Design Strategies for Vertical Farms Under the Low-carbon and Post-pandemic Context

Haiying Li[1] Xingnian Liu[2]

[1,2] School of Architecture and Art, North China University of Technology, Beijing 100144, China
[1]Corresponding author. Email: lhy@ncut.edu.cn

ABSTRACT

Food and vegetable security is an important aspect of urban resilience, and the basis for the survival of large cities. However, unexpected events or weather factors may cause sudden interruptions in the supply chain, which may have a significant impact on the life of large cities. Vertical agriculture can use the limited vertical space of the city to solve the production and supply problems of food and vegetables, effectively reduce pollution, save water and logistics costs. This article sorts out and summarizes the modern vertical agriculture technology, the built examples of vertical farms and related technologies, and puts forward the design methods of lighting, building materials, energy and other aspects of vertical farms, as well as the urban layout and development strategies of vertical farms.

Keywords: *Vertical farm, Plant factory, Planting technology, Building technology, Resilient city.*

1. INTRODUCTION

The history of vertical agriculture can be traced back to the ancient Babylon in the 6th century BC, where there was the world-famous Hanging Gardens; in 1915, American geologist Gilbert Ellis Baile first proposed the idea of hydroponic agriculture in a controlled vertical environment in his book VERTICAL FARMING, believing that this would bring economic and environmental benefits; in the early 1930s, William Frederick Gericke of the University of California, Berkeley pioneered the hydroponic method; in the 1980s, Swedish ecological farmer Ake Olsson designed a spiral track system for planting plants [1]. In 1999, American ecologist and public health professor Dickson Despommiery redefined the concept of vertical agriculture in a class of medical ecology [2], he advocated growing crops in skyscrapers to solve the land and food crisis, while using the photosynthesis of plants to absorb carbon dioxide and cool the earth.

2. VERTICAL AGRICULTURE PLANTING TECHNOLOGY

Currently, there are three main types of vertical agriculture planting technology: hydroponics, aeroponics, and aquaponics.

2.1 Hydroponics

Hydroponics ("Figure 1") is a soilless cultivation method that places the roots of plants in a flowing nutrient solution, or in a medium that provides support, such as gravel, perlite, etc. In this way, the roots of vegetables can absorb water and nutrients from the nutrient solution, and oxygen from the air, thus ensuring the healthy growth of the roots. Hydroponics does not use any animal excrement, so the agricultural products are clean and pollution-free. The yield of hydroponics is ten times that of soil cultivation.

Figure 1 Hydroponics.

a https://www.pinterest.com/pin/560276009887080449/?lp=true

2.2 Aeroponics

Aeroponics ("Figure 2") is a soilless cultivation method that exposes the roots of crops to a sealed cultivation box, where the nutrient solution is sprayed into fine droplets by a sprayer and covers the surface of the roots. Aeroponics has higher water use efficiency and yield, smaller environmental constraints, and is more suitable for vertical planting than hydroponics.

Figure 2 Aeroponics.

a https://www.ackermannarchitekten.com/entry/ueberdachung-des-carports-des-abfallwirtschaftsamts-muenchen/

2.3 Aquaponics

Aquaponics ("Figure 3") is an ecological agriculture model that combines aquaculture and plant cultivation. It uses the organic waste produced by fish in indoor pools as natural fertilizer for plants and uses the roots of plants to purify and filter the water quality of the fish pools, achieving water resource recycling.

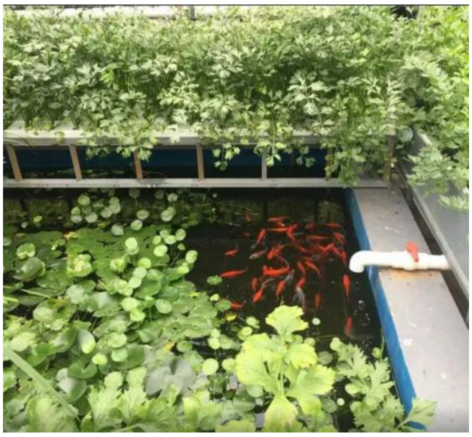

Figure 3 Aquaponics.

a https://www.sohu.com/a/335970302_260793

3. VERTICAL FARM EXAMPLE TECHNOLOGY

Vertical farms are complex and advanced systems that combine modern agricultural and architectural technologies and can achieve efficient agricultural production and urban development in limited space. "Table 1" lists some of the more successful projects [3] [4].

Table 1. List of selected vertical farm projects in the world

Project name	Location	Type	Technology	Features
Nuvege	Toyko,Japan	Low-rise	hydroponics	Four-story building, LED lighting
Spread	Kyoto Prefecture, Japan	Multi-story	hydroponics	LED lighting
Plant Lab	Netherlands Danbos	Underground	aeroponics	Three underground floors, LED lighting, remote formula control, precise control of ambient temperature, humidity, and irrigation.
AeroFarms	Newark, New Jersey, USA	Low-rise	aeroponics	Industrial building renovation, LED lighting, computer-controlled planting
Sky Greens	Singapore	Low-rise	hydroponics	uses a low-carbon, hydraulic-driven system to grow vegetables in a rotating rack.
Green Spirit Farms	New Buffalo, Michigan, USA	Low-rise	hydroponics	Industrial renovation project, using rotating planting (RVGS) and vertical tray planting system (VGS)
Farmed Here	Bedford Park, Illinois, USA	Low-rise	aeroponics aquaponics	A two-story windowless warehouse, artificial lighting
The Plant	Chicago, Illinois, USA	Low-rise	aquaponics	A former meatpacking plant in Chicago that has been converted into a vertical farm and food business incubator, using aquaponics and anaerobic digestion to produce food and energy.
Green Girls Produce	Memphis, Tennessee, USA	Low-rise	hydroponics	Located on the 4th floor of the building, LED lighting
Brooklyn Grange	Brooklyn, New York, USA	Rooftop	Soil plant	Outdoor rooftop
Gotham Greens	Brooklyn, New York, USA	Rooftop	hydroponics	Rooftop greenhouse with natural light, computer-controlled heating, cooling, irrigation and plant nutrition

In recent years, although the plant factory in China started late, but rapid development, many provinces and regions, such as Beijing, Shandong, Zhejiang, Jiangsu, Fujian, Xinjiang, etc., have established plant factory production bases and R & D centres ("Table 2") [5].

Table 2. Plant factory projects in China

Project name	Location	Area (m^2)	Time	Technology	Features
State power Investment	Yan 'an City, Shaanxi Province	3475	2020	hydroponics	Pure LED artificial light environment
Zhongke SAN An plant factory	Quanzhou City, Fujian Province	10000	2016	hydroponics	Three-story building, seedling climate control, substrate and nutrient solution ratio, irrigation tide regulation, artificial LED lighting and other technologies
Jingdong & Mitsubishi Chemical Plant Factory	Tongzhou District, Beijing	10000	2017	hydroponics	The combination of sunshine and artificial light plant factory, which mainly grows green leafy vegetables, has been listed for sale in Jingdong Fresh supermarket.
Agri-things Plant factory	Pinggu District, Beijing	12000	2015	hydroponics	Three-dimensional three-story building factory, the first floor for closed mushroom production, the second floor is LED artificial light plant, the third floor for environmental control greenhouse fruit and vegetable production.
Yuzhuang new Nongyuan LED plant factory	Pinggu District, Beijing	10000	2018	hydroponics	Pure LED artificial light, including vegetable seedling, vegetable production, Chinese herbal medicine planting three workshops.
Shuimu Jiutian Company	20 regions across the country	More than 200000	2014	hydroponics	Tomato planting, natural light plant factory, intelligent environmental control system, intelligent water and fertilizer integrated irrigation system, automated energy control system, artificial intelligence planting system, biological control system

Project name	Location	Area (m²)	Time	Technology	Features
Shenneng Group plant factory	Nanjing, Jiangsu Province	1100	2018	hydroponics	Photovoltaic + agriculture, artificial LED lighting, computer automatic control of temperature, carbon dioxide, nutrient solution and light

Shuimu Jiutian Company combines the waste heat and carbon dioxide generated by thermal power generation with the Shuimu vegetable factory and uses the photosynthesis of crops to fix carbon dioxide into organic matter to achieve the deep combination of agricultural carbon neutrality and industry. At present, there are more vertical farms built in the countryside in China, while multi-storey vertical farms are relatively few, and only a few plant factories are built in the suburbs of big cities, which are mostly converted from factory buildings. However, inside the city, there are many vacant factory buildings, high-rise buildings, and many CO_2-emitting factories, which provide huge spatial potential for the construction of vertical farms.

4. VERTICAL FARM BUILDING DESIGN

4.1 Lighting Design of Vertical Farm

The design of vertical farms needs to consider whether to use pure artificial light or a combination of artificial and natural light. Both methods have advantages and disadvantages, which need to be selected and optimized according to the specific situation and objectives of the vertical farm.

4.1.1 Natural Vertical Farm

4.1.1.1 The Use of Architectural Forms Conducive to Natural Light

In a natural lighting farm, for each plant to get sufficient light, it is necessary to reduce the density of planting and increase the light area. So, the architects experimented with different shapes to allow the plants to absorb more natural light. For example, “Figure 4” shows a twist protruding design, “Figure 5” shows a sloping slope design, and “Figure 6” shows a layer of retreating platform design, all of which allow the plants to better receive sunlight.

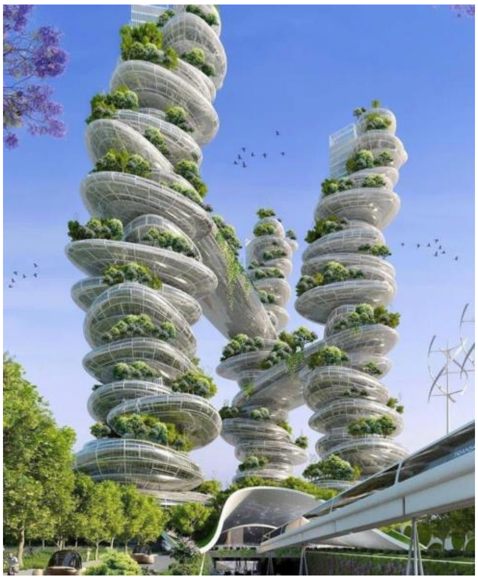

Figure 4 Torsion lift.

a https://homishome.com/2019/08/15/35-best-vertical-farming-architecture-design-inspirations/

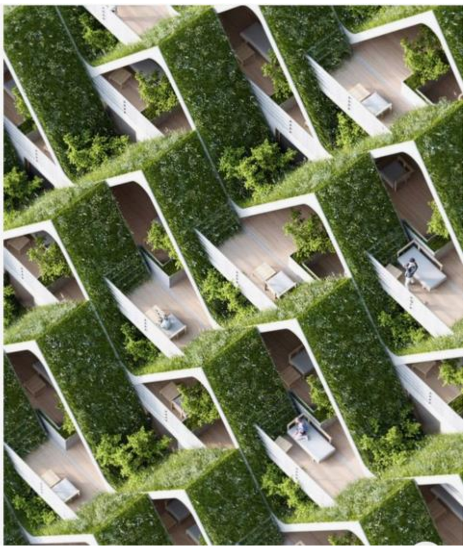

Figure 5 Inclined slope.

a https://www.pinterest.com/pin/48906345941576292/

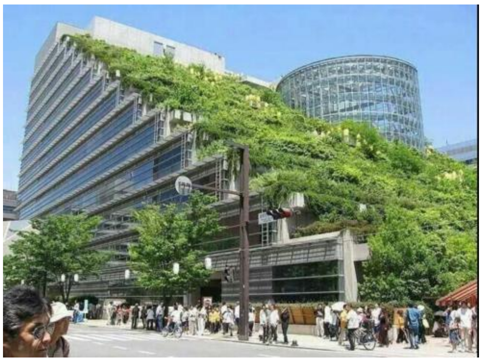

Figure 6 Layer by layer retreat.

a https://baijiahao.baidu.com/s?id=1678346588278238383&wfr=spider&for=pc

4.1.1.2 The Use of light Control Equipment

Natural light is an important way for plants to obtain energy, but architectural design must also consider how to focus, direct and distribute daylight so that plants can fully receive it. Through the light guide tube, light guide fiber, daylighting shelf and light guide prism window and other devices, using the principle of light reflection, refraction or diffraction, natural light can be imported and transported to the required position, providing the necessary energy for plant photosynthesis.

The Sky Green project in Singapore uses the A-Go-Gro planting system (“Figure 7”), which uses A unique water-gravity system to rotate the growth tanks on the 6-meter-tall planting towers around the aluminum towers at a rate of 1 mm per second, thus ensuring an even distribution of sunlight, good air circulation and adequate irrigation of the plants [2]. “Figure 8” shows a multi-layer moving through delivery system that allows the plant to move and receive sufficient light.

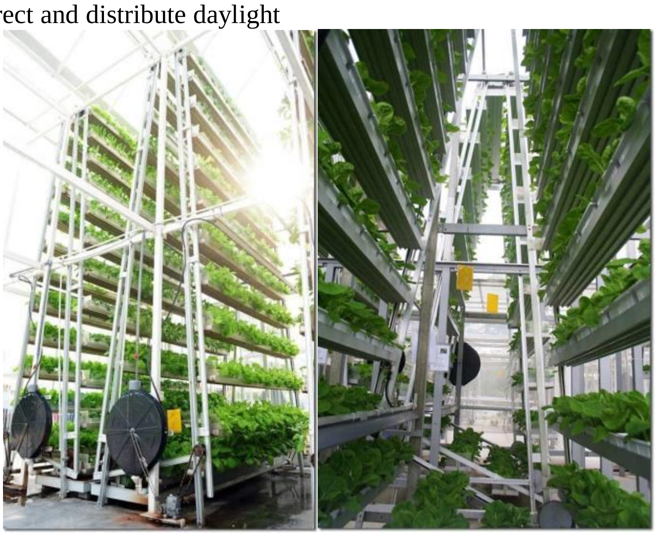

Figure 7 A-Go-Gro Planting System.

a https://minimalistmart.wordpress.com/2014/10/07/go-vertical-for-vegetables/

Figure 8 Mobile multi-layer conveyor system.

a https://ayola.info/?gclid=CjwKCAjwvJyjBhApEiwAWz2nLV4psj2ZN88_-aPEhHKVzgg0sk59s4jCwvYaEi7OdAJqWnzNkokQkhoCZHoQAvD_BwE

4.1.2 Vertical Farm with Artificial Light Source

LED can emit a variety of wavelengths of monochromatic light, the common wavelength of 450nm blue, 660nm red and 735nm far red light. Red light is an essential light source for plant photosynthesis, while blue light is an important factor affecting plant morphogenesis. Artificial lighting can provide enough light energy for vertical farms, which also allows vertical farms to be built in harsh external environments such as deserts, underground space, and space stations (“Figure 9” “Figure 10”).

Figure 9 AeroFarms with artificial light.

a https://www.aerofarms.com/about-us/

Figure 10 Planting scene of artificial light.

a https://www.gfactueel.nl/plantlab-breidt-uit-tot-grootste-indoorteler-europa/

4.2 Building Materials for Vertical Farms

4.2.1 Light-transmitting Materials

Vertical farms using natural light sources are usually built with transparent materials, white glass, diffuse reflection glass, LOW-E glass and various performance glass and PC materials to improve the transmittance of light energy, but also developed polycarbonate, polylactic acid and other biodegradable modified materials, which can reduce heat loss, but also reduce the condensation of internal water vapor. ETFE is a lightweight, transparent material that weighs only 1% of the same area of glass but has a light transmittance of up to 95% ("Figure 11" shows the ETFE film used in the UK's Eden Project). ETFE films can also be combined with flexible thin-film solar cells ("Figure12") to both penetrate light, block part of the sun, and generate electricity.

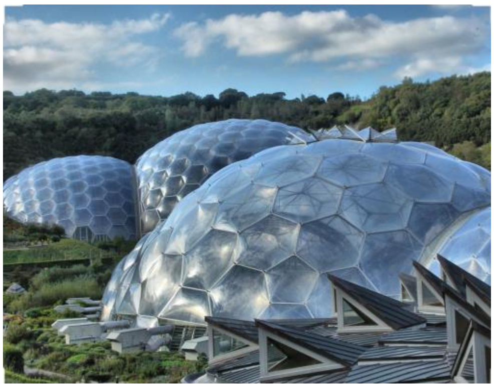

Figure 11 EFFE Membrane Greenhous.

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Figure 12 ETFE membrane + flexible thin film PV.

a https://www.ackermannarchitekten.com/entry/ueberdachung-des-carports-des-abfallwirtschaftsamts-muenchen/

4.2.2 Solar PV

Solar photovoltaic systems can provide renewable clean electricity for vertical farms, which solves the large cost of energy consumption for vertical farms with pure artificial light sources. At the same time, studies have shown that crops under photovoltaic can reduce the direct sunlight on the plant by 75%, relying on diffuse light, making the plant grow better than under high glare. Conventional photovoltaic is a certain shielding, but at present, cadmium telluride thin film solar cells look like transparent glass, which can not only transmit light, but also generate electricity with high efficiency. Therefore, in the envelope structure of vertical farm buildings with artificial light or artificial light, the integrated design method of photovoltaic and envelope is adopted. Obtaining sufficient electricity can also form diffuse light, which not only increases production, but also provides a large amount of electricity for artificial lighting, irrigation, monitoring, automatic planting and picking, and heating in winter and cooling in summer.

4.3 Equipment System of Vertical Farm

4.3.1 Water Circulation System

In vertical farms, the water and the nutrients in it are absorbed by the roots of the plants, the dissolved matter is used, and the remaining water evaporates back into the air through the leaves, and these evaporating waters are pure. They can also be used to irrigate food crops on farms and can even be drunk directly, creating a closed system of water circulation and achieving water self-sufficiency [6].

4.3.2 HVAC system

Vertical farm building design should consider the needs of energy saving and carbon reduction, giving priority to natural ventilation design, forming hot pressure ventilation and wind pressure ventilation, supplemented by mechanical ventilation; Indoor cooling is also preferred to use natural evaporative cooling to reduce energy consumption as much as possible. The energy needs of vertical farms mainly rely on natural light, solar panels, wind turbines, biomass fuel and steam refrigeration, so solar technology, heat pump technology, biomass technology and cogeneration technology can be effectively used to provide heating and cooling energy for vertical farms.

4.3.3 Waste Management System

In vertical farms, the food web principle in the natural ecosystem can be modeled after the rational allocation of animals, plants and microorganisms to achieve efficient use of energy. At the same time, the nutrient solution can be recycled, supplemented and disinfected through closed-loop cycle treatment, so as to achieve the goal of zero discharge of waste liquid.

4.3.4 Intelligent Facility Control System

In vertical farms, all crops are grown in an artificially monitored environment, and an intelligent control system can be built through sensors, computer networks and mobile networks to realize the automatic control of temperature, humidity, light, gas concentration, water nutrition and other parameters of vertical farms and facilities to meet the needs of crop growth. The Dutch company PlantLab has developed a master program, PlantLab OS, to process all the feedback from the sensors and to control the following environmental factors: light color, light intensity, light-color ratio, day length, infrared, light temperature, room temperature, plant temperature, irrigation, nutrition, air velocity, air composition, humidity, and carbon dioxide. Using new information technologies and online applications, farm managers can do most of their daily crop care from a smartphone or tablet, enabling remote management of multiple farms. At present, artificial intelligence environmental control, water and fertilizer integration system, remote expert management system, sorting and packaging system, remote diagnosis system of diseases and pests and other technologies have made agriculture truly realize high-tech production [7].

4.4 Renewable Energy Utilization in Vertical Farms

Indoor vertical farming relies on energy-intensive systems such as LED lights, HVAC air-conditioning systems for temperature regulation, and water filtration systems for recycling and purifying water from hydrated or atomized plants. According to the 2021 Global CEA Census Report, the average energy consumption of vertical farms is 38.8 KWH per kilogram of production, which is much higher than the 5.4 KWH per kilogram of production of traditional greenhouses. The SkyGreen project in Singapore solves the problem of high energy consumption through natural lighting and water gravity circulation, and a 6-meter-tall planting tower consumes only as much energy as a 60W light bulb. In 2023, AeroFarms, an early pioneer of vertical farming, declared bankruptcy because of the high cost of lighting and the higher energy consumption required to run air conditioning and other equipment. Therefore, in the design of vertical farm, solar power generation is the preferred energy source, and the integrated design of the envelope and solar photovoltaic maximizes the power generation area, and photovoltaic panels can be installed not only on the roof but also on the wall. At the same time, it can also take advantage of the solar passive technology of the building, using solar walls or Trumbo walls, as well as variable shading systems, natural ventilation and natural air conditioning. Where conditions exist, wind power can also be used; Geothermal energy can also be used, using heat pump technology. Also of particular concern in vertical farms is biomass energy, which collects organic waste and converts it into biogas for heating and cooling [8].

We also remember vividly that the supply chain crisis triggered by the COVID-19 response led to an extreme shortage of agricultural products in Shanghai, and that extreme weather, sudden disaster events, and long-distance logistics and energy pollution exposed the city's vulnerability. In the context of the COVID-19 pandemic, the energy crisis and the low-carbon development of various countries, vertical agriculture has become one of the important options for resilient cities to cope with the supply chain crisis [9].

Vertical farms can establish single-storey or multi-storey vertical farms in urban suburbs, or transform urban warehouses, abandoned industrial buildings and high-rise buildings. Artificial light sources can be used to meet the growth needs of plants in the basement of large urban commercial residential complex buildings or in the air of high-rise buildings, and supply plants to surrounding restaurants, supermarkets and residents to shorten the supply chain. Reduce transportation costs and food waste; On the roofs of urban public buildings ("Figure 13"), it can also make use of sufficient light on the roofs to carry out vertical agricultural construction on a certain scale, beautify the urban landscape, improve the urban ecological benefits, and provide residents with leisure, sightseeing, picking, education and other functions under the premise of ensuring waterproof and load. It can also be built in urban parks, and people can reach it without a long journey [10]. It is also advocated to build in the community, the use of container or cabinet vertical farms, so that community residents participate in management and labor, so that people living in the city experience low-carbon urban life, while participating in the planting work, it can also make people relax, children understand the source of food, and improve the neighborhood aesthetics, reduce crime and enhance community cohesion("Figure 14"). Vertical farming projects in cities can integrate planting and breeding, ecological restaurants, makerspaces, display education, and deeply explore the "incremental" value of new agriculture.

Figure 13 Rooftop farm with natural light.

a https://www.emergingtechbrew.com/stories/2022/04/21/vertical-farms-have-the-vision-but-do-they-have-the-energy

Figure 14 Community farm cohesion.

a https://aoarchitect.us/projects/k-farm-smart-urban-farming/Urban development strategy of urban vertical farm

5. CONCLUSION

In summary, when designing vertical farms, it is crucial to consider multiple aspects such as crop types, architectural forms, material selection, HVAC systems, renewable energy utilization, and social sustainability. By adopting the aforementioned design strategies, vertical farms can achieve a more sustainable development in the context of low-carbon and post-pandemic scenarios. However, it is important to note that the implementation of these strategies requires a comprehensive consideration of local environmental conditions and social cultures to ensure their feasibility and effectiveness.

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