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From horizontal to vertical. Advanced food production in urban areas though vertical farming projects

Michele D'OSTUNI,[1] Leonardo ZAFFI[2]

(1) Department of Agricultural and Food Sciences (DISTAL), University of Bologna
michele.dostuni@unibo.it
(2) Department of Architecture (DIDA), University of Florence
leonardo.zaffi@unifi.it

Abstract

Vertical farming projects are increasing in number all over Europe, industrialized Asia, and the United States. In a period of great uncertainties after the Covid-19 pandemic where our western society has, for the first time, stopped giving our food for granted, the possibility to produce high yield and high quality food within the cities' borders has receiving increased attention. Furthermore, Vertical Farms can be a way to refurbish the empty or under-used buildings in urban areas, adding new value to our abandoned heritage. Nonetheless, indoor food production in warehouse facilities require high investment costs and high energy inputs that still are hindering the development of vertical farming. In this sense, this paper explores the design requirements that a Vertical Farm should have to produce food in a sustainable manner, assessing advantages and disadvantages of a new, highly technological and digitalized food production.

Keywords: Vertical Farms, Urban Agriculture, Technological Development, Green Buildings

1. Introduction

With the majority of the world's population already living in cities and the urbanization trends confirming the increasing curve over the next 30 years, cities are at the core of the fight against climate change. The important role of cities in achieving sustainable development is reflected across SDGs, and mainly in SDG 11 *Make cities inclusive, safe, resilient and sustainable*, where most targets are directly linked to greenhouse gas (GHG) emission reductions, focusing on the implementation of sustainable transportation systems, green buildings and the reduction of cities' environmental impact. In this context, current food systems will have to adjust to satisfy the rising food demand for an increasing urban population, while productive land is constantly decreasing. According to FAO, it is projected that food production will increase by 70 percent in the world and by 100 percent in the developing countries. However, water resources are finite and already under heavy stress, and, therefore, future agricultural production will need to be more productive and more sustainable at the same time [1]. Indeed, the environmental impacts of modern industrialized agriculture are proven to be unsustainable. Ecologically, industrial agriculture is creating vast, mono-cultural surfaces, where large amounts of synthetic herbicides and pesticides are often applied, causing the desertification of agricultural soils, the depletion and pollution of important water resources and the loss of biodiversity. The environmental effects of these practices are devastating, and it is possible to see their impact in the four ecological pillars of the food system: soil, water, biodiversity, and climate [2].

1.1 A paradigmatic shift in global food production: from horizontal crops to high vertical spaces in buildings

The fact that the global agricultural system is in crisis is undeniable, and today it is possible to understand the deep contradictions of an industrialized system that lives in the paradox of nurturing humans while consuming the earth. Thanks to the technological advancements and their widespread use in agriculture, agricultural production more than tripled between 1960 and 2015 [3]. This caused a significant expansion in the use of land, water and other natural resources for agricultural purposes [3], followed by the constant lengthening of the food supply chain dramatically increasing the physical distance from farm to plate. Thus, the expansion of the food production system and its consecutive economic growth have had a heavy impact on the natural environment: almost one half of the forests that once covered the Earth are gone, leaving the place to monocultural agriculture fields; groundwater sources are being depleted rapidly; biodiversity has been deeply eroded; agricultural CO_2 emissions rose year after year, massively contributing to global warming and climate change [3]. These trends are an actual threat to our possibility of producing enough food in the future for a growing population. The depletion of soils together with the scarcity of land and a reduced capacity of fresh water reservoirs mark the necessity for a transition towards more sustainable and fair production systems. In this scenario, even if it is a consensus opinion that the modern agro-business will be able to produce enough food for a growing population [4], it is also acknowledged that it won't be able to do so in an inclusive and sustainable manner [3]. Several solutions have emerged that promotes a shift towards more sustainable food production practices, often complementary to each other. In this context, the possibility to produce vegetable crops without the constraint of the soil, vertically, inside urban and peri-urban buildings, is becoming a consolidated practice thanks to the technical and digital advancements that allow vertical farmers to reduce the initial investment costs. Accordingly, the objective of this paper is to understand complexities and potentialities of a new vertical agriculture located inside our cities' boundaries that can potentially add a new value to abandoned or underused buildings, fostering their refurbishment.

2. What is a Vertical Farm (VF)?

The vertical farming is a growing phenomenon taking place all over the industrialized world. Existing examples can be found in industrialized Asia, northern Europe, and the United States [5]. Vertical Farms are indoor farms that allow to grow food in indoor, airtight facilities thanks to the use of artificial lights and precise indoor climate control technologies. For this reason they can also be found under the name of Plant Factories with Artificial Lights (PFALs). Accordingly, a VF is a closed production system where the enclosure is designed to maximize production density, productivity and resource use efficiency [6]. High productivity can be achieved by creating indoor climate conditions that favor plants' growth. Thus, the use of technical devices is fundamental to uniform lighting, temperature and relative humidity [6]. In order to reach perfect indoor climate conditions, it is crucial to minimize interactions with the exterior climate. Limiting these interactions can also benefit the efficient use of energy, water and CO_2 [7]. Due to its characteristics, indoor farming is particularly suitable for dense urban areas, as it can maximize production capacity in relatively small urban spaces. In addition, VFs offer new design solutions for the retrofitting of abandoned buildings, repurposing them creating new job opportunities. For these reasons, this growing method has seen an increasing interest in the past years. However, as vertical farming practices are growing, so are the conflicting opinions of practitioners and researchers that claim unsustainable the highly technical food production occurring in the Vertical Farms [8]. Indeed, there is still some resistance to indoor farming, as most opponents of vertical farming initiatives tend to stress the limitation of a system that only uses artificial lights to grow plants, arguing that this will result in an unsustainable use of resources with a worst carbon footprint than traditional agriculture. Furthermore, a diffuse skepticism is connected to the high investment and labor costs required to start a PFAL that may result in zero or very little profits for urban growers, possibly discouraging young entrepreneurs to undertake similar initiatives. However, indoor farming is constantly evolving and new projects are quickly outweighing the disadvantages of the absence of solar energy. For instance, experiences like the SkyGreens in Singapore seem to have reached economic viability with the development of technically sophisticated, highly productive, energy-efficient, and reasonably priced LED grow lights [9]. Here, Table 1 reported the most commonly discussed advantages and disadvantages of indoor farming.

Table 1: Advantages and disadvantages of indoor farming

Type	Characteristics	Advantages	Disadvantages
Vertical Farm	Air-tight, highly insulated structures that have no relationship whatsoever with the external environment.	Stable production all-year-round that can guarantee 10-20 yields per year. Easy to integrate in existing buildings, with the possibility to create new profits and generate new job opportunities. Good design and the implementation of renewable resources use may result in high yield with minimum carbon footprint.	High investment and labor costs. High energy consumption which may result in unsustainable practices. Limited production to leafy greens. Uncertain revenues.

In this scenario, researchers have identified six conditions that, if satisfied, would make VF sustainable [8]:

1. The entire food chain, from production to consumption, should be resource saving and have low CO_2 emissions;
2. Use of water must be reduced as well as the use of chemical pesticides and of fossil fuels for heating and cooling, minimizing the release of environmental pollutants;
3. Resource use efficiency must be optimized, with initial investments on renewable energies;
4. Production stability must be implemented and deliver high quality crops and high yield all year round;
5. Must foster social inclusion creating new employment opportunities;
6. International technology transfer must be facilitated through the development of standardized systems.

The design of VFs enclosure and the chosen system components should aim to satisfy these conditions, providing growers with production spaces that are easy to manage, completely insulated from the exterior climates and adaptable to environmental and social changes. In order to achieve the above mentioned conditions, the design process of a Vertical Farm should take into consideration some basic principles that would maximize the indoor farming performances [10]:

1. The production spaces must be air-tight. The envelope must be thermally well insulated and the structure covered with opa
2. que walls.Multilayer hydroponic culture beds should be disposed in a way to occupy the internal space in the most efficient way to maximize production surfaces. Every layer must be equipped with LED light sources, directly illuminating each culture bed.
3. Heat pumps should be used mainly for cooling and dehumidification, in order to mitigate the heat generated by the growing lamps and eliminate the vapor produced by the plants. Fans for forced air circulation should be provided to achieve uniform air distribution.
4. A CO_2 delivery unity should always be provided in order to reach CO_2 concentration between 800 and 1200 ppm in the growing room, favoring plants' photosynthesis processes, maximizing the production.

5. A fertigation system able to efficiently deliver nutrients to the plants must be installed.
6. A climate control room should be designed in order to always keep indoor environment to optimal growing conditions. It is important to integrate the climate control room with a technical chamber that can constantly monitoring water pH, electric conductivity (EC) and nutrient contents in the nutrient solution.

2.1 Vertical Farms and Hydroponic Greenhouses. A comparison

Another system that has been highly catching on in urban areas is to produce food on top of buildings or in public/private squares or courtyard thanks to the installment of hydroponic greenhouses, that, similarly to VF, use off-soil advanced technologies to maximize yields in limited urban spaces [11]. Greenhouse horticulture is considered a (semi-)controlled environment. Contrary to VF, Greenhouses mainly use solar energy for photosynthesis [6]. Passive strategies can be used to heat the greenhouses through solar radiations and to cool them down through ventilation. In more advanced systems, heating and cooling devices can be used to achieve a fully controlled environment. The main characteristic of all greenhouse typologies is the translucent design, which allow thermal exchange with the exterior climate. In this regard, the relation between the costs (heating and cooling) and benefits (solar radiation) of greenhouse production largely depends on the latitude and external climate conditions of the site [6]. Today, the most commonly used type of hydroponic greenhouse for urban food production are Rooftop Greenhouses (RTG). This type mostly refers to high-tech greenhouses built on host buildings, and can be applied both in retrofitting and new construction projects. In recent years, rooftop greenhouses have seen an increasing success which is primarily connected to the high land costs in urban settings, which brought urban farmers to look for unused spaces within cities. For instance, connecting a greenhouse to an existing building is one possible strategy to revitalize underused spaces and provide locals with fresh food production. RTGs require specific energy inputs to control their indoor climates and improve environmental performances to facilitate effective and economical plant cultivation [12]. However, opposed to VFs, greenhouse operations largely take advantage of passive systems such as natural light and ventilation. Nonetheless, supplementing naturally available energy and resources, such as sunlight, heat, and CO_2 may be optional but will surely boost yields, especially during darker, cooler winter months, allowing for year-round production [9]. In this sense, while the set-ups for RTGs can benefit from passive systems to enhance plants' growth, in Vertical Farms the inputs for production must be generated artificially. Indeed, plant factories are located in air-tight warehouse structure, completely secluded from the external climates. This means that even natural light is forbidden to enter the structure, and it must be substituted by artificial light to start plants' photosynthetic processes. Furthermore, all other natural inputs that contribute to plants' growth need to be completely replaced artificially. Thus, specific technologies, as well as digital climate control systems, are required to properly operate plant factories in order to create the favorable conditions to maximize yields.

2.2 Vertical Farm technologies fostering advanced food production in buildings

As previously mentioned, when talking about hydroponic greenhouses it is important to balance between the technologies that can maximize production, reducing the spatial footprint of the hydroponic systems, maximizing passive strategies that could allow for a lower consumption of resources. Indeed, urban food production needs to respect and protect people's health, increasing the sustainability of local food systems, helping lowering carbon emissions coming from buildings. On the other hand, VFs rely primarily on mechanical systems, which make them independent from external climate conditions, but that require high energy inputs. For this reason, to be viable VFs need to properly integrate the most advanced lighting, hydroponic, and climate control technologies, as their cost can only be justified by a higher production that maximize land surface efficiency, reducing the energy inputs required to produce 1 kg of fresh weight produce [5]. To do so, it is important that all components are designed to achieve maximum productivity:

1. *Production methods:* Maximizing yields while dramatically reducing their spacial footprint is the main objective of Vertical Farms. In this regard, plants can be stacked on multi-layers trays, this way, production per square meter can increase exponentially depending on the number of layers in which plants are cultivated. For this reason, growing methods

should have a relatively low weight and require minimum heights. In this sense, growing beds, deep flow technique (DFT) and aeroponic production are the recommended and most used growing methods in plant factories (Fig. 1).

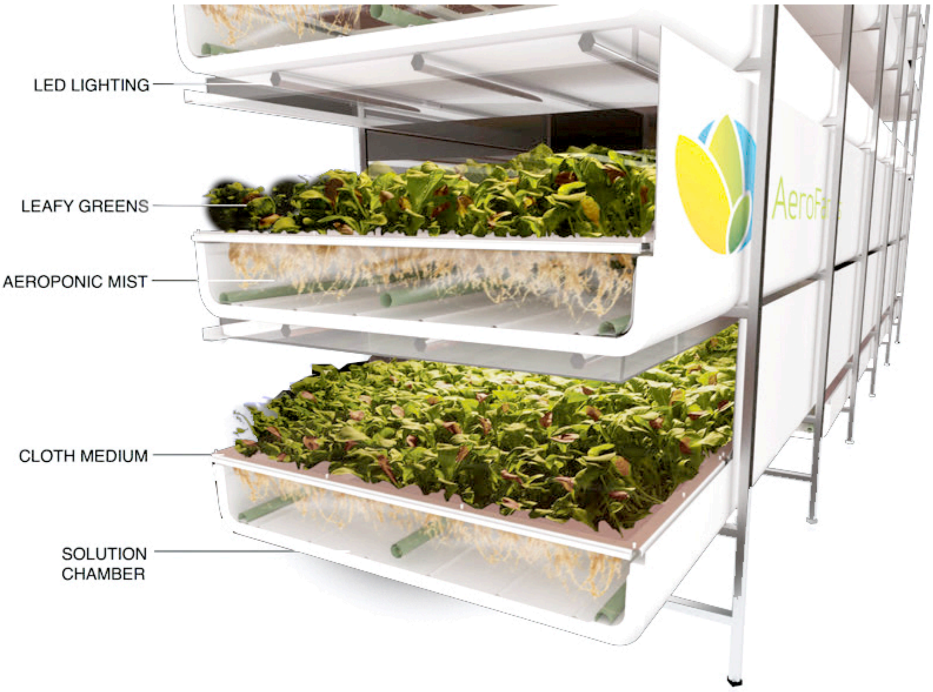

Fig. 1: AeroFarms aeroponic system for vertical farming.
Credits: AeroFarms ® (https://www.aerofarms.com)

2. *Ventilation:* While greenhouses can benefit from natural ventilation, indoor facilities need an automated forced ventilation system. Outdoor ventilation is not encouraged due to the reduction of CO_2 use efficiency and the potential introduction of pests and pathogens from outside [13]. Indeed, within air-tight warehouse facilities, high planting density causes CO_2 concentration to drop below outdoor values, limiting photosynthesis and plant growth (Gómez et al., 2019). Thus, forced ventilation systems should use extractor fans that pull exhaust air out of the growing spaces, providing constant optimal levels of ventilation in the warehouse structures.

3. *Indoor climate control:* Indoor climate in plant factories is automatically controlled to keep steady indoor temperature and humidity. Indeed, microclimate control management is fundamental to guarantee a proper plant development [5]. The typical airtight structure of VFs calls for continuous dehumidification to avoid relative humidity level due to evapotranspiration [5]. Dehumidification can be obtained by using heat pumps that manage the climate control [5]. Moreover, temperatures also need to be uniform inside PFALs to obtain uniform growth [13]. In this sense, air fans that can guarantee homogenous air recirculation inside the PFAL are needed [13]. Commonly adopted strategies for dehumidification in PFAL use heat pumps to manage climate control. Both heat pumps and air fans need electricity-energy, whose costs, summed with those consumed by the artificial lighting system were estimated to account for around the 30% of the total operation costs of a PFAL [14]. In this regard, the use of systems that can maximize energy efficiency are recommended. In a recent article, Yokoyama et al. (2019) [15] reported that conventional heat pump systems can be substituted by co-generation (HVAC) and even tri-generation

equipments. Using the latter would, in fact, allow the production of heat, electricity and CO_2, saving up 30% of the costs connected to climate control management.

4. *Lightening:* In VFs, electric lighting is used in substitution of solar radiation, artificially generating a light/dark photoperiod of generally 16/8 hours daily [13]. However, supplying VFs with artificial light is raising concerns on the environmental and economic sustainability of the system [16]. Lighting system, in fact, contributes to 50-55% of the total operating costs of a VF [15]. Furthermore, it accounts for almost two third of the total energy consumption [6]. Nonetheless, the technological advances made in the lighting sector developed new solution such as light emitting diodes (LEDs), which resulted in highly versatile and energetically efficient lighting systems for paint cultivation [17]. In indoor conditions it is possible to give plants the best light recipe for growth and development [18]. In this sense, LEDs provide the great opportunity to fulfill the light requirements at any cultivation stage, thanks to their capability to emit light in narrow bandwidths [17]. Furthermore, due to their easy adjustability, LEDs lighting systems enable to modulate the quality, intensity and photoperiod of the emitted radiation, leading to an optimization of plants growth in terms of yield and quality [29]. Accordingly, several researches on the application of LED technology for indoor plant cultivation focused on the study of the effect of red (R) and blue (B) light on growth, morphology and physiological responses of plants or toward the identification of the optimal RB ratio within the spectrum. On the other hand, the most claimed weakness of LED lighting technology is the initial cost [17], which resulted 5 to 10 times higher than HPS lamps (Fig. 2). However, when compared to more traditional lighting systems, the capital investments may be counterbalanced by the longer lifespan and greater efficacy of LEDs.

Fig. 2: Use of Blue and Red LED Lights in the Alma VFarm at the Department of Agricultural and Food Sciences of the University of Bologna
Credits: Laura Carotti

5. *CO_2 Enrichment:* The configuration of VFs, which makes them secluded from the exterior climate, prevent outer inputs to enter the warehouse structure. In this sense, PFALs are sealed and, as written before, natural ventilation is highly discouraged. In this sense, in absence of natural ventilation, the high density of plants contained in PFALs rapidly absorb all the CO_2 present in the environment, causing a quick drop in CO_2 concentration that would impede plants' growth. In this regard, the only way to keep optimal CO_2 levels inside the PFAL is with CO_2 enrichment processes. They can be generated by the tri-generation system, together with electricity and heating [15], or through the burning process of natural gas in a gas tank. CO_2 enrichment allows to keep a constant carbon dioxide concentration to at least 800 ppm through the whole stages of production.

3. Conclusion: concerns of integrating vertical farming projects within abandoned or vacant urban buildings

The recent pandemic crisis and the Ukraine war has made us reflect on how little we know about food production and food supply chain in our cities. Urban dwellers in western societies were used to give their food for granted [19], until it wasn't. Recently, the idea of bringing part of the intensive production back within the cities' margins has seen a growing interest ant application. In Asia the number of Vertical Farms has exponentially grown in the last three year. A similar growth was experienced both in the United States and in Europe, where always more young entrepreneurs are building warehouse or retrofitting abandoned buildings to set-up their urban indoor food production. Even universities and research institutions are investing in Vertical Farming projects to foster their research on the matter. An example is represented by the University of Bologna, that in 2019 organized the first UrbanFarm Student Challenge, where students from different backgrounds were called to design integrated urban farming systems in post-industrial, abandon areas. The challenge aimed at tackling the current need for cooperation between different disciplines by bringing together students from different fields of study into international teams specifically addressing the regeneration of three vacant urban spaces [5]. In this sense, as the awareness on the topic is raising, so are the number of researches on Vertical Farming. For instance, inside the Department of Agricultural and Food Sciences of the University of Bologna, it was installed one of the first research facility for vertical farming in Europe (Fig. 3).

Fig. 3: Alma VFarm**.** Experimental Vertical Farm in the Department of Agricultural and Food Science (DISTAL) - University of Bologna
Credits: Ph. Michele D'Ostuni and Leonardo Zaffi

Here, researchers and students have the possibility to evaluate the impact of vertical farming over water consumption, energy, and CO_2 emission compared to the amount of fruits and vegetables that is produced, assessing the best recipe of lights, nutrients, and indoor climate control to minimize resource consumption and maximize yields. The VF was built underground, integrated in the vast parking area of the Agricultural Sciences and Technologies campus. The sample design of the University of Bologna VF offers important design considerations concerning the integration of similar systems in existing buildings:

1. *Insulation*: as repeatedly mention in this paper, it is crucial that Vertical Farms are highly insulated and completely secluded from the exterior climate. However, when integrating VF systems within existing buildings it could be challenging to achieve the required insulation standards. For this reason, it is possible to design a climatic chamber that can be positioned inside the existing buildings, as a sort of “box in a box” concept. The climatic chamber should therefore be designed to maximize the indoor climate control potentiality of the Vertical Farm. In this scenario, existing buildings can literally host a new urban food production, taking advantage of the economic value that can come from selling food and food derivates right where they are produced.

2. *Spatial constraints*: When integrating vertical farming space inside buildings it is important to consider that the architectonic characteristics of the buildings might not be easily adaptable to plants’ growth. For instance, one of the main constraints is represented by the building’s structure and the distribution of the vertical structural elements. Pillars, in fact, may interrupt the continuity of the production spaces, especially when practitioners are forced to design the climatic chambers. Climatic chambers are closed structure that cannot integrate the existing pillars within their structure. In this sense, the climatic chambers must be located within the pillars’ spans, with the consequence of interrupting the continuity of the production spaces, inflating costs and possibly reducing yields. Another constraint is represented by floor’s height. VFs highly benefit from producing vertically on multi-layer trays. In existing buildings, the production height might be limited by the structural height of the slabs, with the consequence of reducing even further the potential yields of the system.

3. *Structural concerns:* As previously mentioned, it is important to chose production systems, such as aeroponic of DFT, that reduce the amount of water that is used during food production, limiting the weight of the system. However, on high multi-layer steel trays, the weight of the material combined with the weight of the produce and of the water might arise structural concern in abandoned buildings. Indeed, they often present structural damages, and structural analysis or structural reconstruction might increase dramatically the initial investment costs.

4. *Accessibility*: With the objective of bringing back to the city an intensive food production, VFs must guarantee very high yields to be profitable and sustainable with the consequence of having to stock and transport high amount of food, tools, and other processed food products. In this regard, integrating VFs inside buildings in highly dense urban environments might arise serious problems concerning access and transportation. VFs should, in fact, grant easy access to trucks to load and unload the inputs (seedlings, substratum, tools, etc.) and the outputs (packaged food and processed food) of the food production. Furthermore, trucks would come and go daily to collect the produced food and deliver it to the markets and other selling points, resulting in a possible increase of traffic and CO_2 emissions in the area where the VF has been designed.

All these concerns and considerations must be taken into account when designing a VF inside urban areas. This is the reason why most VFs are located in the peri-urban fringe of our cities. However, since VFs could help bringing numerous ecosystem services to our cities (Orsini et al, 2020), as well as profitable diversified business plans that can spark a new economy of food in urban areas, it is crucial to fine design strategies that may limit the above mentioned problems and may be able to take advantage of vacant buildings to foster a new, sustainable and green urban renovation.

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