Technological Innovation and Significance of Vertical Farming System in High-Density Urban Areas

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Abstract. Recently, the issue of sustainability of food supply has arisen in some of the high-density cities. To meet the growing demand for food, a solution has been proposed which could be the development of urban vertical farms. Although many practical examples exist, their comprehensive analyses and comparisons still need to be developed more. Therefore, this paper provides an in-depth study of technological innovations in urban vertical farming systems in high-density cities. By selecting some critical cases, such as The Plant in Chicago, Sky Greens in Singapore， Aero Farms in New Jersey, and Sunqiao Urban Agriculture Zone in Shanghai, and explaining their sustainable and innovative applications, the article assesses the strengths and limitations of these developments. In addition, the contribution of urban vertical farming at the individual, city, and natural environment levels is discussed, and it is concluded that the combination of hydroponics and vertical farming is an effective solution to the challenges of urban agriculture. Overall, this study explores the solutions offered by vertical farming in increasing food production, maintaining high quality and safety, and promoting sustainable urban agriculture.

1 Introduction

In the current era, with rapid economic development and steady population growth, especially in developed countries, high-density urbanization is often accompanied by expanding industrial and commercial land use, resulting in a gradual reduction of agricultural land use. Climate warming is widely observed globally, which has threatened the environmental, natural, and human systems in urban areas regarding food security [1]. Dependence on food supplies from the rural hinterland is gradually reaching the limits of sustainability based on the emergence of compound weather extremes2. However, as populations continue to grow, the high demand for urban living standards is forcing a re-examination of urban design solutions, which may be even more threatening in the case of high-density cities such as Hong Kong. It is a high-density city in Asia that faces challenges in its local urban food supply. In Hong Kong, the energy value of imported food reaches a staggering 6.06 x 10^25 SEJ, towering 2-3 orders of magnitude above that of other urban areas 4. Primarily reliant on

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imported vegetables, Hong Kong's food supply was significantly affected during the 2008 global food crisis. This vulnerability stemmed mainly from its reliance on foreign food sources and relatively compact market size [5]. This highlights the vulnerability of food supply and the high dependence on external factors in high-density cities, further emphasizing the need for sustainable urban agriculture and food security.

Among the many solutions, vertical urban agriculture design is considered a green building solution 6. This design solution promotes sustainable development by guaranteeing high yields while occupying a small footprint and enabling environmental protection and resource conservation 7. Although there are some areas for improvement in analytical summaries of current research practices. This article aims to explain the technological applications behind urban vertical farming systems within densely populated cities. An exploration of the innovative and sustainable practices employed in high-density cities, as outlined by [8]Lee et al. (2017), will be a focal point. Subsequently, a thorough evaluation of the merits and constraints inherent in these groundbreaking developments will be provided. The current practical and research-derived new approach is the design and development of vertical farming 6. Although vertical farming is a relatively new idea, vertical farming is an agricultural technology method for large-scale food production in high-rise buildings. This technology relies on controlling environmental conditions and nutrient solutions to accelerate crop growth and enable planned production using advanced greenhouse technologies and methods [9]. However, the implementation of vertical farming still needs several technical and practical application limitations and challenges. Such farmers are expected to cultivate and produce various crops in regions such as China, the United States, and Singapore 10. The following section will detail the most compelling examples of vertical farms in various countries worldwide and assess the feasibility of the diverse types and technologies of vertical farming in different environments.

2 Related Cases

This study will introduce people who will gain insight into applying vertical farming systems globally. Urban vertical farming systems have recently been effectively deployed in diverse countries and regions worldwide. This showcases the systems' flexibility to adapt to local environments while preserving common characteristics that are universally applicable.

In Fig. 1, on the South Side of Chicago, USA, The Plant is becoming a community of innovative businesses focused on reducing food waste. Fig. 1 shows that The Plant in Chicago goes beyond a farming facility that asserts the city can be transformed into areas of environmental and farming gains in the future. At the heart of the facility is the non-profit organization Plant Chicago, which promotes the sustainable management of food, energy, water, and waste in the city through workshops, the promotion of circular economy principles and systems thinking, and multiple research and development projects (in Fig. 1, e.g. aquaponics, fermentation, mushroom labs, algae farming, composting, agriculture, etc.) 11. To achieve its social mission, the Chicago plant organizes regular tours of the facility for educational groups and the general public. It opens farmers' markets throughout the year to showcase products produced by the plant and specialties from the surrounding community 12. Additionally, they have attracted several local and international interns who participate in projects researching the Chicago plant and other tenants in the building, expanding their knowledge and profoundly impacting the community [13].

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Fig. 1. THE PLANT CHICAGO Source: https://chicagodetours.com/the-plant-chicago/

In Fig. 2, also located in the United States, Aero Farms in New Jersey is one of the largest indoor vertical farms in the world, located in a high-density urban area of a developed country and occupying approximately 70,000 sq. ft. Aero Farms grows more than 250 different crops. It produces more than two million tonnes of leafy vegetables annually. Gibson mentioned in 2018 that the farm utilizes modular construction and cutting-edge technology, including LED light sources, mist cultivation, and environmental control systems, as reflected in Fig. 2. This scientific approach to farming allows plants to be grown without soil, sunlight, or pesticides and drastically reduces the growing cycle. The technology can harvest approximately 700 fruits and vegetables in as little as 10 to 14 days, which is 390 times more productive than traditional agriculture. AeroFarms epitomizes a remarkable rise to the field of technology of indoor vertical farming appearing amongst the largest equipment of its kind. [14].

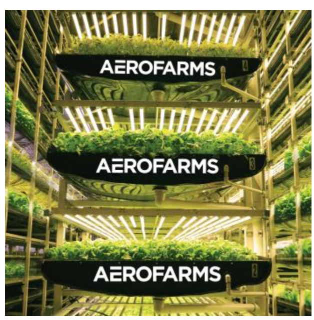

Fig. 2. Aero Farms Source: https://www.aerofarms.com/aerofarms-goose-island-partnership/

In Fig. 3, the Singaporean company Sky Greens has adopted the application of multi-level troughs and gravity-assisted rotary growing systems to reduce supplemental lighting needs and overall energy consumption 14. Fig. 3 illustrates that in this system, crop selection is limited by the space available between each level, with shorter crops able to accommodate more levels and increase yields per unit height. As a result, more minor crops, such as micro herbs and spinach, can also benefit from this type of vertical farming for rapid growth 15. Unlike other vertical farms, in Fig. 3, the Sky Greens' greenhouses are surrounded by clear glass and use solar energy and a pioneering hydro-hydraulic drive system called "A-Go-Gro" to ensure the crops receive plenty of light 16. Maclean (2020) observes that vegetables from Sky Greens are cultivated at locations proximal to consumers and undergo daily harvesting and packaging on the premises. These vegetables are transported in vacuum-sealed cold chain trucks to minimize air exposure and maintain freshness. Before transportation, they are pre-cooled and stored, effectively reducing handling and the need for storage space. Inventorying crops, which have high relevance to its vertical systems, is an example of where Sky Greens apply vertical farming technologies to secure food and sustainability in urban areas, thus solving food shortage [15].

Fig. 3. Sky Greens Source: https://www.skygreens.com/

A notable recent development in urban vertical farming design is the Sunqiao Urban Agriculture Zone in Shanghai, China. This zone integrates vertical farming techniques with research and community engagement, utilizing hydroponic and aquatic systems. Its goal is to foster a model of hyper-local consumption, allowing residents to purchase and consume produce directly from their buildings, thereby addressing food security, enhancing local food production, and contributing to the sustainability of urban areas. These instances showcase varied methods of vertical agriculture, spanning from commercial ventures to educational and community-centric initiatives. The emphasis is on integrating agriculture into urban settings as a solution to increasing food demands, environmental concerns, and the aspiration for sustainable urban life 17.

Standard features include a commitment to sustainable urban management of food, energy, water, and waste and adopting circular economy concepts and systemic thinking in advancing sustainable vertical agriculture via research and development projects and public outreach. The disparities and challenges include the focus of Chicago's The Plant on a collective of innovative businesses 13, the large-scale indoor vertical farms of New Jersey's Aero Farms [18](Gibson, 2018), the distinctive trough and gravity-assisted rotation system utilized by Singapore's Sky Greens 15 and Sunqiao Urban Agriculture Zone emphasizes hyper-local consumption and its combination of vertical farming with research activities 17. Shortcomings include the cost of technology, energy consumption, and complexity of facilities, which are challenges that need to be addressed in the popularisation of vertical farming.

3 Methodology

The research process of this article is shown in Fig. 4. Firstly, in the recent study, a comprehensive review of previous academic and scientific papers on vertical farming is carried out, with the main research question being: What are the advantages and limitations of these papers on vertical farming? In the first step of the research, relevant case studies were conducted. Next, as in Fig. 4, in the second phase, a comparative analysis of the feasibility and advantages of urban vertical farming (hydroponics) system design and the application of technological systems in the design of urban vertical farming is carried out. Finally, Fig. 4 proposes that conclusions are drawn on the future developments and challenges facing the design of urban vertical farming. Relevant information is found by searching for titles, abstracts, and keywords for "vertical farming in urban areas, high-density areas, and food security. Literature is selected from different sources, including journals, academic papers, reports, books, and conference papers from 2008 to 2023, and the collected literature is reviewed, analyzed, and compared to understand how vertical farming affects food security and the practical application of vertical farming in high population density areas.

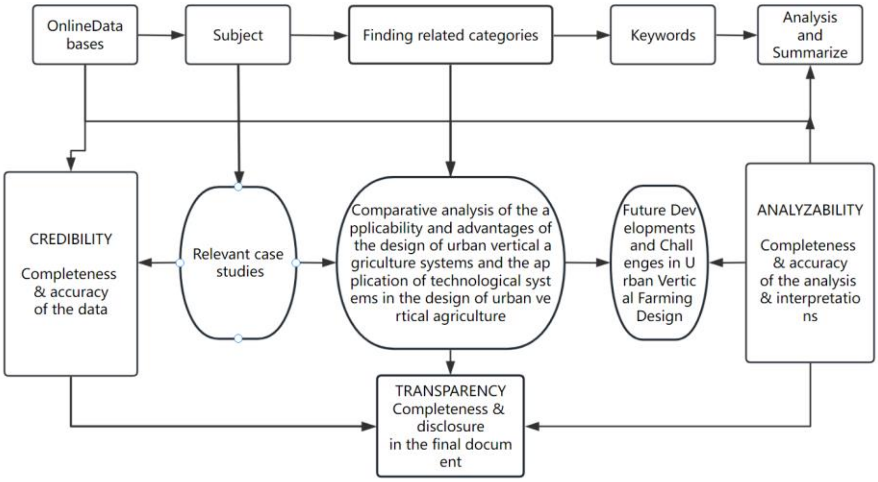

Fig. 4. Research process

4 Comparative Analysis

4.1 Applicability and Advantages of Urban Vertical Farming (Hydroponics)

To solve the above problems of reduced agricultural land, the emergence of extreme weather, and food supply dependence brought about by urbanization, this section presents the applicability of vertical agriculture and hydroponics as well as an analysis of their practical application. Hydroponics takes up only a fraction of the space required for conventional agriculture, uses 90 percent less water, and allows for year-round harvesting of virtually organic produce 19. In the case study mentioned above, AeroFarms built a proprietary, state-of-the-art indoor growing system with precise controls that give their plants unrivaled performance. Goose Island UK and AeroFarms unveil Hail Hydro - a brand-new session IPA made from groundbreaking hydroponic hops grown indoors by AeroFarms. The 4.7% hazy session IPA is made from hydroponic hops grown at AeroFarms [20]. Another example comes from the Sunqiao Urban Agriculture Zone in Shanghai, China, which meets the dietary needs of Shanghai residents for green leafy vegetables through efficient urban hydroponics and aquatic ecosystems. Fig. 5 shows that these leafy greens can thrive without much additional care in their most basic configuration, making them ideal for hydroponic and aquatic growing systems. Due to their fast growth rate and lightweight, these two attributes make them a cost-effective option 21. As in Fig. 5, in contrast to traditional soil-based agriculture, hydroponics does not require soil to cultivate crops. In this technique, plants are grown on natural or artificial substrates, and their roots quickly absorb the nutrients prepared in the solution.

Thus, developing hydroponics is undoubtedly beneficial for vertical farming with a limited land area. Fig. 5 displays this method solves the problem of soil degradation and provides a local food source in cities where space for traditional agriculture is limited 9. Hydroponics, which is showed in Fig. 5, involves growing plants in a nutrient-rich water-based solution and is particularly effective in vertical agriculture due to limited land area in urban environments. This method minimizes water use and is considered sustainable, mainly because it can produce fresh food for urban populations throughout the year 22.

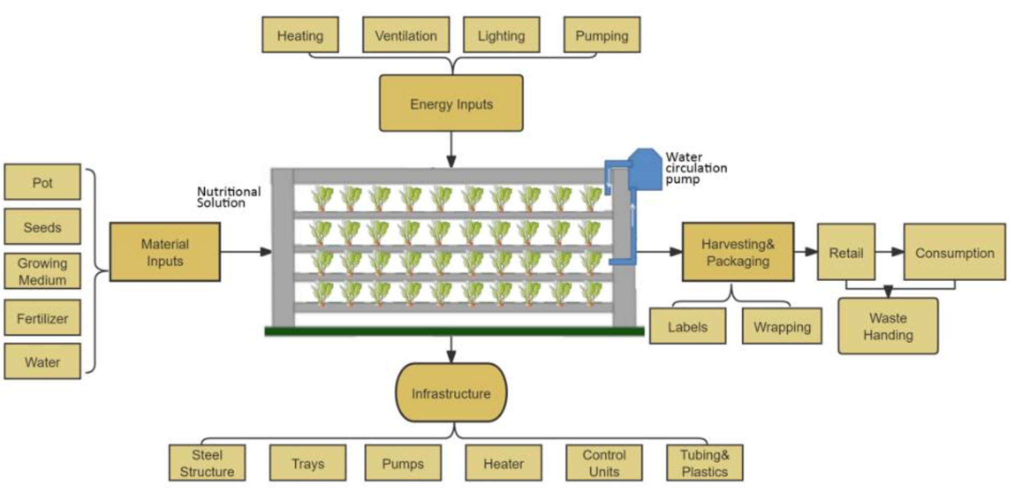

Fig. 5. System boundaries of the study (the dashed line represents the system boundaries)

4.2 Application of technological systems in the design of urban vertical agriculture

As an innovative agricultural model, the urban vertical farming system has some innovative integration of technological systems. In Fig. 6, the use of solar energy in the application of vertical farming reduces the distance vegetables have to be transported. It reduces the emissions associated with traditional agricultural methods, which fits in with the goal of vertical farming - to achieve environmental sustainability. Among other things, to ensure optimal growing conditions, Fig. 6 shows the environmental control system works by regulating temperature, humidity, light, and CO2 levels. An integral component of this system is the utilization of rainwater collectors, which contribute significantly to the purification and recycling of irrigation water. This innovative approach not only ensures sustainable water resource management but also exemplifies a strategic commitment to environmental conservation, as Fig. 6 illustrates. Moreover, the Urban Vertical Farming System integrates a compost recycling station with renewable cultivation beds, augmenting sustainability 23.

This urban vertical farming setup can be envisioned as an innovative production hub, offering elements absent in conventional models - vertical spatial expansion, ecological education, a robust self-sustaining food supply chain, and sustainable job prospects for the community [24]. Fig. 6, also envisages that every fifth vertical skyscraper-like structure forms a productive community unit. These encompass a central skyscraper functioning as a multi-purpose facility, including sales spaces (like farmers' markets, canning, and floral arrangement areas), marketing modules, signage modules, and cultivation modules. In contrast, the other four skyscrapers are predominantly used for cultivation 25. Technological innovations in urban vertical farming systems are vital in achieving environmental sustainability and ensuring food security. Innovative elements such as applying solar energy, rainwater harvesting systems, and recycled composting facilities increase resource efficiency and mitigate adverse environmental impacts.

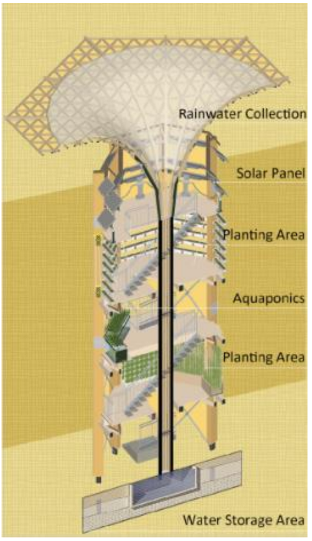

Fig. 6. Conceptual design of urban farming inside the high-density areas of cities.

4.3 Current status and challenges and prospects of urban vertical farming design

According to the previous analyses of the application of technological systems in the design of urban vertical agriculture and the findings of many scientists, urban vertical agriculture can be further developed in several ways to promote the individual and the urban society. Therefore, the section assesses the contribution of urban vertical agriculture system design to individuals, cities, and natural environments to discuss the main prospects and challenges for enhancing urban vertical agriculture systems.

For individuals, vertical agriculture at the community level increases the diversity of job opportunities, enhances residents' quality of life, and effectively raises economic income per capita [26]. In addition, the advanced technological systems and efficient logistics chains used in vertical agriculture can enable low-cost vegetable sales, reducing residents' expenditures on vegetable purchases. Regarding social and urban development, vertical farming significantly improves land use efficiency and saves more space for urban expansion. [26]Thomaier (2015) states that vertical farming uses only 17 percent of the land required for traditional farms, providing an ideal solution for high-density cities. Vertical farms allow for upward expansion from existing buildings, reusing abandoned warehouses and buildings, which is more feasible than expanding outward. According to 26Thomaier (2015), vertical farming promotes crop growth through its sophisticated technological systems that are independent of the natural environment in controlling production conditions such as light, temperature, and humidity, significantly increasing productivity and reducing the loss of the annual harvest by a significant amount compared to conventional farms. This ensures that city dwellers have daily access to the vegetables they need and reduces wastage of resources. Vertical farms often sell food locally, reducing emissions from transport and shortening the time it takes to get products from production to consumers. As [27]Cabannes and Marocchino (2018) point out, food can be delivered in a matter of hours rather than spoilage that can take days in transit. Vertical farming has contributed significantly to urban agricultural development and socio-economic incomes due to its superior yields and quick distribution. In addition, as described by 28Bob (2008), vertical farming also functions as a production and education center designed to encourage community feedback, facilitate collaboration with communities and schools, and provide opportunities to educate children on how to grow vegetables and develop effective work habits.

Urban vertical farming significantly contributes to modern social and economic progress in various aspects, such as efficient land utilization, advancement in agriculture, and enhancement of community services.

From the standpoint of environmental protection, this form of agriculture effectively lessens the use of numerous resources. For instance, the issue of water loss due to inefficient irrigation methods is substantially alleviated with vertical farming practices. Its streamlined supply network greatly diminishes carbon footprints compared to conventional farming and transportation methods. [29]Hindman (2018) notes that vertical agriculture upholds its eco-friendly nature by reutilizing and recycling resources. This includes collecting rainwater for meticulous irrigation, employing solar power for lighting and energy, and recycling food scraps or agricultural produce into compost, demonstrating the practical application of sustainable development.

The government's diversity and adaptability in land use allow for flexibility in adapting to changing landscapes and needs. However, there are limitations to vertical farming. Notably, not all crops are suitable for growing in vertical farms. For example, a crop like potatoes may need to bring in more profit to justify indoor growing. For crops that dominate the Western diet, such as wheat and rice, vertical farms are impractical due to their space and weight requirements.

In addition, the higher construction and operational costs required for advanced technological systems pose significant challenges in the early stages of vertical farming development30. At the same time, there are no laws and regulations for vertical farms, which may make it difficult to obtain loan financing and insurance.

Undeniably, vertical farming brings multiple advantages regarding individual, social, and urban development, including advanced technological systems and efficient supply chains that reduce resource wastage. In contrast, vertical farming serves as a center for community development and education, providing children with learning opportunities in vegetable farming. However, vertical farming also needs more crop choices, high construction costs, and inadequate regulations. Future development will require technological innovation, regulatory development, research and education, and support for sustainable practices to facilitate its contribution to urban agriculture and socio-economics.

5 Conclusion

By analyzing a series of case studies, this study concludes that in recent years, urban vertical farming design has played an essential role in high-density urban development as an effective space-using cropping model. The article describes the vertical farming designs in cities such as New Jersey, USA, Chicago, Singapore, and Shanghai, China, showing their characteristics, design structures, and outcomes. In these areas, the demand for food is rapidly increasing due to high population densities, and traditional agriculture struggles to meet this demand 26. Vertical agricultural design, therefore, offers the feasibility of local food production in urban areas.

Ultimately, a comprehensive assessment of the contributions of urban vertical agricultural design was conducted, including improved land use, increased crop yields, improved economic income and employment opportunities, and conservation and reuse of resources. These assessments cover different dimensions, from the individual to society and urban development to the natural environment. 21st-century urbanism challenges the conditions of our cities, and vertical farming is seen as a solution to these challenges. By combining these objectives, this approach contributes to global food security and ensures sustainable standards of environmental compatibility in line with public acceptance [31]. While the current assessment highlights the multifaceted benefits of urban vertical agricultural design, ongoing research is essential to address existing gaps and propel the field forward. Future scholars are encouraged to delve deeper, gathering more diverse data and conducting sophisticated analyses, with the aspiration of achieving more comprehensive applicable insights for the sustainable evolution of urban farming.

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