to climate change, transportation is the second. This energy use refers to the supply chain logistics of the food industry (Figure 4). The flowchart in the figure describes a typical food supply logistics cycle. It can be inferred that the vertical farming technique can save a large portion of fossil fuels and time. Many resources such as varieties of machinery, labor, and money are spent in the food industry. The most important resource is time, which is heavily invested in providing food to the people. The rapid depletion of fossil fuels and the development of new technology have led to rethinking the processes of food production and delivery. Vertical farming can be promising for saving the precious resources of the planet and providing better health opportunities to the common man. Most importantly, there is a cost involved in every step of this process, which can be diverted into producing more food for the common people [30,31]. The vertical farming concept enables a minimal use of resources such as fossil fuels, fertilizers, man power, and equipment, among others. The output of these farms can revolutionize the way we perceive agriculture.

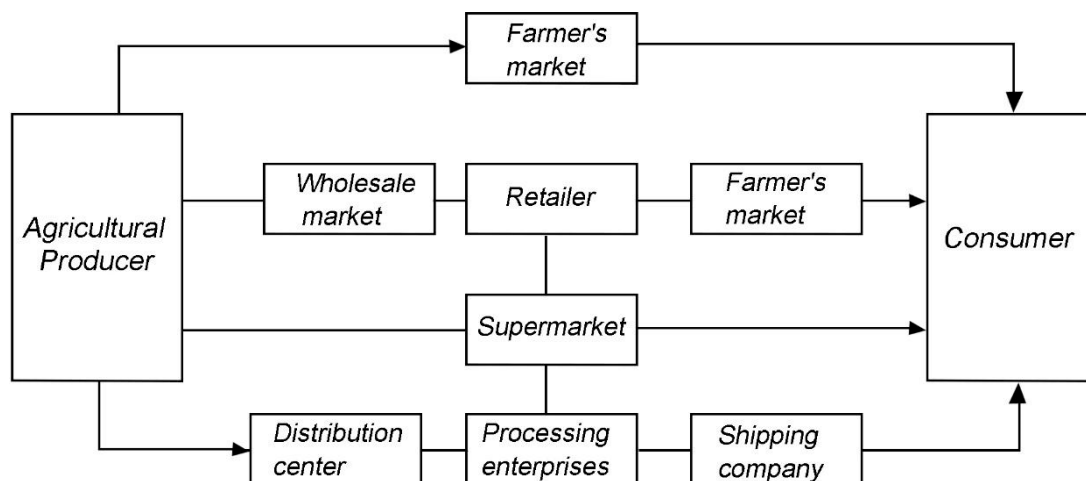


Figure 4. Agricultural producer to consumer logistic cycle.

2.3. Types of Vertical Farming

2.3.1. Aquaponics

This is a type of vegetation production that includes edible and non-edible sources that combine supporting the aquatic ecosystem (fish, snails, and others) with a hydroponic system (harvesting with only water and nutrients) in a symbiotic environment. The residue from the aquatic animals being

raised in the tank, which gets suspended, increase the toxicity of the water. These are then broken down by the nitrogen-fixing bacteria into nitrates and nitrites, which are fed into the hydroponics systems and used by the plants as nutrients. This is a continuous cycle where the water is constantly recirculated; through this process, the roots of the plants are fed nutrient-rich water. The water that has passed through the hydroponic subsystem is cleaned, oxygenated, and then returned to the aquaculture tanks. These systems working together enable the ammonia that is toxic to the aquatic animals to be filtered out of the system, while at the same time providing nutrients to the plants [32].

2.3.2. Hydroponics

Hydroponics is a subdivision of hydroculture in which the plants are grown without soil, instead of using mineral nutrient solutions in a water solvent. Certain plants such as terrestrial plants can be grown with their roots exposed to the mineral solutions, which could be supported by an inert medium. One of the interesting parts of this system is that the nutrients can come from a plethora of sources and are not confined to duck manure or fish waste [33]. This requires minimal labor, time, and energy. Additionally, there many methods of installing these systems, and can be selected according to the owner's preference. The shift from traditional irrigation to hydroponics will result in the decreased use of toxic agrochemicals, pesticides, and others. To prevent excess costs and increase profits, hydroponics is based on the automation of the nutrient supply. Several types of research are aimed at the automation of the nutrient cycle in closed systems and the standardization of the substrate analysis [34].

2.3.3. Aeroponics

Aeroponics is based on the principle of cultivating plants where the roots are not immersed in any kind of substratum or soil, but instead immersed in containers filled with flowing plant nutrition (Figure 5). This method uses a continuous cycle in an enclosed space and enables the workforce to learn the skills in a short time, whereas in traditional agriculture, the workforce requires skills that are not easily transferable. To put these systems into perspective, producing one kilometer of tomatoes requires up to 400 L in traditional irrigation, 70 L in hydroponics, and only 20 L in aeroponics [35]. Furthermore, instead of using the richest soil for plants in traditional methods, aeroponics allows the oxygen to provide nutrients to the rhizosphere, which is the root zone of the plant [36].

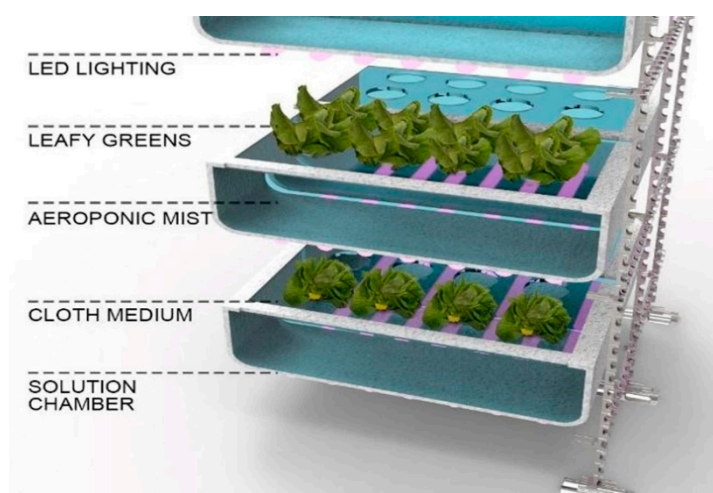


Figure 5. Pictorial representation of an aeroponics system (recreated by author).

2.4. Advantages of Vertical Farming

Vertical farming can produce a harvest that is environmentally friendly, nutritious, and affordable [37]. These farms would not require long-distance transportation, resulting in reduced fuel usage, which is currently uses 20% of all the energy consumption in the United States (USA) [38,39].

Plants would be grown using technologies such as aeroponics or hydroponics, which require little or no soil-based traditional agricultural practices [40]. Vertical farming not only produce crops year-round and is more environmentally friendly, it will also enable a more efficient use of waste. According to Despommier (2007), a city's grey, brown, and black water waste could be used for irrigation. Solid waste and plant matter could be converted to methane gas using anaerobic digesters, which could then be used to generate electricity for the farm.

A vertical farm could also help diminish the unemployment issues that many urban settings face, as the farm would need workers to construct and maintain its structure. Also, it can include a system of grocery stores, organic food markets, and eateries, as well as local distribution and transportation networks that would offer opportunities to a variety of other food-service related positions [9,41]. From a psychosocial perspective, consumers will find confidence and comfort in knowing where their produce came from [42].

By growing food in a neighborhood, natives would not only have access to a year-round supply of healthy food, they would also have the security that their food is locally grown. Furthermore, because there is a limited transportation demand, the prices would be lower. Due to lower prices and better access to a healthy diet, the neighborhood could witness an increase in their general health by lowering their risks of diseases [43]. Employees of the farm can directly sell their produce at reasonable prices to the members of the community. It is reported that these types of farmers feel more satisfied in selling the food to people with whom they have long-term relationships [38]. As an example, the Den Bosch farm in the Netherlands has been able to achieve yields that are virtually three times greater than the average soil-based production system while using 90% less water than a conventional farm [44].

2.5. Existing Vertical Farms

There are several examples in the world that prove that vertical farming is a much better alternative to traditional agriculture. Although there are many case studies over the world, the right amount of information is still not accessible. The paper investigates four such success stories that have set an example by having vertical farming; their details are included in Table 1. The future farm that is known as a 'plant lab' in Den Bosch, Netherlands uses artificial environmental planning for growing strawberries, bananas, and other fruits. It showed that the plants grew three times faster with light-emitting diodes (LED) and hydroponics than in general conditions, which would rely on pesticides and agrochemicals [45].

Table 1. Existing vertical farms in the world. NGO: non-governmental organization.

Location	Owner	Details	Location Type	URL
South Korea	Rural development authority	Three stories tall Experimental Uses grow lights	Rural	N/A
Japan	Plant factories (numerous, 50+) Nuvege	Half use sunlight, and the others use grow lights (Nuvege) Many are commercially successful	Peridomestic	www.nuvege.com
Singapore	Sky Greens	Commercial Uses sunlight Four stories tall	Inside the city limits	www.skygreens.com
Chicago	The plant	Three stories NGO Uses grow lights	Inside the city limits	www.theplant.com
Chicago	Farmed Here	Commercial Uses sunlight	Inside the city limits	www.farmadhere.com
Vancouver	Alterrus	Uses sunlight Four stories tall	Inside the city limits	www.alterrus.com

An office headquarters of Pasona that is located in downtown Tokyo and is nine stories tall has been using hydroponics and soil-based farming inside the building. Apart from profits of plantation and beauty, the shading causes a reduction in energy usage, improved occupant health, and the increased comfort of employees, among other benefits. The office contains 200 species of fruits, vegetables and rice, which comprises a total space of 43,000 square feet [46]. Other techniques, such as underground controlled environment agriculture (CEA) and underground pharming, have also been applied. This shows a golden opportunity for commercial sectors to be independent of the current food chain and logistics and become self-sustainable. Research has shown that there is immense potential in using community and roof gardens to produce vegetables and fruits in dense neighborhoods. The farming concrete project in New York mapped all the community gardens in the city and tracked the production of the plants.

A study at the University of Bonn (Germany) studied the economic feasibility of vertical farming by constructing a farm. The farm was hosted by a 37-floor high building and was simulated in Berlin. The farm yielded about 3500 of vegetables and fruits and produced 140 tons of tilapia fillets, which was 516 times more than a quarter-hectare's footprint due to stacking multiple harvests. The building cost up to € 210.5 million dollars, including the equipment [8]. Buildings that house vertical farms can be net zero for energy, water, and waste, as there would no human habitat, and the interior structure would remain simple. The building can go through many programs such as LEED (Leadership in Energy and Environmental Design), LBC (Living Building Challenge), and others to ensure sustainability and generate revenue throughout the lifecycle of the building.

Innovations in Fuji City (Japan) experimented with vertical farming in March 2015. The total floor space enclosed 185.5 square meters and focused on leafy vegetables. The production rate was around 12,420 stems/roots/day. The factory grew five varieties of lettuces, which consisted of mainly frilled lettuce, green leaf, and romaine. It had advanced, automatically controlled equipment that monitored everything from air temperature, humidity, and CO₂ concentration to nutrient liquid. Secondly, a company named SPREAD Co. Ltd. has implemented one of the world's first large-scale fully automated vegetation areas in form of vertical farming. It is proficient, producing 30,000 head of lettuce per day. It encloses an area of 4400 square meters and is projected to start shipping in the summer of 2017. The investment including research and development (R&D) services and test facilities was approximately 1.6 to two billion yuan. The plant recycles 98% of the water that is used for cultivation in the factory. Labor cost has been reduced by 50% by fully automating the processes from seeding to harvest. Importantly, the energy cost has been reduced by around 30% per head of lettuce with the use of LED lights specifically created for SPREAD and the development of a unique air conditioning system, which enabled an initial investment reduction of 25% cost per head of lettuce [47]. It is estimated that roughly 20% of plant factories are making profit, 60% are breaking even, and 20% are losing money. The number and percentage of plant factories that are profitable have been increasing steadily since 2009. Depreciation costs account for roughly 30% of the total costs, while labor costs account for approximately 25%, and electricity accounts for 25% of the production costs [48]. In 2014, Mirai and Mitsui Fudosan Co., Ltd. (Kashiwa, Japan) initiated a full-scale operation of one of the largest plant factories in Kashiwa-no-ha Smart City, Japan. The facility was targeted to produce 15 types of vegetable. The building enclosed a gross floor area of 1260 square meters [49]. Singapore has also been successful in regard to vertical farms, and there are many case studies to learn from. One of them is the Singapore Sky Greens. The four-story rotating greenhouse produces one ton of leafy greens on alternate days using a hydraulic-driven system that rotates and provides sunlight for the growing holders. The farm consists of 1000 vertical towers and produces 800 kg of spinach, Chinese cabbage, and other greens for everyday use for the active Southeast Asian metropolis [50]. The challenge of this technology is that it is sporadic throughout the world. There have been no significant studies that have been conducted to investigate large-scale use such as in universities, office parks, residential complexes, etc. and further into the city scale. This study investigates the feasibility of using vertical farming at the university scale.

2.6. A Spotlight on China

China is one of the largest countries in the world, with a population of 1.42 billion as of 2017 [51]. It has also experienced high rates of urbanization in recent years. One indicator of this growth is that the floor space of completed buildings in 2013 was almost double that in 2007 [52]. The United Nations predicted that the percentage of China's urban residents was expected to be 60% by 2020, and the urban population would increase 350 million by 2025, with 219 cities having a population of more than one million (compared to 35 cities in Europe) [53]. The demand for land for urban housing soared along with the demand for business and built-up land use. Consequently, much of the farmland was converted into non-agricultural built-up environments [54,55]. A land alternation survey performed by the Ministry of Land and Resources in 2011 found that about 91.05% of the farmland loss was caused by usurpation for construction; cultivated land was down to only 0.08 ha/person nationwide, which is only 40% of the world average [56]. For all these reasons, China started the research and practice of vertical farming in early 2004, and it was widely introduced in the market in 2011. Meanwhile, because of the low manufacturing costs and labor costs relative to other developed countries, the industry attracted a huge amount of investment. For instance, in 2014, the Evergrande group from China invested a billion dollars to establish 22 vertical farms [57]. Dr. Qichang Yang as the chief scientist, presided over the research, which funded eight million USD in intelligent plant factory production technology, national high science, and technology projects. This funding was organized by Chinese Academy of Agriculture sciences [58]. However, even though the vertical farm in China is growing rapidly, the government policy and economic support still provide only a very limited contribution in relation to its full potential, which lead to project defects regarding its operational capability, as well as maintenance defects. Furthermore, it caused low economic benefits and high energy consumption [57]. Under the current national policy and legal system, it is hard to solve the problems related to the lifecycle cost of a vertical farming project such as maintenance, monitoring, marketing, and energy utility. Furthermore, it is hard to increase the acceptability of vertical farming between the public community. Another adverse factor is a lack of regional scientific research institutions except for certain state-level labs that are doing research on vertical farming. As a result, to the local vertical farming project cannot receive effective technical support [59,60]. This paper focuses on developing a framework to look at the feasibility of having vertical farms, starting from at the university scale.

Universities have a huge demand from young people. As of 2016, China had 2596 universities compared to its population of 1.379 billion [61]. This implies the staff and students will be on a constant growing curve in the upcoming years. We believe that educational universities have managed to maintain stable income sources for many years. A 2017 report by Economic Commentary stated that the individual fees of the students have risen in private and public universities [62]. This is a very big opportunity to introduce vertical farming to showcase the benefits and encourage other industries to apply these techniques.

According to a 2017 report, the unit price for a kilogram of rice is \$0.75–0.77. It takes about 100–240 days, with two production periods (April–July and August–October) [63]. For 0.0667 hectares (equals one mu), the costs involved include \$22.3 RMB for fertilizer and seed, \$23 for the corresponding pesticides, \$46.15 for the labor force, and \$46.5 to rent the land, which equals a total cost of \$107.7–138.5 in typical conditions. In 1996, 19.51 hundred million mu of farming area was available, but in 2010, only 18.26 hundred million mu of farming area was available. The area of farmland per capita is 1.38 (only 40% of the global average). Only 6.09% of total farming land has the ability to produce over 1000 kg per mu. Table 2 is an example where it shows the agricultural demand of China in 2012; the numbers increase as the population rises. This is a burden on the farmers, as well as on the acquisition of more fertile land.

Table 2. Average agricultural demand in China in 2012.

	Daily Product	Beans and Nuts	Livestock	Fish and Shrimp	Eggs	Vegetables	Fruits	Grains
Daily demand (g/person/day)	300	30–50	50–75	75–100	25–100	300–500	200–400	250–400
Conversion factor (1/edible rate)	1.00	1.30	1.00	1.75	1.19	1.15	1.39	1.19
Annual min. demand (kg/person)	110	14	18	48	11	126	101	109
Annual max. demand (kg/person)	110	24	27	64	22	210	203	174
Population 100 (million)	13.08	13.08	13.08	13.08	13.08	13.08	13.08	13.08
Annual min. demand (100 million tons)	1.432	0.186	0.238	0.626	0.142	1.647	1.327	1.420
Annual max. demand (100 million tons)	1.432	0.310	0.358	0.835	0.284	2.745	2.654	2.272

Wuhan is a city in China that has a population of 10.2 million an urban area of 8494 square kilometers. There is a severe shortage of agricultural land and resources; as a result, its economy suffers from price inflation. Only 61.3% of agricultural land is cultivable; the rest includes forestland, pasture area, park area, and other types of land. The national land contamination rate in China is 19.4%. Over 4.7 million hectares of land require steep slope cultivation, which gives rise to serious soil erosion; the main component parts of erosion matter are coming from farmlands. Additionally, there is a huge economic issue for these farmers, and direct farm income is no longer the only source [64]. Wuhan has many universities, and one of them is Huazhong University of Science and Technology, which is one of the largest universities in China. This university was chosen to test the feasibility of implementing vertical farming on a campus scale.

2.7. Methodology

This study reviewed the latest trends in technology and best practices on vertical farming from Google Scholar and trade information around the world. In the first step, the data of existing vertical farm practices was collected through a media and literature research. A survey was carried out at Huazhong University of Science and Technology (HUST) in the city of Wuhan, China to find out the average daily food requirements across the campus for its students, staff, and faculty. HUST is one of the largest universities in China. The campus has 24 canteens, which bring food from all over the province to feed its enormous population of 57,839 people. The university as of January 2018 has 24,599 undergraduates, 23,140 graduates, and 5500 staff, and a further 4600 people are retired (but still living near the school) [65]. The climate, logistics, and demand of the city were taken into consideration while analyzing the demand proportions. In the survey, with the help of the General Services Department and Data Information Center of HUST, food consumption and demand data were collected from all of the canteens and restaurants in the campus boundary. The data was then segregated into types of food, seasonal variations, consumption amounts, and cost. A mixed method mode was chosen for this research to find the feasibility and challenges to introducing vertical farming on the campus of HUST, which could encourage sustainable urban agriculture and be self-sustainable while being independent of external farming conditions. Based on the central limit theorem, a statistical concept model was developed to determine the financial scenario if a vertical farm was built and operated on campus to supply food to the people belonging to the university. Using this model as well as previous case studies, a qualitative and quantitative analysis was carried out for governing the advantages and challenges of modern urban agriculture in this genre of our built environment. The data focused on two aspects. One is the production capacity of the current global vertical farms, including annual output value, production efficiency, vegetable species, and economic benefits. These are the usage conditions of vertical farming technologies. In the next step, we chose Huazhong University of Science and Technology (HUST) as a sample to gather the specific information of all 24 canteens regarding their procurement chain and supply quantity. The data for total fruits and vegetables consumed in the year 2016 was collected. According to the annual report, the total amount of fruits and vegetables consumed were 2,639,720.40 and 108,164 kg respectively, which resulted in a total cost of \$2,477,247.38. The individual breakdown of these plants and their associated costs were collected and analyzed.

The assumptions that were made for the model to conduct this study were:

1. The vertical farm building has a simple a box shape and a building footprint of 5000 square meters.
2. The building can provide more than 6.67 hectares of planting space by multilayer cultivation.
3. The construction price for each square meter is about 1450 RMB or USD \$227 (in Wuhan, China).
4. Unpredictable factors such as building materials were temporarily ignored; the resulting average building cost was 5.25 million RMB per floor.
5. The total farm space for each floor was 0.0667 hectares, which is equal to one mu (Chinese standard farmland area unit).
6. Under typical conditions, the costs included 145 RMB of fertilizer, 150 RMB of corresponding electricity and water, 300 RMB of labor, and 300 RMB of land, which comes to a total rental cost of 700 RMB to 900 RMB.
7. For the first year, annual operating costs are 5000 RMB (USD \$775.20).
8. We give two types of changes of operating costs per year. One is that the annual cost this year is 500 more than the previous year, and the other is that the annual cost this year is 1.1 times that of the previous year.
9. The canteen's vegetable prices are considered fixed each year.
10. The crops that were purchased by the canteen cost more than the wholesale price of the market (five times).
11. Cucumber, once a year: 30,000 kg per 0.0667 hectares/year.
12. Tomatoes, twice a year: 20,000 kg per 0.0667 hectares; 40,000 kg per 0.0667 hectares/year.
13. Pepper, once a year: 5000 kg per 0.0667 hectares/year.
14. Carrots, twice a year: 10,000 kg per 0.0667 hectares/year.
15. Chinese cabbage, once a year: 10,000 kg per 0.0667 hectares/year.
16. Chinese cabbage, eight times a year: 10,000 kg per 0.0667 hectares/year.
17. Kale, twice times a year: 3000 kg per 0.0667 hectares, 6000 kg per 0.0667 hectares/year.
18. Lotus root, once a year: 2000 kg per 0.0667 hectares/year.
19. If the building has only one floor, then we can assume the cost of the building is about 15 million; if the building has three floors, then we can assume the cost of the building is about $15 + 10 + 10 = 35$ million.

In order to make a trade-off between the faster payback and guaranteed diversity of dishes provided in the canteens, the top high-yielding vegetables are selected based on the value of their yield. We implement statistical modeling to determine the goals of the study, which include determining the breakeven point of constructing a vertical farm, calculating its economical and environmental benefits, and therefore knowing if the technology is feasible at the university scale.

Central Limit Theorem

Central limit theorem is the distribution of random variables expressed by limit theory in probability theory. The theorem expresses that when the sample size is large, the sum and average of the random variables will approach, and then obey, a normal distribution. Here, the random variable refers to the yield per hectare; the individual is the unit area of planting a certain crop, the population (statistical noun, referring to all of the individuals) refers to the total land area where the crop is planted in the vicinity of Wuhan city. We can assume that the average yield per hectare obeys a normal distribution. If we set the standard deviation of the normal distribution to 1/10th of the average yield per hectare, we can see from the distribution characteristics that we have 95.4% confidence that the actual value of the average yield will not fluctuate in different years. Exceeding 20% of the calculated average yield, there is 68.3% confidence that the actual value of the average yield will not exceed 10% of the calculated average yield per year in different years, in a vertical farm environment. The average yield per hectare will be more stable, so this assumption is reasonable. From the central limit theorem, the output is set for nine varieties of vegetables to be random variables that satisfy the

normal distribution. The mean value is the aforesaid annual output of mu, and the standard deviation parameter is set to 1/10th of the yield per 0.0667 hectares per year, as shown in Formula (1):

$$\begin{cases} output_1 \sim N(\mu_1, \sigma_1^2) \\ output_i \sim N(\mu_i, \sigma_i^2) \\ \vdots \\ output_10 \sim N(\mu_{10}, \sigma_{10}^2) \end{cases} \quad (1)$$

The formula shows the annual output of each of the nine varieties of vegetables that satisfies the normal distribution expression. The output of different vegetables does not affect each other independently (assuming that climate conditions are maintained). W is used to indicate the silent costs, which are the initial investment of the vertical farm. Op costs (operating costs) is used to represent the annual operating costs, and num_unit_i represents the number of 0.0667 hectares of *i*th vegetables. For example, num_unit_1 = 2 and num_unit_9 = 1 means that $[2 \times 0.0667]$ hectares of cucumber are planted, and cabbage is planted in $[0.0667 \times \text{hectares}]$. Price [*i*] represents the price of each vegetable. The “rec” years represents that the recovery/breakeven years of the recycling cost can be expressed as the total cost divided by the annual profit, as shown in Formula (2):

$$rec_years = \frac{W}{\sum_{i=1}^{10} (output_i \times num_unit_i \times price_i) - op_costs} \quad (2)$$

The parameters of the random variables representing the output value of each of nine kinds of vegetables per 0.0667 hectares are calculated. Therefore, the average value is mentioned per mu per year, and the standard deviation parameter is set to 1/10th of the annual yield per 0.0667 hectares. First, (cucumber, tomato, potato, cabbage, and five kinds of vegetables) are planted on 2×0.0667 hectares, and the rest are not planted. They can be expressed as shown in Formula (3):

$$\begin{cases} output_1 \sim N(30,000, 3000^2) & \text{straight cucumber} \\ output_2 \sim N(40,000, 4000^2) & \text{tomato} \\ output_5 \sim N(11,000, 1100^2) & \text{big potato} \\ output_7 \sim N(10,000, 1000^2) & \text{pakchoi} \\ output_8 \sim N(15,000, 1500^2) & \text{cabbage plans} \end{cases} \quad (3)$$

The result of the breakeven and profits are shown in Table 3. The above vegetables are chosen for the calculations because in the vertical farm environment, relative to nature, we can better ensure that the yield can be maintained at a stable level, or can even be increased in subsequent years. From a statistical standpoint, in some cases, we tend to draw conservative but more credible conclusions, which include calculating the breakeven period. In practical applications, it is very likely that the situation will be more optimistic. If the indoor environment of the vertical farms is strictly controlled, indicators of the plant growth environment may have higher annual returns and a shorter payback period.

Table 3. Vegetable types and corresponding planting indicators.

Vegetable Type	Total Demand (kg)	Total Value (\$)	Unit Price (\$)	Harvest Per mu (kg)	Harvest Per 0.0667 Hectare (Value)
Straight cucumber	83,195.45	50,971	0.612308	30000	531.2425
Tomato	156,396.1	106,263	0.68	40000	785.532
Paprika	127,100.1	95,116.12	0.747692	5000	108.15
Lotus root	75,351.15	116,168.2	1.538462	2000	88.93333
Carrot	81,530.15	51,019.56	0.626154	10000	180.8699
Big potato fresh	295,895.9	251,485.2	0.849231	11000	270.2179
Chinese cabbage	105,107.7	56,234.68	0.535385	10000	154.6385
Pak choi	86,014.5	53,960.81	0.627692	10000	181.3238
Cabbage plants	85,700.4	66,504.91	0.775385	15000	336.4419
Cabbage	157,831	77,881.81	0.493846	6000	85.57423

The payback period is obtained by dividing the fixed cost by the annual net profit (total revenue–operating cost). The profits are maximized as the purchase costs are higher than the wholesale costs. If the actual operating cost is different from the one proposed, the breakeven could also be calculated by a similar method (Table 4).

Table 4. Cost recovery period with changes in crop yields.

	+sigma	−sigma	+2sigma	−2sigma
Average farm cost per floor (three floors total) \$1,794,872	40,435.94	33,083.95	44,111.93	29,407.96
	59,791.39	48,920.23	65,226.97	43,484.65
	20,567.85	16,828.24	22,437.66	14,958.44
	13,801.6	11,292.22	15,056.29	10,037.53
	25,608.54	20,952.44	27,936.59	18,624.39
Total profit	160,205.3	131,077.1	174,769.4	116,513
Fastest breakeven (years)	11.25	13.76	10.31	15.49
Slowest breakeven	11.29	13.82	10.34	15.57

Here +sigma, −sigma, +2sigma, and −2sigma represent fluctuations in the average yield per hectare of crops. (+sigma) represents a 10% increase in yield when all of the crop yields change due to various factors, and (−2 sigma) represents a 20% reduction in average yield. It is important to note that this group of results (breakeven periods) that we calculated was from a consideration of the operating expenses in Wuhan and the price of particular canteens. It is only for reference to the university cafeteria in the vicinity of Wuhan. If applied to other situations, this method of modeling is applicable and translatable. In other words, the yield of crops is still subject to normal distribution, but the data needs to be replaced with local operating costs, fixed costs, crop yields, and selling prices.

3. Results

According to the distribution law of the normal distribution of random variables, if the building has only one floor, then, regardless of how the annual operating costs change, the average years of recycling costs is 11.5 years. The substitution calculation can get the 68.3% confidence to recover the cost between 10.5–12.9 years; there is 95.4% confidence to recover the cost between 9.6–14.5 years. If the climate is suitable and technical management is good, the cost may be recovered in 10 years. If the technical management and climate situation are poor, the cost will also be recovered in 15 years.

If the average value and fluctuation range of production are changed in the actual situation, the value of the parameters in the model can be adjusted and recalculated.

After recovering the cost, we can choose to grow (2×0.0667) hectares of cucumbers, tomatoes, potatoes, bok choy, and cabbage steadily each year. The average income is about 947,000 RMB (\$148,000). There is 68.3% certainty that the annual income is between 825,000–1,041,000 RMB (\$129,000–\$163,000). There is 95.4% certainty that the income will range between 757,000–1,136,000 RMB (\$118,000–\$177,500) per year.

We can also select cucumbers, tomatoes, peppers, carrots, potatoes and Chinese cabbage. Each of the nine high-yield and high-demand vegetables grow on 0.0667 hectares for each variety, and the remaining land can be allocated on its own, which can achieve an average annual stable profit of 592,000 RMB (\$92,500). Even if the remaining land is not cultivated, there is 68.3% certainty, which makes an annual income of 533,000–651,000 RMB (\$83,000–\$102,000), with 95.4% of the determination to make an annual income about 474,000–710,000 RMB (\$74,000–\$110,000).

Additionally, if the building has three floors, then, regardless of how the annual operating costs change, the average years of recycling costs would be nine years, the substitution calculation can obtain 68.3% certainty to recover the cost between 8.2–10 years, and there is 95.4% certainty to recover the cost between 7.5–11.3 years. The annual income of planting vegetables is three times that of the original strategy where the building has only one floor. If the building has 10 floors, then we can assume that the cost of the whole building is about 120 million RMB (\$18.75 million). Then, the whole building can provide more than ($10 \times 10 \times 0.0667$) hectares of planting space. The building can plant all kinds of vegetation to meet the demand of the university. The calculation method is the same as above.

4. Discussion

Universities have multiple sources of income through research, industry involvement, investment, government grants, and others. This is one of the major reasons why universities can implement new technologies such as vertical farming for their students and staff. The increasing population will also increase the demand–supply chain of food systems. This can be managed by installing vertical farming.

Introducing vertical farms in university campuses will not only save money and resources, but also facilitate multiple streams of income. Research labs can be established in these farm buildings where people from national and international institutions can be brought in for new innovations and technologies. These farms will be able to supply specific foods according to specific seasons. Additionally, universities can monitor the production and usage in real time and make decisions that could benefit the society. This will start an incredible chain of advanced research and development in the field of sustainability, science, social science, business, materials, agriculture, mathematics, and other interdisciplinary domains. The universities can set an example of taking bold initiative, which would bring them fame and enable them to attract resources. In the educational industry, profits need not be focused on short-term gains; rather, the goal can be to push boundaries for students and faculty, which will lead the universities to financially benefiting in the long term.

The construction of vertical farming can save labor, packaging, and logistics costs. Logistics have direct and indirect impacts on the environment. The use of plastic sheets, Styrofoam, and other such packaging elements are often non-biodegradable. Also, using fossil fuels in vehicles has a direct impact on the air pollution and depletion of natural resources. The produce from vertical farming is free from any harmful chemicals and is thus healthier than traditional farming. Furthermore, as the space used is vertical in nature, natural land area can be conserved, which will decrease the load on the agricultural industry. Furthermore, this system produces the least waste, which is highly beneficial. The vertical farming building can serve as a teaching space for students all over the world and can inspire other institutions to become involved in advanced urban agriculture. For the general production of plants, the students can be considered a key element. Training and part/full-time employment can motivate them to get involved in the process. This will enable them to create a strong sense of community and belongingness. Whenever there is excess production, the vegetation can be donated or sold at

a reasonable price to people outside the university. The building can be built through best sustainable practices and the operational energy can be harnessed from renewable sources such as solar, wind, and hydropower. Finally, there can be multiple opportunities for bringing in financial resources from research labs, innovations in the technological sector, governmental capitalizations, and other areas.

5. Conclusions

The concept of introducing vertical farming can be a strong tool used in the built environment for fighting food insecurity and environmental protection. As per the study conducted on various scenarios, a vertical farm can break even economically in 10–20 years and could alleviate the present stress on the environment. According to our analysis, the breakeven on investment in vertical farms will be in about 11.5 years, and afterwards, the annual profit can reach \$92,000 (592,000 RMB). For universities of a similar scale in central China, the models and calculations proposed by the authors are universal. When applied to other regions, the method can be calculated based on the actual crop yield, unit price, and vertical farm cost. Additionally, the stress on fertile land all over the world can be reduced to great extent when industries start becoming self-sustainable. The technology has been sporadic in nature throughout the countries, which makes it difficult to recognize its true value. Furthermore, enterprises that have initiated vertical farming have not been completely transparent, which results in less awareness among industries; as a result, the application of vertical farms on a large scale is not yet evident. The quality of all of the aspects of technologies in vertical farms is also important, because it relates to the ability of these to achieve sustainable development, cost recovery, and profitability. The technology allows the circular economy in its processes, elevating the social and economic status of the community. However, in the vertical farm environment, the yield and fluctuation of crops are still unclear, and further practical experiments and conclusions are needed. For using vertical farming on a pragmatic undertaking, there should more research that is focused on industrial scale, location-based climate analysis, financial models scoring lower the breakeven time, and higher profit margins. There can be federal and state incentives to push this idea among the citizens. We believe that vertical farming and sustainable urban agriculture has tremendous potential to recover from social and planetary issues.

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