



Opinion

What You May Not Realize about Vertical Farming

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Abstract: Vertical farming (VF) is a newer crop production practice that is attracting attention from all around the world. VF is defined as growing indoor crops on multiple layers, either on the same floor or on multiple stories. Most VF operations are located in urban environments, substantially reducing the distance between producer and consumer. Some people claim that VF is the beginning of a new era in controlled environment agriculture, with the potential to substantially increase resource-use efficiencies. However, since most vertical farms exclusively use electric lighting to grow crops, the energy input for VF is typically very high. Additional challenges include finding and converting growing space, constructing growing systems, maintaining equipment, selecting suitable plant species, maintaining a disease- and pest-free environment, attracting and training workers, optimizing the control of environmental parameters, managing data-driven decision making, and marketing. The objective of the paper is to highlight several of the challenges and issues associated with planning and operating a successful vertical farm. Industry-specific information and knowledge will help investors and growers make informed decisions about financing and operating a vertical farm.

Keywords: controlled environment agriculture; indoor crop production; planning and operation; resource-use efficiency



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1. Introduction

Vertical farming is one of the crop production strategies that falls under the term controlled environment agriculture. Plants are grown indoors in purpose-designed structures where they are mostly or completely protected from the vagaries of the weather. Worldwide interest in vertical farming has increased substantially over the last decade due to concerns about the continued growth of the world population, the impacts of climate change, and the availability of nutritious food and resources (land, water, energy). Technological advances in sensing and control systems, plant breeding, automation and robotics, and energy-efficient equipment have supported the rise in vertical farming, as have disruptions in food supply systems due to man-made or weather-related climate-change events. Large population centers have started to pay more attention to resiliency, as well as the distance food travels, and vertical farming seems to be a logical fit in terms of a more reliable food supply.

Vertical farming is practiced using a variety of different growing systems. These systems include growing on multiple levels on a single floor (using shelving systems) or growing on multiple floors in a single building (using a single growing layer per floor or a shelving system on each floor). Other systems that are often considered vertical farming include vertically mounted growing systems (e.g., growing troughs suspended from the ceiling), A-frames, and (largely) vertical conveyor systems. While vertical farming can include the production of fish, animals and crops, this paper focuses primarily on crop production.

During the last decade, substantial investments have been made in vertical farming operations, giving the impression that vertical farming will become a major player in our food supply system. However, vertical farming typically increases production costs due to higher capital investments and higher energy requirements. These higher costs are acceptable to consumers only when the product has higher quality attributes, is fresher, or is not otherwise available. However, the higher production costs of vertical farming make it unlikely that staple crops (corn, soybean, wheat, rice, potato, etc.) can be grown economically in vertical farms. Therefore, vertical farming is likely to remain focused on the production of leafy greens, herbs, and some fruiting crops (e.g., strawberries, tomatoes, peppers), i.e., produce that does not ship or store well. Therefore, we believe that vertical farming will contribute to our food supply system, but only with respect to a limited number of crops. On the other hand, vertical farming does provide innovative and financially attractive opportunities to grow medicinal crops, especially cannabis, and we see opportunities for increased production capacity where security and/or environmental isolation may be necessary. While accurate numbers are difficult to ascertain, we estimate that worldwide investments over the last decade in the VF industry exceed well over USD 1 billion.

Most crop agriculture uses sunlight as the sole energy source for photosynthesis. As we move crop production indoors, the available sunlight is not always sufficient for vigorous year-round crop production. Therefore, indoor crop production often requires the use of supplemental lighting. When we move crop production into fully enclosed structures (as is often the case for vertical farming operations), all the energy required for photosynthesis needs to be provided by a so-called sole-source lighting system. Since relatively high light intensities are needed for vigorous plant growth, the electricity consumption associated with plant lighting systems is typically high and will have a major impact on the production costs. [1] reported on the key performance characteristics of the various lamp types used for horticultural applications, including their power consumption and efficacy. In addition to labor costs, the other major expense for vertical farming operations involves temperature and humidity control (often accomplished with air-conditioning systems). Additionally, when crops are grown on multiple floors, the cost of continually pumping water can be quite substantial.

As with other forms of agriculture, vertical farming systems are often perfected by trial and error. This process takes time and money and results in systems that are often site-specific based on local conditions and restrictions. It also makes the developers protective of their approaches and solutions. While understandable, this attitude has resulted in start-up companies often having to ‘reinvent the wheel’, and has prevented extensive collaborations with researchers at academic institutions. We believe that this situation has hindered progress and we encourage the vertical farming industry to find arrangements that allow for the protection of key production elements, while also allowing for more collaboration and information exchange.

The objective of this paper is to provide considerations for those planning or operating a vertical farm. We recognize the potential vertical farming has to make portions of our food supply system more efficient and resilient, and to increase the availability of nutritious food, especially in high-density population centers. On the other hand, we want to point out several challenges that we believe require more discussion and research.

2. Planning a Vertical Farm

Vertical farming operations can be expensive in terms of capital and operating expenses [2]. The larger vertical farms often require investments from venture capital or investment firms. Finding a suitable location can be challenging, particularly in urban areas where land and building prices are high. Operating expenses include labor, energy, and supplies needed to grow, harvest, and possibly store the crop [3]. After labor, energy is typically the second-largest operational expense, but other inputs (e.g., water, nutrients, carbon dioxide, shipping supplies, product labels) are also needed. As the vertical farming

industry expands, and production systems and practices become more mainstream, it is expected that production costs will come down [4].

According to [5], most cities have a variety of sites suitable for vertical farming, and appropriate planning can ensure operations can turn a profit while providing important services to nearby communities. However, in many locations there is still a lack of institutional, financial, and technological support [6]. In addition, planners and decision makers sometimes have insufficient knowledge about commercial indoor crop-production practices, making it less likely they will make supportive decisions. Therefore, it may take a lot of effort to explain the proposed plans and convince decision makers that vertical farming can have measurable benefits for local communities.

Vertical farming can make efficient use of urban spaces, including previously vacant warehouses, rooftops, and other abandoned or vacant areas. Such under-utilized buildings/areas are readily available throughout the U.S. Some companies are planning to build their facilities just outside urban centers in order to reduce cost and still require limited transportation times. The suitability of sites and buildings that can be converted into vertical farming operations depends on how long a property is available, how much space is available, and how the site is zoned. While some municipalities, districts, counties, or states will have regulations, codes, or guidelines in place that support agriculture and the associated construction of facilities (e.g., [7]), such rules typically do not address the unique issues associated with vertical farming. Additionally, since vertical farms are not very common, zoning variance may have to be secured and zoning officials may have to be educated about the proposed usage and any potential impacts. Therefore, additional time may be needed to secure all the permits required to operate a vertical farm. A comprehensive feasibility study can help address all concerns that may arise when developers propose new vertical farming operations [8].

When choosing a crop to grow in a vertical farm, two broad categories need to be considered: grow-technical challenges and marketability. Grow-technical challenges involve the ability to design and operate a vertical farming system that cultivates the selected crop. Marketability refers to the competitiveness of the products grown in such a system. Theoretically, any crop can be grown in a vertical farm, but most will create major technical and growing challenges. For example, many vertical farming systems produce leafy greens (e.g., head lettuce, leaf lettuce, leafy herbs) because of their small size, fast growing cycles, and relatively low energy requirements [9]. On the other hand, large, energy-intensive crops, such as heavy vining crops (e.g., melon) or tree fruit, may require a special design that is different from that of a typical vertical farming system. Therefore, such crops are seldom grown in a vertical farm. Developing special designs for vertical farming systems is the domain of companies focused on designing vertical farming technology.

In addition to looking at what is grow-technically feasible, operators must also consider several questions related to how marketable their product is. How will the product be distributed? What is a fair price? Is there seasonal demand? Crops from vertical farms usually cannot compete on price compared to conventionally grown crops because of the higher labor and energy inputs [10]. Consequently, their products need to have some additional value compared to conventionally grown crops. Examples of added value are: 1. Distribution channels can be less complicated because the location of the farm is very close to its final destination; 2. crops—for example, ornamentals and cannabis—can have a higher quality from being grown in a controlled environment; 3. crops can be marketed as being more resource efficient, and hence environmentally friendly, adding to their value [11]; and 4. certain crops with high demand during their conventional off-season might be able to command a premium price. Essentially, vertical farm operators must have some sort of marketing advantage to counteract the higher operational costs of running a vertical farm.

The primary goal of most businesses is to maximize profits for the owners or a group of stakeholders. After that, most businesses will focus on their customers, the local environ-

ment, and society at large. Vertical farming operations that promote transparency and are willing to engage with their customers and local communities are well positioned to provide needed solutions to the existential challenges that our communities face today [6]. The high degree of control over crop-production practices that is possible with vertical farming operations ensures that growers can maximize resource-use efficiency while minimizing negative environmental and societal impacts [4].

On the other hand, commercial businesses need to be competitive and strategic. Growing high-yielding, fast-growing plants that have low production costs in areas with adequate marketing potential will be crucial for the success for vertical farming operations. Branding and consumer education are important business tools that can help develop a loyal customer base [12]. Today's consumers are more and more focused on local production that helps create jobs and adheres to environmentally friendly production practices.

3. Operating a Vertical Farm

A variety of challenges must be understood in order to successfully run a vertical farm. Picking a crop that can be grown profitably and safely is paramount to a vertical farm's success. The inherent complexity of the system requires a cohesive team and delegation of tasks. Similar to a traditional farm during its growing season, vertical farms need constant upkeep, with the main difference being that a vertical farm's growing season continues year-round. Upkeep includes managing the growing system, crop growth, and pests. A systematic approach to data collection, processing, and analysis is necessary to continuously track production and evaluate further optimization strategies for the farm.

As discussed above, vertical farm operators should generally focus on a cultivation system that has been used in other similar settings and leave development of new systems to specialized companies. Depending on the crop(s) cultivated, there are a variety of systems to choose from. The most popular systems use some form of hydroponics to minimize weight and maximize water and nutrient use efficiency. These systems break down into two broad categories: stacked horizontal layers and vertical columns. Stacked horizontal layer systems create multiple layers of typical hydroponic systems (e.g., nutrient film technique and flood tables) and stack them vertically. On the other hand, vertical columns use tall columns that either drip or spray nutrient solution onto the suspended roots of plants. Stacked horizontal layer systems are significantly more complex and costly to implement than vertical columns. Operators must deliver fresh, climate-controlled air, nutrient solution, and lighting to each layer of their system, which is typically facilitated by a complex network of electrics, plumbing, and heating, ventilation, and air conditioning (HVAC). The main disadvantage of vertical column systems is the necessity of inter-canopy lighting. With current lighting technology, top lighting for vertical columns cannot achieve homogenous light distribution for the entire column. Inter-canopy lighting adds complexity and cost to the system. Ultimately, each cultivation system has its own unique advantages and disadvantages that an operator must consider before implementation in their vertical farm.

Once a crop and cultivation system has been selected, close attention must be paid to pest management. Without an integrated pest management (IPM) program, a vertical farm will almost certainly succumb to pest-related crop failure. The main pests encountered in controlled settings are fungal or arthropods (e.g., mites and gnats). Since vertical farms operate in a contained space, pests are almost always coming in from the outside, either on personnel, seeds, in the air, or in the water. Exclusion of these pests through air showers, coveralls, seed sterilization, air filtration, and water treatment can prevent pests from entering the facility. Exclusion of pests through various decontamination protocols should be the first line of defense, but it cannot be the only one [13]. Eventually, pests will enter the facility and proper management is necessary to avoid crop loss. Proper environmental control is essential to avoid humidity buildup and condensation, which can favor fungal growth. Biocontrol agents can help control outbreaks of arthropod pests. However, they must be used as a proactive strategy, because introduction in reaction to an outbreak will typically not be fast enough to stop crop damage. Beneficial insects must be introduced

prior to outbreaks and their populations must be maintained in the facility for maximum effectiveness [13].

Safely growing crops in a vertical farm requires a separate set of standards compared to crops grown using conventional agricultural practices. Organizations such as the CEA Food Safety Coalition and the Global Food Safety Initiative have developed food-safety guidelines for vertical farming operations. In order to meet these guidelines, operators need to consider all factors that could potentially contaminate food. These can include water, other inputs, seeds, product handling, storage, and shipping. A major area of concern is water quality. Recirculating water systems can easily spread pathogens when the nutrient solution is not treated properly. Potential food-safety concerns can be monitored through data collection and traceability, allowing for quick action in case of a pathogen outbreak.

Labor is by far the highest cost for VF operations [10]. Compared to conventional field agriculture, vertical farming is significantly more labor intensive and lacks widespread automation. Without significant advances in automation, operators will need to rely on a human workforce for the time being. Given that vertical farms operate year-round, a local labor force is preferred, compared to conventional farms that hire seasonal labor. Considering that most vertical farms are located in urban areas, they typically have access to a large local labor force. However, laborers sourced from urban areas typically have little to no experience or training for the labor required on a vertical farm [14]. Thus, operators will need to invest significant resources to train their workforce. Proper training is needed for cultivation techniques, integrated pest management, food safety and handling, and data collection. As discussed earlier, failure in any of these areas can have severe consequences for the profitability of a vertical farm. Relying on undertrained and inexperienced employees might be necessary without a developed workforce, which is a major risk to a new vertical farm. Beyond training employees, operators must create a workplace culture with open communication. This allows employees to quickly relay information related to issues on the farm, potential inefficiencies, and areas that need a more experienced point of view. Additionally, operators need to manage their workplace culture to minimize turnover. A high turnover rate interrupts the optimization process and wastes training resources and time. A significant source of institutional knowledge on the farm is the collective experience of the workforce. Their input is crucial for exposing inefficiencies in operations. However, this can only take place if the employees are well trained and accustomed to the operations. Ultimately, a well-trained, cohesive local labor force is necessary to run a vertical farm.

Labor automation, as mentioned above, can alleviate some of the labor costs associated with VF operations. Automated systems can control seeding, planting, moving plants, irrigation, harvesting, and post-harvest processing. These systems do not eschew the need for any labor. Quality control (of the production system and finished products) and maintenance of these systems is difficult to automate and requires highly skilled workers. On top of this, automated systems are capital intensive and out of reach for most small operations. A cost-effective approach to reducing labor in VF operations is a combination of automation and efficient systems. Efficiency can also be gained by reducing movement of laborers during routine maintenance of the crop, harvesting, and post-harvest processing.

Data collection and environmental monitoring enables optimization of a vertical farming system. Optimization of yields and energy efficiency is needed to increase the economic viability of VF. A main advantage of VF systems is their high degree of controllability, which can be enhanced by data-driven decisions. Operators can collect large amounts of data related to environmental parameters and plant growth. Environmental parameters include air temperature, root-zone temperature, humidity/vapor pressure deficit, CO₂ concentration, dissolved O₂ in the nutrient solution, nutrient concentrations, water flow rate, and light intensity. Plant growth data include observations from quantitative measurements such as plant fresh weight or shoot length, and qualitative measurements such as physiological disorders (e.g., tip burn) and leaf color. Monitoring of these parameters needs to take place throughout the vertical farm to uncover any heterogeneous conditions [15]. A data-management system is needed to aggregate and analyze the large amounts of data

gathered from a vertical farm. An Internet of Things (IoT) system, such as the one proposed by [15], can allow for remote and distributed access to the data generated by the farm. Advances in artificial intelligence (AI) can accelerate data-driven decision making. For example, data can be used to alter inputs and environmental set points to increase yields or can be used to predict harvest timing. Typically, AI algorithms are proprietary, precluding the sharing of information and data-processing techniques. Without such sharing, critical advancements in decision-making capabilities across the entire industry are slowed. AI can also assist expert growers with decision making and adjusting environmental control set points, which can reduce the labor costs and resource consumption in the long run [16].

4. Miscellaneous Issues

4.1. *Why Using Aquaponics May Not Be a Good Idea*

Aquaponics (the combination of aquaculture with hydroponics) is often touted as a means to improve the environmental sustainability of the production of both fish and hydroponically grown crops. The theory is that waste generated by the fish provides nutrients for the crop, while the crop removes nutrients from the water that is returned to the fish [17]. Modern aquaponics is generally considered to have started in the 1970s and has lately begun to move into “vertical” production systems. While conceptually an attractive idea, there are a number of challenges when it comes to coupling hydroponic plant production and aquaculture. Specifically, system optimization is the most challenging [18]. Both aquaculture and hydroponics have quite well-defined optimum requirements for several environmental factors, and deviation from these optimums frequently results in reduced production. In an economically competitive environment, even a small loss of production can result in a business failing. Some disconnects between aquaculture and hydroponics are:

- pH: The pH of the nutrient solution affects the solubility/availability of nutrients, which is of particular concern for hydroponic crop production. Typically, the optimal pH for hydroponics is on the slightly acidic side at 5.5 to 6.5. While it varies by species, fish typically require a pH of 6.5 to 9. Therefore, combining aquaculture with hydroponics requires frequent and careful adjustment of the pH.
- Temperature: The uptake of feed and growth of fish is closely tied to water temperature. Depending on the type of fish produced, a compromise may be necessary, particularly for tropical fish which may not grow much below 25 °C. Depending on the crop selected, nutrient solution temperatures between 18 and 25 °C are usually considered optimal.
- Scheduling: The production of fish is typically on a much longer time-scale than common hydroponic crops. For example, Tilapia can take approximately 130 days to reach a harvestable size, whereas a lettuce crop grown under optimal conditions can be ready for harvest in as little as 35 days. To maintain comparable production and balanced nutrient uptake rates while the uptake and production rates for fish and plants differ can become a challenging juggling act [19].
- Nutrient production: The waste from fish production (excess food and excrement) contains high levels of nitrogen and phosphorus (which is why treating the waste stream is such an important part of aquaculture). However, the forms of nitrogen in the recirculating water are not always those preferred by hydroponics crops (ammonia vs. nitrate) and/or in the preferred ratio. Regular compositional testing of the nutrient solution beyond the typical electrical conductivity (EC) and pH measurements is required to ensure that the correct amounts of macro and micronutrients are available to both fish and plants.

4.2. *Data Sharing*

Another significant challenge facing the vertical farming industry is the lack of collaboration and data sharing among vertical farmers and researchers. The generally secretive nature of the industry leads to companies often ‘re-inventing the wheel’ without shar-

ing strategies and technologies that are truly innovative. Much effort could be saved if companies were more open about their energy and resource consumption and growing strategies. Such data would also help in the development of more realistic business plans and would give partners and investors more confidence when they consider supporting new projects, expansions, or technology upgrades. Partnering with external researchers at universities or seeking help from Cooperative Extension personnel could allow vertical farming operations to take advantage of the knowledge base already developed for greenhouse crop-production systems, which share the same fundamentals.

4.3. Accessibility

Additionally, products produced through VF are sometimes termed ‘techno local food’, which may be available only to wealthier consumers because of the higher prices [16]. On the other hand, regional and cultural difference can be another factor, as in some countries social acceptance is greater for rooftop gardens than it is for VF, and vertical farms might be labeled as plant factories, which may create a less desirable image in a consumer’s mind [16].

4.4. Impacts on Workers and Consumers

For workers in vertical farms, it is important to minimize any potential health effects of long-term exposure to high-intensity electric lighting. Moreover, while VF techniques can increase the nutritional value of products, it is also important to assess any potential negative impacts from the consumption of certain plant phytochemicals [16]. More research on the impacts on workers and consumers is needed.

4.5. Carbon Footprint of Vertical Farming

Some early work on life-cycle analysis (LCA) comparing vertical farming with conventional farming has shown that vertical farming has a much higher carbon footprint, unless the electricity used in vertical farming is sourced from renewables or nuclear power [20]. Moreover, accurate LCA is only possible when detailed information is available about the production method, including control strategies and resource input [20].

On the other hand, vertical farming can reduce the use of fossil fuels by eliminating the use of tractors and large farm equipment [21]. Larger-scale vertical farming is more sustainable, and it can reduce its environmental impact (including CO₂ emission, air pollution, and water runoff) per unit of production. In addition, there are typically fewer transportation requirements for crops produced in vertical farming operations, since they are often produced close to the end-use location.

According to [22], the greenhouse gas (GHG) emissions from the food sector mainly come from production (83% in US), transportation (11%), and final distribution (4%). Renewable energy systems appear a natural fit for the philosophy behind vertical farming. Using renewable energy can reduce the carbon footprint associated with vertical farming. However, most vertical farming systems require a significant amount of electricity for lighting, temperature, and humidity control, which can make them less climate friendly [21]. The use of LED lighting and smart air-conditioning systems can improve the overall energy efficiency.

Increasing the Light-Use Efficiency (LUE) could be another approach to lower the energy requirement for VF. Maintaining a continuously closed canopy can minimize light loss [16]. Beneficial strategies that can be considered are: 1. using a continuous production mode; 2. frequent plant-density adjustments; and 3. using a carefully designed lighting strategy. Selecting crops for their specific plant architecture can make it easier to distribute light more uniformly over the entire growing area. Crop breeding programs that take the specific conditions in VF operations into consideration can help improve system efficiency, and thus overall profitability [16].

5. Conclusions

Whether VF will be a major component of the future of agriculture remains to be seen. It provides opportunities to reduce water consumption and land degradation, lower the use of pesticides, shorten the distance between producer and consumer, and increase crop quality. Nevertheless, VF is facing several major challenges such as higher initial investment and operating cost, complexity, costs of maintaining the optimum growing conditions, and an industry that is generally reluctant to share detailed information and experiences. As a result, VF operations tend to ‘reinvent the wheel’ unnecessarily and have begun to receive more scrutiny with respect to their environmental footprint. We suggest that more collaboration and sharing of data is necessary in order for the VF industry to keep expanding and solidifying its place as an important component of agriculture in general.

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