

GLOBAL DEVELOPMENT TRENDS AND STRATEGIC OUTLOOK OF VERTICAL AGRICULTURE

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Abstract

This paper aims to comprehensively understand the global development trends of vertical agriculture, analyze the key factors influencing its development, and then formulate forward-looking and feasible strategic plans. This research has both theoretical and practical significance. It can enrich the theories of agriculture and industrial development, guide enterprise decision-making, and assist in policy formulation, thereby ensuring global food security and promoting the sustainable development of agriculture. This paper systematically introduces the development history and trends of the vertical agriculture industry, comprehensively analyzes the key technologies and breakthroughs in the current vertical agriculture field, and examines the bottlenecks, challenges, and feasible countermeasures in industrial application. From a strategic perspective, it puts forward policy suggestions to promote the development of vertical agriculture, providing references and guidance for industry decision-makers and researchers.

Key words: vertical agriculture, light efficiency, development suggestions, urban agriculture, smart agriculture.

INTRODUCTION

In recent years, vertical agriculture has been emerging as a global development hotspot. Vertical agriculture is an advanced agricultural system. Through internal high-precision environmental control, such as using computers to automatically control environmental factors like temperature, humidity, light, CO₂ concentration, and nutrient solutions during the crop growth process, the production process is not restricted by natural conditions. It enables continuous and efficient crop production throughout the year and can significantly reduce labour costs (Yang, 2019).

Vertical agriculture makes full use of high-end technological means such as new materials, semiconductor light sources, biotechnology, hydroponics, intelligent decision-making, and even artificial intelligence and robots. This technology-intensive production method is internationally recognized as the most advanced stage of development in protected agriculture.

Vertical agriculture has a wide range of unique application scenarios. In urban environments, it can be established using idle urban spaces such as abandoned factories, rooftops of high-rise

buildings, and underground garages to produce fresh, safe, and high-quality agricultural products like vegetables and herbs, meeting the urban residents' demand for green food and alleviating the shortage of urban land resources (Blom et al., 2023). In remote areas or places with harsh natural conditions, such as deserts, islands, and polar regions, vertical agriculture can overcome the limitations of extreme climates and soil conditions, providing a stable food supply for local residents and ensuring their basic living needs. In the aerospace field, vertical agriculture is one of the key technologies for long-term survival in space, providing astronauts with fresh vegetables and oxygen to maintain the balance of the life-support system. In addition, in the scientific research field, vertical agriculture can precisely control environmental factors such as light, temperature, humidity, and gas composition, providing an ideal experimental platform for research in plant physiology, genetic breeding, etc., which helps to accelerate the scientific research process and achieve innovative results. There are numerous reasons why vertical agriculture has attracted global attention. Firstly, the global population is growing

rapidly while the available arable land is constantly decreasing, posing challenges to food security. According to the prediction of the Food and Agriculture Organization of the United Nations (FAO), by 2050, the global population will reach 9.1 billion, and the food demand will increase by more than 70% compared to the present, while the per-capita arable land will decrease by more than 20% (FAO 2009). This has led people to pay increasing attention to applying modern technologies and innovative methods such as vertical agriculture to improve agricultural production efficiency and meet the growing global food demand with limited arable land. Secondly, the high-precision environmental control in vertical agriculture can effectively reduce the use of pesticides and fertilizers, decrease environmental pollution, and provide safer and healthier agricultural products. It has become an important means to drive the transformation of healthy food production methods. In addition, the aging of the agricultural workforce and the reluctance of young people to engage in agriculture are becoming increasingly prominent. In some countries such as China and Japan, more than 60% of the agricultural labor force is over 60 years old. In this context, as a modern and high-tech agricultural production method, vertical agriculture provides more attractive agricultural employment opportunities for the younger generation and is expected to alleviate the problem of the aging agricultural workforce and promote the development of agricultural production in a more healthy and sustainable direction (Yang, 2019).

This paper conducts an in-depth analysis of the development process and innovative breakthroughs of vertical agriculture technology, and comprehensively investigates and summarizes the key technological breakthroughs in aspects such as improving production and resource utilization efficiency and facility automation. The paper also elaborates on the difficulties and challenges faced by the vertical agriculture industry in the process of achieving commercial application, including problems such as high costs, lack of market demand, and insufficient commercial profitability. It explores solutions from multiple aspects such as technology, funds, and policies,

aiming to provide theoretical support and practical guidance for the healthy development of the vertical agriculture industry.

DEVELOPMENT PROCESS OF VERTICAL AGRICULTURE

Vertical agriculture has a history of over 60 years to date and has mainly gone through three stages. The early exploration stage began in the 1950s. Breakthroughs were made in “artificial simulated environment and climate control technology” and “nutrient solution cultivation technology”. Vertical agriculture started in developed countries and regions in Europe and America. In 1957, Denmark built the world's first vertical farm covering an area of 1,000 square meters. In 1960, the United States started to research and develop vertical farms using artificial light. In 1963, Austria built a 30-meter-high tower-type vertical farm. However, there were problems such as imperfect environmental control in technology, high costs, low automation levels, and a limited variety of applicable crops.

The rapid development stage spanned from the 1960s to the end of the 1990s. Numerous enterprises in countries like the United States, the Netherlands, and Japan carried out R & D and achieved remarkable technological results. The first real vertical farm using artificial light was established, and the industrial scale gradually expanded. Nevertheless, the application of light sources was restricted. High-pressure sodium lamps were initially used and later replaced by fluorescent lamps. The relatively high energy consumption limited large-scale promotion.

The stage of gradual maturity started in the 21st century. With the emergence of blue-light LED technology (Kusuma et al., 2020), the successful development of red-blue LED combined light sources, and the widespread application of intelligent control technology, the energy consumption of vertical agriculture has been reduced, and the space utilization rate has been improved. By 2022, there were about 300 vertical farms in Japan. South Korea has launched a variety of products and owns the world's largest tunnel-type vertical farm. The United States has carried out R & D and industrialization of various types of vertical agriculture, and some enterprises have received

substantial financing. In Europe, for example, the United Kingdom is also building vertical farms.

According to a 2023 prediction by Mordor Intelligence, a well-known international consulting firm, the global vertical agriculture industry will enter a period of rapid development in the next five years, with an average annual growth rate of over 10%. In Europe, the average annual growth rate of vertical agriculture will reach more than 22%, and its market size will reach \$4.19 billion (approximately RMB 30.3 billion) in 2029 (Mordor Intelligence 2023). The New York-based fund company Insight Partners predicts that the global vertical agriculture market size will reach \$19.864 billion (approximately RMB 143.8 billion) in 2028 (The Insight Partners 2021). Some well-known international enterprises (such as Siemens (Siemens vertical farming 2023), General Electric (General energy 2020), etc.) have also entered the field of vertical agriculture technology R & D and actively participated in industrialization promotion. The vertical agriculture-related industries globally are showing a booming development trend.

KEY TECHNOLOGIES IN VERTICAL AGRICULTURE

Vertical agriculture is an industry highly intensive in technology. Meanwhile, it incurs relatively high investment costs and operational energy consumption. Over the years, countries around the world have been conducting technological research to meet industrial demands such as significantly reducing energy consumption, enhancing the level of intelligence, and improving product quality, and have made important progress. In particular, a series of innovative achievements have been made in aspects such as the creation of plant light recipes and their LED light sources, energy-saving environmental control through light-temperature coupling, the improvement of vegetable nutritional quality, and AI-based intelligent management and control (Chang et al., 2021). These achievements have continuously enhanced the production efficiency of vertical agriculture and strongly supported the development of the vertical agriculture industry.

Vertical agriculture is technology-intensive, with high investment costs and high operational energy consumption. Over the years, countries have been working on technological breakthroughs to reduce energy consumption, improve the level of intelligence, and enhance product quality. Innovative achievements have been made in areas such as the creation of plant light recipes and LED light sources, which support the development of the industry. In terms of light source technology, the progress of new semiconductor materials has promoted the improvement of the luminous efficacy of LEDs in vertical agriculture. Light sources mainly composed of red and blue LEDs have been created, and the optimized parameters of light recipes have been mastered, enabling intelligent control of the dynamic light environment. Laser light sources have also been developed to reduce energy consumption. Advances in environmental control technology have reduced the energy consumption of air-conditioning systems. The combination with clean energy has gradually made commercial profitability a reality. The expansion of vertical space has attracted attention. Multi-layer vertical farms have been built in countries such as China, Japan, the United Kingdom, and the United States. The Chinese Academy of Agricultural Sciences has built a 20-storey vertical farm (Figure 1).

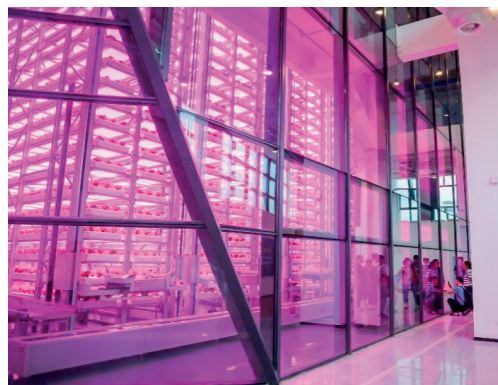


Figure 1. The vertical agriculture in Institute of Urban Agriculture, Chinese Academy of Agricultural Sciences

Building-type vertical agricultural systems can reduce energy consumption. The Chinese Academy of Agricultural Sciences has proposed the concept of a skyscraper plant

building (Zhang et al., 2023). Reducing labor costs and improving mechanization and automation are the research and development directions. Environmental monitoring and coordinated control are achieved through intelligent sensors, and complete sets of equipment and intelligent devices have been created.

Intelligent management and control technology has become an important direction, laying the foundation for intelligent unmanned operations. The combination of vertical agriculture and AI is an innovative approach. AI can monitor and adjust the growth environment, optimize decision-making, achieve personalized planting, and also automate harvesting and quality inspection, optimizing energy utilization efficiency and promoting the intelligent and sustainable development of agriculture (Chang et al., 2021). In addition, vertical agriculture provides support for space exploration and the development of remote areas. It can provide food and oxygen in the extreme environment of space. In harsh regions such as deserts and polar areas, it can efficiently utilize resources and provide a stable food supply.

THE INDUSTRIALIZATION OF VERTICAL AGRICULTURE

Vertical agriculture, as an important direction for the development of protected agriculture at present and in the future, has unique advantages such as significantly improving resource utilization efficiency, greatly increasing crop yield and quality, and attracting young people to engage in agriculture. However, it also faces many challenges in the development process (Van et al., 2021).

Its investment and operation costs include construction and equipment costs (the cost of buildings, artificial light sources, and cultivation systems accounts for over 70%, with artificial light sources accounting for 40-50%, and the average initial construction cost being 400-600 yuan per square meter) and production and operation costs (including electricity bills, materials, labor fees, etc., as well as equipment depreciation fees).

Energy consumption is also a limiting factor, accounting for about 28% of the total operating costs (Kozai et al., 2018). Artificial light illumination accounts for 60%, air-conditioning

accounts for 35%, and other equipment accounts for 5%. Although there are energy-saving technologies, 7-10 kWh of electricity is still required for each kilogram of leafy vegetables.

The specialized market for vertical agriculture involves multiple entities and rich trading contents, and can bring important values from the economic, social, agricultural, and technological aspects. It can be cultivated through strategies such as products, prices, channels, promotions, market education, and cooperation alliances. Currently, due to large upfront investments, immature market cultivation, and operating models, the profitability level is not satisfactory. For example, about 20% of vertical farms in Japan are operating at a loss (Kozai et al., 2018).

To achieve profitability, it is necessary to improve yield and quality, precisely regulate the environment and nutrition, conduct phased cultivation, coordinately regulate light and nutrient supply, and select functional plants. However, with technological and business model innovation, it is estimated that by 2030, the construction investment cost will be reduced by 40%, the operating cost will be reduced by 60%, the added value of products will increase by 40%, and the comprehensive benefits will increase by over 120%. At that time, the economic benefits and large-scale application will be significantly improved.

SUGGESTIONS FOR THE DEVELOPMENT OF VERTICAL AGRICULTURE

As a “future scenario” for modern agriculture, vertical agriculture is crucial for ensuring food security and addressing climate change and resource constraints. It requires the coordinated promotion of policy guidance, technological innovation, international cooperation, and market cultivation. Countries should formulate differentiated strategies to promote its efficient, low-carbon, and sustainable development. The specific measures are as follows: Firstly, strengthen the cultivation of professional talents. Establish a talent cultivation system jointly formed by universities, research institutions, and enterprises, and formulate attractive talent policies to provide high-quality and interdisciplinary talents. Secondly, from a

strategic perspective, increase the intensity of innovation and R & D. Vertical agriculture is a key area in the international competition of agricultural high-tech. Finally, promote the industrial development in a step-by-step manner. Formulate long-term plans, start with small-scale demonstrations and then carry out large-scale promotions. Prioritize meeting the needs of special places and increase publicity to enhance public awareness and product recognition.

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