



CONCEPTUAL ANALYSIS OF THE APPLICATION OF VERTICAL FARMING SYSTEMS TO SUPPORT URBAN FOOD SECURITY

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ABSTRACT

Problem: The rapid urbanization and limited agricultural land in urban areas pose significant challenges to food security, particularly in densely populated countries like Indonesia. As urban populations grow, there is an increasing need for innovative solutions to ensure a sustainable, efficient food supply. **Objective:** This study aims to analyze the potential, challenges, and implementation strategies of vertical farming systems to support urban food security in Indonesia. **Method:** A qualitative research approach was used, supported by a comprehensive literature review of scientific publications, technical reports, and best practices in vertical farming from various countries. The analysis covers the technological, economic, social, and environmental aspects of vertical farming systems. **Results:** The study finds that vertical farming can achieve 10 to 20 times higher productivity per unit area than conventional farming, with water-use efficiency of up to 95% and a reduction in the carbon footprint of food transportation by up to 80%. It enables year-round fresh food production with a 30-50% faster harvest time. However, challenges include high initial investments, energy costs, and limitations on the types of crops that can be cultivated economically. Key implementation strategies include developing sustainable business models, integrating renewable energy technologies, offering government incentives, providing human resource training, and fostering collaboration between the government, private sector, and academia.

Keywords : vertical farming, food security, urban, hydroponics, agricultural technology, sustainability

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1. INTRODUCTION

Rapid urban population growth has created enormous pressure on the global food system. According to a report published in Tempo.co on February 8, 2024, "The urbanization rate in Indonesia reached 57.3 percent in 2023, with a projection to increase to 66.6 percent in 2035. This increase in the urban population poses a serious challenge in providing adequate food. At the same time, productive agricultural land continues to shrink due to conversion

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for infrastructure and settlement development" (Tempo.co, 2024). This condition underscores the urgency of developing alternative food production systems that can operate efficiently within the limitations of urban space.

Vertical farming is an innovative concept that involves food production in multi-level structures using modern cultivation technologies such as hydroponics, aeroponics, or aquaponics. This system enables the production of food crops in a controlled environment within multi-story buildings, optimizing the use of underutilized vertical space in urban areas. This approach offers several potential advantages, including much higher productivity per unit area, efficient use of water and nutrients, year-round production independent of weather, and reduced distance between production sites and consumers, which can minimize transportation-related carbon emissions.

Dickson Despommier of Columbia University first popularized the concept of vertical farming in the early 2000s in response to projections of global population growth and increasing food demand. Since then, this technology has developed rapidly, with commercial implementation in countries such as Singapore, Japan, the United States, and Europe. Singapore, which faces severe constraints on agricultural land, has made vertical farming an integral part of its national food security strategy, aiming to produce 30 percent of domestic food needs by 2030 through urban farming technology.

In Indonesia, although the concept of vertical farming is still relatively new and has not been widely implemented, there is significant potential for its development, given the rapid rate of urbanization and the increasingly serious problem of agricultural land conversion. Jakarta, Surabaya, Bandung, and other major cities face challenges in providing fresh food for their populations, with most vegetables and horticultural products having to be imported from buffer areas hundreds of kilometers away. This situation not only increases food costs but also reduces product freshness and increases the transportation-related carbon footprint.

This conceptual study is essential, given the limited comprehensive literature analyzing the potential and challenges of implementing vertical farming in the Indonesian context. Most research and implementation of vertical farming has been conducted in developed countries with socio-economic conditions, infrastructure, and policies that differ from those in Indonesia. Therefore, an in-depth analysis is needed to determine how vertical farming systems can be adapted and implemented effectively to support urban food security in Indonesia, while accounting for local conditions, available technologies, economic factors, and community readiness.

Based on this background, this study aims to: (1) analyze the concept and technology of vertical farming systems and their development at the global level, (2) evaluate the potential and advantages of vertical farming in the context of urban food security, (3) identify the challenges and obstacles to the implementation of vertical farming in Indonesia, (4) formulate strategies and policy recommendations for the development of vertical farming as part of a sustainable urban food security system. This study is expected to provide a conceptual and practical basis for policymakers, business actors, and academics in developing vertical farming systems in Indonesia.

2. LITERATURE REVIEW

Concept and History of Vertical Farming

Vertical farming is the practice of growing crops in stacked layers, often in controlled environments such as buildings, modified shipping containers, or other enclosed structures. This concept combines modern agricultural techniques with building architecture to create food production systems that are efficient in their use of space. Despommier (2020), in his revised book, explains that vertical farming is an evolution of protected agriculture practices that have existed since the era of traditional greenhouses, but with the application of much more sophisticated environmental control technology and a vertical orientation to maximize productivity per unit of floor space.

The history of modern vertical farming began in 1999 when Dickson Despommier taught a medical ecology course at Columbia University. Together with his students, he developed the concept of a multi-story agricultural building capable of producing food for thousands of people. Since the publication of his initial idea, vertical farming technology has advanced rapidly with the integration of energy-efficient LED lighting, artificial intelligence-based automation systems, Internet of Things sensors for real-time monitoring of plant conditions, and increasingly sophisticated soil-less cultivation techniques. Research by Kozai and Niu (2020) shows that advances in LED technology and precision climate control have reduced vertical farming's operational costs by up to 40 percent over the last decade.

The first commercial implementations of vertical farming were carried out by companies such as AeroFarms in New Jersey, Plenty in California, and Sky Greens in Singapore in the early 2010s. Sky Greens, founded in 2012, became the world's first commercial vertical farm to operate with a hydraulic-powered rotating system to optimize sunlight exposure. Meanwhile, AeroFarms developed a large-scale aeroponic system capable of producing up to 900 tons of green vegetables per year in a 6,500-square-meter facility. A case study by Martin and Molin (2021) on AeroFarms' operations shows that with precision environmental control technology, productivity can reach 390 times that of traditional field farming per unit area per year.

Technology in Vertical Farming Systems

Vertical farming relies on integrated technologies to create an optimal environment for plant growth. Soilless cultivation systems are a fundamental component, with three main approaches: hydroponics, which uses nutrient solutions in water; aeroponics, which sprays nutrient mist directly onto the roots of plants suspended in the air; and aquaponics, which integrates fish farming with plants in a symbiotic system. A comparative study by Graamans, Baeza, van den Dobbelen, Tsafaras, and Stanghellini (2020) shows that aeroponic systems have the highest water-use efficiency, with savings of up to 98 percent compared to conventional agriculture, while hydroponics offers the best balance between productivity and operational ease for commercial-scale implementation.

Artificial lighting is a crucial component in indoor vertical farming. LED technology has revolutionized vertical agriculture by providing a light spectrum tailored to each plant's growth phase. Modern LEDs can produce a combination of red, blue, and other spectrums that optimize photosynthesis with much higher energy efficiency than traditional lamps. A study by

Pattison, Tsao, Brainard, and Bugbee (2022) shows that the latest generation of horticultural LEDs has a photosynthetic efficiency of 2.7 micromoles per joule, nearly double that of previous-generation LEDs, which significantly reduces operational energy costs, the most significant component in the cost structure of vertical farming.

Environmental control and automation systems utilize Internet of Things sensors, artificial intelligence, and machine learning to optimize plant growth conditions. Parameters such as temperature, humidity, carbon dioxide concentration, pH, electrical conductivity of nutrient solutions, and light intensity are monitored in real time and automatically adjusted to maximize plant growth. Research by Shamshiri, Kalantari, Ting, Thorp, Hameed, Weltzien, Ahmad, and Shad (2020) developed a machine-learning-based predictive model that optimizes energy use by up to 35 percent while maintaining maximum productivity by predicting plant environmental requirements based on historical data and real-time conditions.

Urban Food Security and Vertical Farming

Food security is defined by the Food and Agriculture Organization (FAO) as a condition in which all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life. In an urban context, food security faces unique challenges, including high population density, reliance on long-distance food supply chains, vulnerability to distribution disruptions, and limited access to fresh, nutritious food for low-income communities. A study by Pulighe and Lupia (2020) identified that cities in developing countries face higher food security risks due to inadequate infrastructure, high import dependency, and food price volatility.

Vertical farming offers significant contributions to urban food security through various mechanisms. First, local production reduces dependence on long-distance food supply chains that are vulnerable to disruptions such as extreme weather, natural disasters, or logistical crises. Second, year-round production regardless of season increases food supply stability. Third, production locations close to consumers increase product freshness and nutritional value by minimizing the time between harvest and consumption. Research by Benke and Tomkins (2021) shows that green vegetables from vertical farming retain up to 40 percent more vitamin C than similar products transported over long distances due to minimal nutrient degradation.

From an environmental sustainability perspective, vertical farming helps reduce the ecological footprint of urban food systems. Highly efficient water use is a key advantage, with recirculation systems reducing water consumption by up to 95 percent compared to conventional farming. Eliminating pesticide use in controlled environments reduces environmental contamination and yields organic products free of chemical residues. A life cycle analysis study by Martin, Molin, Visser, Fan, Blasiak, and Östergren (2022) compared the carbon footprint of lettuce from urban vertical farming with that of conventional field farming transported 500 kilometers, finding that although vertical farming has higher energy consumption, the reduction in transportation emissions and agricultural input use resulted in an overall carbon footprint that was 30 percent lower.

3. THEORETICAL FRAMEWORK

This study is grounded in several key theories and concepts related to vertical farming and urban food security. Vertical farming is rooted in the theory of sustainable agricultural intensification, which emphasizes maximizing food production while minimizing environmental impact, particularly in urban environments where space and resources are limited. The study draws on systems theory to analyze the technological, economic, social, and environmental aspects of vertical farming, examining how these components interact to create a sustainable and efficient food production system. The diffusion of innovations theory is also applied to understand how vertical farming technology, an innovative solution, can be adopted in urban areas and its potential to reshape food security in Indonesia. Furthermore, the study draws on food security theory, particularly in the context of urbanization, to highlight the challenges and opportunities vertical farming offers for addressing urban food security. By applying these theoretical perspectives, the study aims to comprehensively evaluate vertical farming's role in ensuring a stable, sustainable food supply in urban areas, particularly in rapidly urbanizing regions such as Indonesia.



4. METHODOLOGY

Study Approach. This study uses a qualitative approach, with a systematic literature review and conceptual analysis, to explore the potential, challenges, and implementation strategies of vertical farming systems for supporting urban food security. A qualitative approach was chosen because the study's objective was to develop a deep and comprehensive understanding of a relatively new and complex phenomenon, for which empirical quantitative data in the Indonesian context remain limited. This method allows for the synthesis of information from various sources and perspectives to produce a holistic conceptual framework.

Data Sources and Information Collection. The primary data sources for this study were scientific publications from reputable international journals indexed in the Scopus and Web of Science databases, with a focus on the last five years to ensure relevance and recency. The literature search was conducted using structured keywords: vertical farming, urban agriculture,

food security, controlled environment agriculture, hydroponics, and combinations thereof. A total of 156 scientific articles were identified in the initial stage and filtered for relevance, resulting in 68 articles analyzed in depth. In addition to scientific publications, this study used technical reports from international organizations such as the FAO, vertical agriculture industry publications, commercial implementation case studies, and statistical data from Indonesian government agencies on urbanization and food security.

Data analysis was conducted using a thematic analysis approach, involving the identification, organization, and interpretation of themes in the collected data. The analysis process was carried out in five stages: (1) familiarization with the data through repeated Reading of the collected literature, (2) initial coding to identify important concepts and information, (3) grouping codes into broader themes, (4) reviewing and refining themes to ensure consistency and relevance, and (5) defining and naming the final themes that represent the main findings of the study. To increase the validity of the analysis, source triangulation was conducted by comparing information across various publication types and different geographical contexts.

5. RESULTS AND DISCUSSIONS

Potential and Advantages of Vertical Farming

A literature analysis identified several significant advantages of vertical farming systems, making them a potential solution for urban food security. The first and most prominent advantage is the extraordinarily high land productivity. With multi-level vertical planting, productivity per unit of floor area can increase 10 to 20 times compared to conventional horizontal farming. In fact, some studies report productivity factors of up to 390 times per unit area per year when considering much faster harvest cycles in a controlled environment. This is particularly relevant in an urban context where land prices are very high, and land availability is limited.

Table 1. Comparison of Vertical Farming Efficiency with Conventional Farming

Parameter	Conventional Agriculture	Vertical Farming
Productivity per m ² per year	1x (base)	10-20x
Water use efficiency	100	5% (95% savings)
Pesticide use	High	Zero
Harvest cycle (lettuce)	60-70 days	28-35 days
Weather dependence	High	None
Transport emissions	100% (long distance)	20% (urban locations)

Source: Compiled from various literature (Graamans et al., 2020; Kozai & Niu, 2020; Martin et al., 2022)

Water use efficiency is another significant advantage. The recirculation system in vertical farming allows water to be reused multiple times, with only a small portion absorbed by plants or evaporated. Research shows water savings of up to 95 percent compared to conventional agriculture. In an era of climate change with increasing water scarcity, this efficiency is particularly relevant, especially for urban areas that often face

pressure on water resources. In addition, precise nutrient control in hydroponic or aeroponic systems reduces nutrient waste and groundwater pollution, which often occur in conventional agriculture.

The third advantage is consistent product quality and reduced risk of crop failure. The controlled environment eliminates variability caused by weather, pests, and diseases. This results in consistent quality products throughout the year, facilitating production planning and meeting modern market standards that demand high consistency. Pesticide-free production also adds significant value, meeting consumer demand for organic and safe food. Market research shows that urban consumers are willing to pay a 20 to 40 percent premium for local, fresh, pesticide-free products, which can help the economic viability of vertical farming.

Challenges in Implementing Vertical Farming

Despite its many advantages, vertical farming faces substantial challenges that must be overcome to scale up. The biggest challenge is the very high initial capital investment. The construction of commercial-scale vertical farming facilities requires an investment of between US\$1,500 and US\$3,000 per square meter, which is much higher than conventional greenhouses, which cost between US\$200 and US\$500 per square meter. These costs include building structures, hydroponic or aeroponic systems, LED lighting, climate control and automation systems, and other supporting infrastructure. The high initial investment is a significant barrier for businesses, especially in developing countries such as Indonesia, where access to low-interest financing is still limited.

High energy consumption is the second crucial challenge. Artificial lighting, climate control, and circulation systems require substantial electrical energy. In a context where electricity is still predominantly derived from fossil fuels, high energy consumption can result in a significant carbon footprint, potentially negating the environmental benefits of reduced transportation and water efficiency. Studies show that energy costs can account for 25-30% of vertical farming's total operating costs. Dependence on electricity also makes the system vulnerable to power supply disruptions and energy price volatility. A potential solution is integration with renewable energy sources such as solar panels or wind turbines, but this adds complexity and investment costs.

The limitation of the types of crops that can be grown economically is the third challenge. Currently, vertical farming is most effective for high-value crops with fast harvest cycles, such as leafy greens, herbs, and some types of strawberries. Crops with high energy requirements for flowering and fruiting, or crops with long harvest periods, such as rice, corn, or fruit trees, are not yet economical to cultivate in vertical systems with current technology. This limits the contribution of vertical farming to food security, diversity, and calorie adequacy, as staple crops must still be produced through conventional agriculture.

In the Indonesian context, additional specific challenges include limited availability of technology and technical expertise. Key technological components, such as high-quality horticultural LEDs, precision sensors, and automated control systems, are still imported at high prices. The lack of trained technical personnel to operate complex vertical farming systems is

also an obstacle. In addition, market awareness and acceptance of vertical farming products still need to be developed, as Indonesian consumers are not yet thoroughly familiar with the concept and may require education on its advantages.

Implementation Strategies for the Indonesian Context

Based on an analysis of the potential and challenges, several implementation strategies are recommended to develop vertical farming in Indonesia. First, developing an appropriate and sustainable business model must be a priority. Business models can be adapted to the local context, ranging from large-scale commercial vertical farming to supply supermarkets and high-end restaurants, medium-scale vertical farming integrated with local communities or institutions such as universities and hospitals, to small-scale modular systems for micro-enterprises and households. Diversification of business models allows for broader market penetration and reduces risk.

Second, integration with renewable energy sources is crucial for long-term sustainability. Installing photovoltaic solar panels on the roofs of vertical farming facilities can reduce reliance on the grid and lower operating energy costs. Indonesia has enormous solar energy potential with an average solar radiation intensity of 4.8 kilowatt-hours per square meter per day. Although the initial investment for renewable energy systems is high, the return on investment period can be accelerated by government incentive schemes and the continuing decline in solar technology costs. Battery systems for energy storage must also be considered to ensure operational continuity.

Third, government policy support plays a crucial role in fostering a conducive ecosystem for vertical farming. Recommended policies include: fiscal incentives in the form of tax breaks or subsidies for investments in vertical farming technology, simplified licensing and regulations for urban farming businesses, research and development programs for adapting technology to local conditions, training and capacity building for human resources, and the integration of vertical farming into urban spatial planning. Singapore provides a successful example with its 30x30 program, which aims to achieve 30 percent local food production by 2030 through comprehensive support for urban agriculture, including vertical farming.

Fourth, multi-stakeholder collaboration between the government, private sector, academia, and communities needs to be facilitated. Universities and research institutions can play a role in developing technology suited to Indonesian conditions, testing optimal plant varieties for vertical systems, and training technical personnel. The private sector brings operational expertise and market access, while the government provides a regulatory framework and policy support. Local communities need to be involved to ensure social acceptability and inclusive benefits. Partnership models between vertical farming companies and traditional farmers can also be developed for knowledge and skills transfer.

Fifth, a phased approach and pilot projects need to be adopted to minimize risk and facilitate learning. Implementation can begin with small to medium-scale pilot projects in major cities such as Jakarta, Surabaya, and Bandung to test technical and economic viability in the local context. The results and lessons learned from pilot projects can be used to refine models and strategies before wider replication. A phased approach also allows for the

organic development of local supply chains for technology components and workforce capacity building.

Implications for Urban Food Security

The implementation of vertical farming has significant implications for various dimensions of urban food security. In terms of availability, vertical farming can increase the supply of fresh food, especially green vegetables and horticultural products in urban areas, reducing dependence on long-distance supplies that are vulnerable to disruption. Although vertical farming cannot wholly replace conventional farming across all types of commodities, its contribution to diversifying urban food sources remains important. Projections show that with optimal development, vertical farming could meet 10 to 15 percent of the fresh vegetable needs of large cities in the next two decades.

From an accessibility perspective, vertical farming can increase the availability of high-quality fresh food in previously underserved locations. The concept of food deserts, or urban areas with limited access to fresh and nutritious food, is a real problem in many large cities. Small- to medium-scale vertical farms strategically located across the city can improve access to fresh food for various segments of society. Inclusive business models, such as community cooperatives or partnership programs with local governments, can ensure that the benefits are enjoyed not only by the upper-middle class but also by low-income communities.

From a utilization perspective, pesticide-free vertical-farming products harvested at optimal ripeness have higher nutritional value than those transported over long distances. Better freshness also increases palatability, which can encourage higher consumption of vegetables and fruits among urban communities. The educational aspect is also important, as vertical farming facilities can serve as a means for urban communities, especially the younger generation, to learn about food production, nutrition, and environmental sustainability.

From a stability perspective, vertical farming offers resilience to various disruptions that can undermine food security. Production in a controlled environment is unaffected by extreme weather, floods, droughts, or the increasingly unpredictable effects of climate change. In the context of a pandemic or other crises that disrupt long-distance food supply chains, local production capacity through vertical farming can serve as a buffer, enhancing the overall resilience of the urban food system. Diversifying food sources by adding a component of local urban production reduces the systemic risk of dependence on a single or centralized source.

6. CONCLUSION

This conceptual study concludes that vertical farming systems have significant potential to contribute to urban food security in Indonesia through various mechanisms. Key advantages include extremely high land productivity, water use efficiency of up to 95 percent, elimination of pesticide use, year-round production independent of weather, and reduced food transportation emissions. In the context of increasing urbanization and pressure on productive agricultural land, vertical farming offers an innovative solution for producing fresh food locally in urban areas constrained by land. However, the implementation of vertical farming faces substantial challenges, including

very high initial capital investment, high energy consumption, limited economically viable crop types, and limited availability of technology and expertise in Indonesia.

To address these challenges, a strategic approach and multi-stakeholder support are essential. Developing appropriate and sustainable business models, integrating renewable energy sources, providing comprehensive government policy support, building human resource capacity, and fostering close collaboration among the government, private sector, academia, and the community are critical for successful implementation. Policy recommendations include offering fiscal incentives for vertical farming investments, developing research and development programs to adapt technology to local conditions, training skilled technical personnel, integrating vertical farming into urban spatial planning, and facilitating access to low-interest financing. A phased approach through pilot projects in major cities can minimize risks and facilitate learning before wider replication. Further research and development are needed to optimize vertical farming systems for the Indonesian context, including testing suitable local plant varieties, developing technologies with local components to reduce import dependency, analyzing economic feasibility across various operational scales, and conducting comprehensive social and environmental impact assessments. With a holistic approach and long-term commitment, vertical farming can become an integral part of transforming urban food systems toward greater sustainability and resilience.

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