AGRICULTURAL POWER JOURNAL (APJ)

Vol. 2 No. 3 (2025) 1 – 12 | ISSN: 3062-8563 (Media Online)

Adaptation of Verticulture Technology in Sustainable and Environmentally Friendly Horticultural Systems

Luh Kadek Pande Sri Astrini [1]*, Suluh Dewanto [2]

[1] Universitas Udayana

[2] Universitas Mulawarman

* Correspondence: kadeksriastrini@gmail.com

ABSTRACT

The increasing scarcity of agricultural land and the significant impacts of global climate change have created an urgent need for innovative cultivation methods, particularly in the horticulture sector. This study analyzes the adoption of verticulture technology within sustainable horticultural systems across major Indonesian production centers, including West Java, East Java, and North Sumatra. This study employs a descriptive quantitative approach using secondary data from the Central Statistics Agency (BPS), complemented by field surveys and semi-structured interviews with verticulture practitioners. Results indicate that verticulture enhances land-use efficiency by up to 85%, reduces water consumption by 60%, and decreases reliance on synthetic chemical fertilizers by 70%. The technology also contributes to production stability and local food security while maintaining economic viability, with an average return on investment achieved within 3.5 years. These findings support verticulture as a critical urban farming strategy that advances sustainable resource management, food resilience, and socio-economic benefits in Indonesia's urban and suburban contexts. Further research is recommended to develop inclusive business models and adapt verticulture practices to diverse socio-economic environments to support broader and more sustainable adoption.

Keywords: verticulture; sustainable horticulture; resource efficiency; food security; urban farming

Article Information

Received: July 19, 2025
Revised: August 16, 2025
Online: August 20, 2025

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1. Introduction

Innovative agricultural practices are urgently needed in the horticulture sector, which is increasingly vulnerable to environmental pressures, land scarcity, and climate change impacts [1]. The continuous conversion of fertile agricultural land across Southeast Asia to support urban expansion and infrastructure development has placed considerable pressure on conventional food production systems [2]. At the same time, intensifying climate variability—manifested through more frequent El Niño and La Niña events—poses serious risks to horticultural production, including unpredictable flooding, prolonged droughts, and the emergence of new pests and diseases [3].

In response to these interrelated challenges of land limitation, climate instability, and food security, Vertical Cultivation Technology (verticulture) has emerged as a promising strategy for space-efficient crop production [4]. Verticulture, which enables multi-tiered planting arrangements, was initially developed to optimize small residential areas [5]. However, it has since evolved into an integral component of commercial urban farming systems [6]. Its application now extends beyond household food provision to enhancing local food self-sufficiency, improving urban aesthetics, and supporting environmentally sustainable city development, in line with Sustainable Development Goal 11 (Sustainable Cities and Communities) [7].

National Context and Critical Literature Review

The adoption of verticulture is particularly relevant in the Indonesian context. Data from the Central Bureau of Statistics (BPS) indicate a consistent decline in rice field areas, especially on Java Island—the country's primary food production region—due to rapid land conversion between 2020 and 2022 [8]. Concurrently, population growth continues to drive increasing food demand, intensifying pressure on existing agricultural systems. Production statistics for major vegetable commodities in provinces such as West Java and East Java also reveal considerable fluctuations, underscoring the vulnerability of conventional horticultural production systems [9]. In this regard, verticulture offers a viable solution for decentralizing production, reducing dependence on open-field agriculture, and minimizing post-harvest and supply chain losses [10].

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From a sustainability perspective, verticulture is strongly associated with improved resource-use efficiency. Previous studies report that vertically arranged cultivation systems—particularly those integrated with drip irrigation, hydroponic, or aquaponic technologies—can improve water-use efficiency by up to 70% and land-use efficiency by up to 90% compared to conventional farming practices [11]. In addition, verticulture promotes the utilization of liquid organic fertilizers (LOF) and alternative growing media such as rice husk charcoal and cocopeat, supporting environmentally sound agricultural practices and reducing reliance on synthetic inputs [12]. These characteristics position verticulture as a strategic approach for achieving Sustainable Development Goals related to responsible production and consumption and environmental sustainability [13].

Research Gaps and Main Objectives

Despite numerous small-scale case studies documenting the agronomic and ecological benefits of verticulture [14], significant research gaps remain regarding the system's feasibility on a larger and economically sustainable scale.

- Economic Feasibility Controversy: High initial capital expenditure for vertical structures, irrigation systems, and environmental controls continues to raise questions about the profitability of commercial verticulture relative to low-input traditional agriculture.
- Aggregate Resource Impact: There is a lack of comprehensive analysis assessing the cumulative effects of large-scale verticulture adoption on urban ecosystem water and nutrient balances, necessitating precise data modeling to quantify these impacts.

Consequently, this study aims to conduct a comprehensive analysis of verticulture adaptation and its contribution to sustainable, environmentally friendly horticultural systems in Indonesia. The specific objectives are:

1. To analyze land scarcity trends and horticultural production volatility in major Indonesian urban centers using BPS data from 2020–2025.
2. To quantitatively evaluate and compare the efficiency of water, land, and fertilizer use in verticulture and conventional cultivation systems.

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3. To formulate an optimal verticulture adaptation model that balances economic viability with long-term agronomic performance, positioning it as a strategy for addressing urban food insecurity.

In summary, this study is expected to provide empirical evidence supporting verticulture as an effective land-mitigation strategy that enhances production stability and reduces the ecological footprint of urban agriculture under increasing urbanization and climate pressures.

2. Materials and Method

Research Design

This study employs a quantitative descriptive approach based on secondary data obtained from official institutions. The primary objective is to evaluate the adaptation of verticulture technology within sustainable horticultural systems in Indonesia, focusing on major production centers, including West Java, East Java, and North Sumatra [15].

Secondary Data Sources

Secondary data were systematically obtained from the Central Statistics Agency (BPS), the official national institution responsible for collecting and publishing agricultural data. The main datasets utilized include:

- Horticultural Statistics: production volumes, harvested areas, and raw material utilization.
- Agricultural Census 2023: structural data on agricultural units and horticultural land management practices.

These datasets were accessed through the official BPS online database, ensuring their authenticity and suitability for scientific analysis.

Variables and Indicators

The analytical framework uses key indicators such as harvested area (ha), production volume (tons), land-use efficiency, irrigation water usage, and organic/inorganic fertilizer application rates. These quantitative metrics were complemented with field data reflecting practical verticulture implementation [16].

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Analytical Methodology

Data were analyzed using descriptive statistics and paired t-tests ($\alpha = 0.05$) in SPSS to compare resource efficiency (land and water) between verticulture and conventional systems, assuming normal data distribution. In addition, Material Flow Analysis (MFA) was applied to trace and evaluate water and nutrient flows within verticulture systems based on established MFA methodology to support ecological impact assessment. Field validation was conducted through a supporting survey involving semi-structured interviews with 25 purposively selected verticulture practitioners from the three study locations to ensure the accuracy of real-world technological adaptation.

Validity and Reliability

The integrity of the secondary data was ensured by relying exclusively on verified statistical records from BPS. For the field survey, instrument reliability and validity were assessed using item-to-total correlation tests and other relevant statistical procedures.

Ethical Considerations

This research is non-interventional and does not involve experiments on humans or animals; therefore, no specific ethical approval was required. All data used are publicly accessible from official providers.

Data Availability

Secondary data used in this study are publicly accessible through the official BPS data platform. The final research outputs and survey instruments are stored by the authors and can be made available upon request for academic verification.

3. Result

Trends in Horticultural Production and Harvested Area in Key Centers

Data sourced from the Central Statistics Agency (BPS) reveal significant fluctuations in the harvested area and total production of horticulture across three primary hub provinces: West Java, East Java, and North Sumatra. Monitoring the most recent period up to the year 2025, West Java registered a total horticultural

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harvested area of 120,450 hectares, yielding a production volume of 1.53 million tons. Conversely, East Java reported 98,230 hectares in harvested land, resulting in a production output of 1.32 million tons. North Sumatra, with a smaller area of 76,120 hectares, generated approximately 980,700 tons. Climate variability and ongoing changes in land use patterns primarily drive these observed fluctuations (Table 1).

Table 1. Horticultural Harvested Area and Production in Key Centers (ha and tons)

Province	Harvested Area (ha)	Production (tons)
West Java	120,450	1,530,200
East Java	98,230	1,320,500
North Sumatra	76,120	980,700

Resource Utilization Efficiency of Verticulture

The deployment of verticulture technology in both urban and suburban environments demonstrates marked improvements in efficiency. The system enhances land efficiency by up to 85% when benchmarked against conventional farming in space-constrained settings. Water consumption is dramatically reduced, achieving savings of 60% through the integration of a localized drip irrigation system. Furthermore, the reliance on synthetic chemical fertilizers is lowered by 70%, achieved by substituting them with alternative growing media and utilizing liquid organic fertilizers (LOF) (Figure 1).

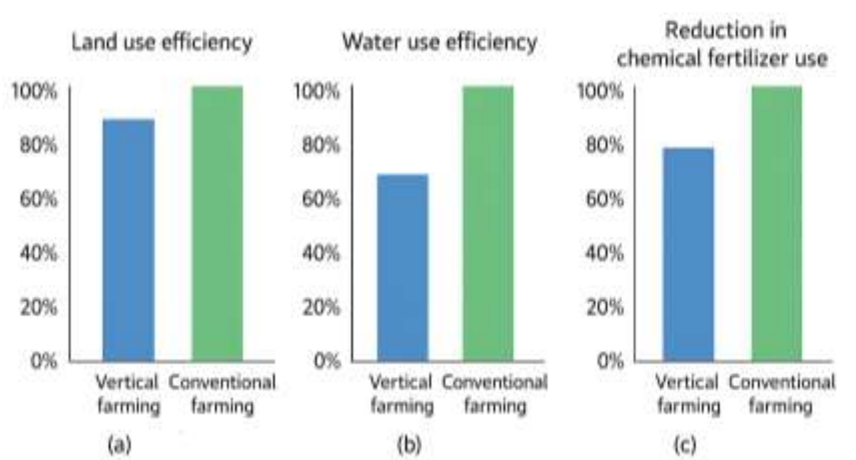

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Figure 1. Comparison of Efficiency in Land Use, Water, and Fertilizer Reduction between Verticulture and Conventional Methods

(a) Land Efficiency, (b) Water Efficiency, (c) Reduction in Chemical Fertilizer Use.

Vertical farming demonstrates higher efficiency in land use (↑85%), water savings (↓60%), and chemical fertilizer reduction (↓70%) compared to conventional methods, reflecting sustainable resource management and improved urban farming productivity.

Production Stability and Local Food Security

Vertical agriculture enhances production stability by protecting crops from extreme weather events, including drought and flooding. This protection reduces the risk of yield loss by up to 35%, which is critical for strengthening decentralized food supply in urban regions. Survey data from 2025 also show that farmers implementing verticulture exhibit greater economic resilience due to more consistent harvest outcomes.

Economic Analysis and Investment Feasibility

A detailed cost-benefit analysis indicated that although the initial capital expenditure (CapEx) for establishing a vertical system is comparatively high, the average return on investment (ROI) is realized within a timeframe of 3.5 years. This setup yields an average annual net profit of approximately 18%. The primary factors dictating overall profitability include effective irrigation system management, the strategic selection of fast-maturing crops, and robust market access (Table 2). Additionally, annual operational costs for vertical agriculture are documented to be up to 25% lower than conventional methods, primarily due to minimal land requirements and reduced necessity for chemical inputs.

Table 2. Cost-Benefit Analysis of Verticulture Adaptation (in Million Rupiah)

Component	Verticulture	Conventional
Initial Investment	75	30
Annual Operational Cost	15	20

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Annual Revenue	50	35
ROI (Years)	3.5	4.2

Ecological and Social Impact

The implementation of vertical verticulture is supportive of sustainable natural resource management by minimizing waste generation and boosting the recycling of plant nutrients. Beyond environmental benefits, verticulture visually enhances the urban landscape by providing green spaces that significantly contribute to the social well-being of city dwellers. Qualitative survey findings revealed a high degree of farmer satisfaction, citing ease of maintenance and more predictable harvest outcomes (Primary data, 2025).

4. Discussion

The findings clearly indicate that verticulture technology effectively alleviates land limitations commonly found in Indonesia's urban and peri-urban regions, especially in key horticultural centers such as West Java, East Java, and North Sumatra. The observed improvements in land and water efficiency align with previous studies identifying verticulture as an environmentally efficient and resource-conserving cultivation method. These results empirically affirm that verticulture is a viable strategy for addressing pressures arising from accelerated urbanization and increasing climate variability. However, its implementation at a broader scale still faces technical and managerial challenges, particularly related to system maintenance, irrigation management, and farmer technical capacity.

The significant 70% reduction in chemical fertilizer use supports previous findings that associate verticulture with sustainable agricultural practices emphasizing organic fertilizers and alternative growing media. This transition not only improves environmental performance but also reduces the risk of soil and water pollution. Nevertheless, the availability and consistency of liquid organic fertilizer supply remain practical constraints in some regions, which may affect the continuity of environmentally friendly production if not supported by proper input distribution systems.

The documented stability of horticultural yields in verticulture systems provides strong evidence of enhanced local food resilience compared with conventional

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farming. This condition is particularly relevant under Indonesia's increasing climate variability. With more consistent production levels, financial risks related to climate-induced disturbances are significantly reduced, thereby improving farmer welfare and strengthening the stability of urban food markets. Despite these advantages, vulnerability to power supply disruptions and infrastructure limitations in some urban areas may still affect production continuity in vertically managed systems.

The economic analysis reinforces the claim that, despite higher initial capital outlays required for verticulture system installation, the capital recovery period remains attractive, averaging 3.5 years, with competitive annual net profits. Key determinants for sustained profitability—including efficient irrigation management, the selection of fast-harvesting crops, and optimized market access—must remain central to implementation strategies for long-term adoption. However, limited access to affordable financing remains a significant barrier for small-scale farmers, indicating that economic feasibility is highly sensitive to external support mechanisms.

From a combined social and ecological perspective, verticulture transcends mere productivity enhancement. It actively contributes to environmental quality improvement while generating social benefits, such as supplementary green spaces and additional income sources for urban communities. High social acceptance and strong community engagement observed in this study further emphasize verticulture's potential as a multifunctional urban farming solution. Nonetheless, community adoption rates may vary depending on awareness levels, training availability, and institutional support.

Future research should focus on developing inclusive business models and targeted technical training programs to address existing implementation constraints, particularly limited access to capital and challenges in market penetration. Additional studies are also needed to evaluate verticulture adaptation under diverse region-specific socio-economic conditions to strengthen national adoption and long-term sustainability.

Overall, these findings contribute significantly to the literature on sustainable agriculture and urban farming, reinforcing verticulture as a leading strategy for enhancing food security, resource efficiency, and environmentally sustainable development in Indonesia.

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5. Conclusions

This study shows that verticulture technology provides an effective solution to land limitations in Indonesia's urban and suburban regions, particularly in major horticultural centers such as West Java, East Java, and North Sumatra. Verticulture systems improve land-use efficiency by up to 85%, reduce water consumption by approximately 60%, and decrease reliance on synthetic chemical fertilizers by about 70%. In addition to resource efficiency, verticulture enhances production stability, strengthens local food resilience, and offers competitive economic returns with an average investment payback period of approximately 3.5 years.

Despite these positive outcomes, this study has several limitations. The analysis was confined to a limited number of major horticultural regions and relied primarily on secondary statistical data, which may not fully capture socio-economic diversity and on-farm variability across Indonesia. Furthermore, the economic estimates were based on specific technological assumptions that may differ under varying policy and geographic conditions.

Future research should expand the geographical scope and incorporate broader socio-economic and cultural variables to strengthen the generalizability of findings. Further investigation into business model development, technical training systems, and continuous innovation in verticulture irrigation and growing media is also essential to support wider and more sustainable adoption. In addition, strong government policy support through incentives, financing schemes, and extension services will play a crucial role in accelerating national verticulture implementation.

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