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Review – Thematic Issue

Applications of vertical farming in urban agriculture

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Summary

With the acceleration of global urbanization, vertical farming and urban agriculture have been proposed for addressing food security and sustainable development challenges. As a modern agricultural technology, vertical farming plays an increasingly important role in urban agriculture because of its efficient use of space, resources, and energy. Vertical farming maximizes land use by cultivating crops in stacked layers, allowing large-scale agricultural production in a limited space, thus alleviating land resource shortages. By precisely controlling environmental factors, such as light, temperature, humidity, CO_2, and nutrient solutions, vertical farming provides crops with optimal growing conditions and increases yields while reducing reliance on fertilizers and pesticides and minimizing negative environmental impacts. Vertical farming has become an essential component of urban agriculture for food production. Owing to the efforts of researchers in related fields, vertical farming technology has made considerable progress in China. Optimizing the design and operation of vertical farms enables them to adapt better to urban environments and become sustainable pillars of the urban food supply chains. Despite progress, more research is needed to further improve vertical farming technology to meet the increasing demand for food in growing urban populations and achieve sustainable agricultural development. This article discusses the applications, technological advancements, and prospects of vertical farming for urban agriculture.

Keywords
artificial intelligence, closed environment, food security, hydroponics, plant factory, sustainable development

Significance of this study

What is already known on this subject?

- Plant factories, also known as vertical farms, have been recognized for their potential to revolutionize agriculture in urban settings. The concept involves growing plants indoors in controlled environments using artificial lighting, temperature regulation, and hydroponic or aeroponic systems.

What are the new findings?

- New findings in this field continually emerge, focusing on refining techniques to optimize plant growth, energy efficiency, and resource utilization. Research is also exploring the integration of automation and artificial intelligence to enhance productivity and reduce labor costs.

What is the expected impact on horticulture?

- Vertical farming can potentially increase food security in urban areas by providing locally grown fresh produce, reduce transportation costs and carbon emissions associated with food distribution, and offer a sustainable solution to global food demand challenges. Additionally, the controlled environment allows for the cultivation of high-value crops and medicinal plants, expanding the scope of horticultural practices.

Introduction

Vertical farming is a production model that uses indoor environmental control technology to grow crops in a closed environment (Kozai et al., 2019; Ji et al., 2023). It usually adopts a stacked planting architecture, utilizes artificial light sources (Kaiser et al., 2024), and tightly controls temperature, humidity, CO_2 concentration, nutrient solution flow (Baiyin et al., 2024), and other parameters to improve crop yield and quality (Shamshiri et al., 2018). With the acceleration of global urbanization and increasing scarcity of agricultural resources, traditional agricultural models face many challenges, such as limited land, scarce water resources, and climate change (Maja and Ayano, 2021). Vertical farming has high development potential and far-reaching impact on the global agricultural industry (Giller et al., 2021). In the current context of global land resource scarcity, accelerated urbanization, and climate change, vertical farming is drawing increasing attention and investment as a sustainable and efficient agricultural model (Van Delden et al., 2021).

Vertical farming is widely applied in urban environments and has demonstrated advantages in addressing challenges faced by traditional agriculture (Specht et al., 2014). First, vertical farming offers a solution for growing food in limited space (Kalantari et al., 2018). By utilizing multilayered planting structures, vertical farming transforms land surfaces into stacked growing spaces, thereby increasing land-utilization efficiency (Al-Kodmany, 2018). Second, vertical farming used advanced technology and intelligent systems for environmental control to regulate factors, such as light, temperature, humidity, and CO_2 concentration, and provides optimal conditions for plant growth. This precise environmental control helps increase crop yield and quality and reduces the demand for fertilizers and pesticides, thus lowering the negative impact of crop cultivation on the environment. Thus, vertical farming can achieve higher yields than traditional farmland exploitation, providing city residents with more fresh agricultural products.

Consumers are increasingly in pursuit of organic, pollution-free, and sustainable food, and vertical farming can bet-

ter meet these demands by providing healthy and safe food (Avgoustaki and Xydis, 2020a). By building vertical farming in urban areas, agricultural products can be grown closer to consumers, providing fresher and safer agricultural products and ensuring the safety and quality of food.

From an international perspective, Japan has conducted a considerable amount of research into vertical farming (Al-Kodmany, 2018). The large-scale application of vertical farming for growing vegetables in Japan has become an international model, with many countries following suit (Ampim et al., 2022). Other developed countries, such as the United States (Van Gerrewey et al., 2021), the Netherlands (Blom et al., 2022), and Singapore (Jaeger et al., 2023), are actively promoting and applying vertical farming technologies. In China, several major cities, such as Beijing, Shanghai, Guangzhou, Shenzhen, and Chengdu, have successfully built vertical farms to meet the demands of urban residents for high-quality agricultural products (Xu et al., 2021).

Vertical farming represents a modern form of agriculture that is expected to play an increasingly important role in food production (Hati and Singh, 2021) given its efficient land utilization, sustainable production methods, and alignment with consumer demands. Applying vertical farming technologies globally may provide new solutions to address global food security, alleviate urban land resource constraints, and promote sustainable agricultural development (De Bon et al., 2010).

Applications of vertical farming in urban agriculture

Food safety assurance

As an advanced indoor agricultural system, vertical farming has extensive applications in urban agriculture and plays a crucial role in ensuring food safety (Gómez et al., 2019). Vertical farming adopts enclosed growing environments in which temperature, humidity, light, CO_2, and nutrient solutions (Baiyin et al., 2021) are tightly controlled. These conditions minimize the impact of external environmental pollution on agricultural products and thus enable the growth of pesticide-free, safe, and healthy agricultural products. Vertical farms are not affected by seasons and weather, providing a stable supply of agricultural products throughout the year, ensuring that urban residents always have access to fresh and high-quality agricultural products, reducing their dependence on imported food and improving food supply security. The use of intelligent management systems to achieve real-time monitoring, data recording, and traceability of agricultural products enhances consumer trust in product quality and safety. In addition, vertical farming efficiently utilizes land resources, saves water and energy, reduces the use of chemical pesticides and fertilizers, decreases the risk of environmental pollution, and promotes food safety.

Vertical farms are often located within or near urban areas, which reduces food transportation distance, allows agricultural products to reach consumers more quickly, lowers the risk of food contamination during transportation, and maintains food freshness and safety (Armanda et al., 2019). Owing to the high degree of automation in vertical farming, production efficiency and quality stability have improved, further ensuring food safety.

The flexibility and scalability built into the systems allows for adjustments and increased production capacity according to market demand (Avgoustaki and Xydis, 2020b). Through precise cultivation management and data analysis, vertical farms can efficiently utilize resources, minimize waste, and reduce environmental pollution. Furthermore, vertical farming can diversify agricultural production by cultivating vegetables and fruits, as well as various herbal plants and flowers, to meet the demand for different agricultural products.

To achieve efficient production management and enable decision support, vertical farming systems can be integrated with other technologies, such as the Internet of Things, artificial intelligence (AI), and big data analysis (Chang et al., 2022). Through real-time monitoring and data analysis, problems during cultivation can be promptly detected and solved, thereby improving production efficiency and product quality. Moreover, AI technology can be used for accurate predictions and optimization to maximize the yield and quality of agricultural products.

In summary, as an advanced indoor agricultural system, vertical farming has immense potential for use in urban agriculture. Through pollution-free growing environments, a stable year-round supply of products, traceability system assurance, reduced food transportation distances, flexibility, scalability, and integration with other technologies, vertical farming can provide urban residents with safe, fresh, and diverse agricultural products, promote sustainable agricultural development, and improve overall quality of life. With further technological advancements, vertical farming will continue to play an increasingly important role in ensuring food safety in urban agriculture.

Environmental protection

From the perspective of sustainability and carbon neutrality, vertical farming not only improves the output efficiency of urban agriculture but also effectively reduces the impact on the environment and natural resources, making urban agriculture more sustainable. Vertical farms utilize advanced irrigation systems to recycle water resources and reduce waste. Compared with traditional agricultural methods, they can save more than 70% of water, alleviating water shortages in urban areas (Wang et al., 2002). Closed production spaces can effectively prevent the occurrence of crop diseases and pests as well as decreasing the extent of environmental pollution and eliminating potential risks to human health from chemical pesticides. This ensures the quality and safety of crops while meeting modern society's demand for a healthy and sustainable environment (Koohafkan et al., 2012).

Regarding energy usage, vertical farms use more electricity energy than fossil energy. The use of LED lights not only provides stable lighting conditions and uniform light intensity but also relieves energy consumption pressure. Compared with the energy demands of traditional field planting methods (tractors and other agricultural machinery require the consumption of fossil fuels), vertical farms are more energy efficient, which can help alleviate energy shortage issues faced by urban areas. Furthermore, the natural circulation system formed by vertical farming maximizes the recycling of organic waste, effectively reduces the cost of organic waste disposal and its impact on the atmosphere, and helps the transition to carbon neutrality (Kozai and Niu, 2020).

Vertical farming improves land-use efficiency (Van Gerrewey et al., 2021) by maximizing planting space and arable area. This helps to achieve maximal use of land resources and effectively increases the yield of urban agriculture.

In summary, vertical farming has important application value and practical significance in urban agriculture.

Leveraging the various advantages of vertical farming to promote the development of sustainable, healthy, efficient, and sustainable urban agriculture is one of the important paths for future urban sustainable development.

Technological advances in vertical farming in the context of urban agriculture

Vertical farming represents a highly technology-intensive industry, with relatively high initial investment costs and operating energy consumption levels (Petrovics and Giezen, 2022). Countries worldwide have been investing in research to reduce energy consumption and enhance product quality in response to industry demands. Progress has been made, especially in areas such as plant light formulas, LED light source development, light–temperature coupled energy-saving environmental control, vegetable nutrition quality improvement, and AI-based management systems. These advances have continuously improved the production efficiency of vertical farming and provided strong support for the development of the industry (Merrill et al., 2016).

Breakthroughs in technology improvements for light and energy efficiency

With the advancement of semiconductors, the light efficiency of multi-color LED chips has been increasing (Mitchell and Sheibani, 2020). Research on the mechanisms of monochromatic spectra in plant photobiology and big data analysis of light formulas has led to breakthroughs in technology that improve the light efficiency of vertical farming LEDs (Goto, 2012). Based on the biological mechanism whereby the chlorophyll absorption peaks of plant bodies are mainly concentrated in the red and blue light bands, a plant light source dominated by red and blue LEDs has been developed, which reduces energy consumption (Arcel et al., 2021). Meanwhile, with the advancement of LED chip and packaging technology, the luminous efficiency of LEDs has been increasing year by year, from less than 1 μmol J^{-1} over 20 years ago to the current level of 4.1 μmol J^{-1} (Yoon and Choi, 2011). Through the study of monochromatic light effects on plant photosynthetic physiological mechanisms, optimized light formula parameters for different varieties and growth stages of crops have been determined, driving technological advances in energy-saving LED light sources for plant growth (Shimizu et al., 2011).

Through systematic research on the control parameters of light environment optimization targeting plant photosynthetic needs, breakthroughs in intelligent control technology for dynamic light environments throughout plant growth stages have been achieved (Akiyama and Kozai, 2016). The development of vertically moving LED light-source devices has led to the construction of dynamic systems based on changes in plant height. By researching plant photobiological mechanisms and applying lasers, breakthroughs have been made in new light sources and energy-saving light environment control technology for vertical farming, which has considerably reduced energy consumption (Song, 2016).

Advances in precision-control technology in vertical farming environments has led to a reduction in the energy consumption of air-conditioning systems. The use of outdoor natural cold sources and light–temperature-coupled energy-saving environment control technology utilized during night hours has reduced air conditioning energy consumption by 24.6–63.0% (Kikuchi et al., 2018). Breakthroughs in localized control technology for root zone microenvironments in the cultivation layers has greatly reduced the energy consumption (Tan et al., 2021) required for environmental control (Graamans et al., 2017). By improving light and energy efficiency, the overall energy consumption of vertical farming has been reduced by more than 56%, with the electricity consumption per kilogram of leafy vegetables falling below 7 kWh (Kwon et al., 2014). Additionally, by adopting low-cost clean energy and new energy technologies, further reductions in energy consumption and operational costs have been achieved, making vertical farms more commercially profitable (Huang et al., 2018).

Vertical space expansion and efficient resource utilization technologies

In recent years, the efficient utilization of land resources has received increasing attention, and countries worldwide are exploring the expansion of vertical spaces to improve land-use efficiency. The vertical farms developed by Osaka Prefecture University in Japan contain 18 cultivation layers (Gu et al., 2021); the vertical strawberry factory built in Essex, U.K., contains 17 cultivation layers; and the AeroFarms company in the United States has completed a mist cultivation vertical farm with 12 cultivation layers (Newton, 2020; Howitt and Rausser, 2022). In 2023, the Urban Agriculture Research Institute of the Chinese Academy of Agricultural Sciences completed the world's first vertical farm with 20 cultivation layers, using 16 robots and mechanical hands to assist operations, achieving unmanned production in vertical space and land-use efficiency exceeding 120 fields of cultivation. However, achieving uniformity in elements, such as airflow, temperature, humidity, and CO_2, in such vertical farms, as well as operation machinery, auxiliary robots, and automation equipment in ultra-high-rise spaces, will be the focus of future research (Zhang et al., 2023).

High-rise vertical agricultural systems have received increasing attention. Integration of vertical farming with multistory buildings to form vertical agricultural complexes was shown to reduce annual energy consumption by 12–51% (Ghazal et al., 2023). Moreover, this model of industrialized food production can contribute to improving urban environments and sustainable development. The Institute of Urban Agriculture of the Chinese Academy of Agricultural Sciences (IUA-CAAS) proposed a concept for a skyscraper crop factory that would integrate vertical farming with technologies, such as the Internet of Things, energy conservation, new energy utilization, resource circulation, and sustainable development (Zhang et al., 2023). This approach aims to save natural resources, such as land, stabilize the supply of staple crops, and mitigate food shortages (Figure 1).

Mechanical and automation technologies

Labor costs account for approximately 25% of the total cost of vertical farming (Zaręba et al., 2021). These costs can be reduced by increasing mechanization and automation. By applying intelligent biological and environmental sensors, decision-making models, and automated control technology, real-time dynamic monitoring of the vertical farming environment, including nutrient and crop physiological information, and multivariable coordinated optimization can be achieved. The agronomic processes involved in vertical farming, from sowing and transplanting to harvesting, can be mechanized. Manual labor can be replaced by equipment, including robots, for mechanized sowing, germination, seedling raising, transplantation, interplanting, harvesting, and packaging. Improved mechanization and automation should greatly increase productivity and reduce labor costs (Butturini and Marcelis, 2020).



Figure 1. Mechanical automation multi-layer vertical farming in the IUA-CAAS.

The development of intelligent control technology can also help improve the efficiency of vertical farming. By applying technologies, such as computer vision analysis, machine learning, spectral analysis, intelligent sensors, big data, model prediction, and blockchain, vertical farming production efficiency, product quality, and traceability can be improved. Such advancements will establish a solid technical foundation for the unmanned operation of vertical farms (Wang et al., 2021).

Combination of vertical farming and AI technologies

The application of AI technologies in vertical farming has many advantages. AI systems can also help monitor and regulate plant growth, leading to increased yield, better quality, and higher sustainability of crops. Sensor networks can monitor parameters, such as the temperature, humidity, light intensity, and CO_2 concentration, in real time and transmit these data to an AI system, which would, in turn, automatically control lighting, ventilation, irrigation, and other aspects of the environment to ensure that crops grow under suitable environmental conditions (Chang et al., 2021). For example, upon detection of high temperature, the climate control system would automatically adjust the operation of the ventilation system to lower the temperature. When there is insufficient light, AI could adjust the brightness and timing of LEDs to provide sufficient light intensity (Tian et al., 2022). Such intelligent control systems can provide crops with optimal growth conditions that are not affected by external environmental factors.

Regarding decision optimization, AI can learn from historical data through machine learning algorithms and big data analysis to predict future crop growth conditions and market demand, thereby helping agricultural producers optimize production plans (Hyunjin and Sainan, 2021). For example, based on the market demand and climatic conditions, AI can help determine when to plant, how to fertilize, when to harvest, and how to maximize production efficiency and profits. In addition, by analyzing the growth and needs of each plant, AI can provide customized growth plans for each plant, including lighting, water, and nutrient supply. This will optimize plant growth and improve crop adaptability and yield (Baek et al., 2023).

AI can facilitate automated crop harvesting and quality inspection to increase harvesting efficiency and reduce labor costs. AI systems can identify mature fruits through image recognition technology and guide robotic arms to perform precise harvesting actions, ensuring high-quality harvesting results (Rizkiana et al., 2021). Simultaneously, through data analysis and AI algorithms, quality assessment and grading of harvested crops can be conducted to improve product quality and market competitiveness. In addition, AI can help optimize energy-utilization efficiency. Through real-time monitoring of the use of energy and considering the growth needs of crops, AI systems can adjust lighting and temperature parameters to minimize energy consumption, achieving a sustainable, low-carbon production model. The combination of vertical farming and AI technology brings many benefits to agricultural production, including improved production efficiency, optimized decision-making, intelligent management, and automated harvesting. With the continuous advancement and application of AI, we expect to see more innovation that would drive agricultural industry toward intelligent and sustainable development (Hu and You, 2024).

Future prospects

Traditional agricultural models are increasingly facing challenges associated with the continuous acceleration of urbanization and sustained population expansion. Vertical farming and urban agriculture have emerged as new agricultural development models. Vertical farms utilize advanced

indoor agricultural technologies to completely control the planting environment within enclosed spaces. Through the use of AI, automated systems, LED lighting, and other cutting-edge technologies, the precise control of conditions for crop growth, including lighting, temperature, humidity, and CO_2 concentration, can be achieved, which would maximize crop yield and quality. Compared with traditional outdoor farming approaches, vertical farming has distinct advantages in resource utilization efficiency and environmental protection, such as water conservation, land preservation, pesticide-free cultivation, and absence of seasonal limitations, thus meeting the urgent need for sustainable development.

With ongoing technological development and innovation, the application of more advanced environmental control technologies is expected in the future. For example, the use of big data, the Internet of Things, machine learning, and other technological innovations can achieve more precise management and real-time monitoring of plant growth environments, further enhancing crop production efficiency and quality. More efficient energy utilization will become a crucial direction for the future development of vertical farming. In addition to promoting the use of renewable energy sources, such as solar and wind power, the exploration of new energy sources, such as biomass and geothermal energy, can reduce running costs and enhance economic benefits and sustainability.

More diverse crop planting approaches should be explored, including the production of different types of vegetables, fruits, and herbs to cater to consumers' demand for diversified, healthy, and safe food. With improvements in living standards and increasing concern for food quality and safety, vertical farming will become a hot spot for investment in the future. Such farms will provide urban residents with a convenient, safe, and sustainable supply of agricultural products. In summary, vertical farming has broad prospects in promoting the sustainable development of urban agriculture.

Conclusion

Vertical farming is an innovative agricultural production model that has demonstrated advantages for sustainably developing urban agriculture and addressing global food security. The active contribution of researchers to this field has laid a solid foundation for the development of vertical farming and established a cornerstone for the sustainable development of urban agriculture. We look forward to the widespread application of vertical farming in urban areas in the near future to provide a safer, healthier, and more sustainable method of food production.

Conflict of interest

The authors declare no conflicts of interest.

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