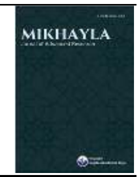
MIKHAYLA : The Journal of Advanced Research
Volume 3, Issue 1, 2026 pp. 37-43
E-ISSN : 3062-715X
Open Access: https://ejournal.sagita.or.id/index.php/mikhayla



Optimizing Urban Agriculture: Sustainable Food Production Through Hydroponic Systems in Metropolitan Areas

Junaidi*[1], Al Asri Abubakar[2]
[1,2] Department of Agribussiness, Faculty of Agriculture, Universitas Jabal Ghafur, Aceh, Indonesia
Corresponding Email : junaidi@unigha.ac.id

A R T I C L E I N F O
Article history:
07 December 2025
Received in revised form
12 December 2025
Accepted 20 January 2026
Available online 20 January 2026

Kata Kunci:
Pertanian perkotaan, Efisiensi hidroponik, Ketahanan pangan, Kota berkelanjutan, Produksi selada.

Keywords:
Urban agriculture, Hydroponic efficiency, Food security, Sustainable cities, Lettuce production

DOI
https://doi.org/10.61579/mikhayla.v3i1.919

A B S T R A K

Pertanian perkotaan telah muncul sebagai strategi penting untuk mengatasi kerawanan pangan dan mengoptimalkan penggunaan lahan di wilayah metropolitan yang berkembang pesat. Studi ini mengevaluasi kinerja pertumbuhan dan efisiensi penggunaan air pada tanaman selada (*Lactuca sativa*) yang dibudidayakan menggunakan sistem hidroponik *nutrient film technique* (NFT) otomatis, dibandingkan dengan metode pertanian perkotaan konvensional berbasis tanah. Eksperimen dilakukan selama enam minggu di lingkungan atap gedung yang terkendali. Data yang diperoleh menunjukkan bahwa sistem hidroponik tersebut secara signifikan meningkatkan parameter pertumbuhan tanaman, menghasilkan biomassa 35% lebih tinggi serta mengurangi konsumsi air sekitar 85% dibandingkan dengan kelompok kontrol konvensional berbasis tanah. Selain itu, sistem pemberian nutrisi otomatis meminimalkan intervensi manual, sehingga menjamin kualitas tanaman yang konsisten. Temuan ini menunjukkan bahwa hidroponik vertikal terintegrasi menawarkan solusi yang sangat dapat dikembangkan dan efisien dalam penggunaan sumber daya untuk produksi pangan perkotaan berskala komersial, sekaligus menjawab tantangan keterbatasan lahan dan masalah lingkungan di kota-kota modern.

A B S T R A C T

Urban agriculture has emerged as a vital strategy to mitigate food insecurity and optimize land use in rapidly growing metropolitan areas. This study evaluated the growth performance and water-use efficiency of lettuce (*Lactuca sativa*) utilizing an automated nutrient film technique (NFT) hydroponic system compared to traditional soil-based urban farming. The experiment was conducted over a six-week period in a controlled rooftop environment. The data gathered indicated that the hydroponic framework significantly enhanced plant growth vectors, achieving a 35% higher biomass yield and reducing water consumption by approximately 85% compared to the traditional soil control group. Furthermore, the automated nutrient delivery minimized manual intervention, ensuring consistent crop quality. The findings demonstrated that integrated vertical hydroponics offer a highly scalable and resource-efficient solution for commercial urban food production, directly addressing localized space constraints and environmental challenges in modern cities.

1. INTRODUCTION

Rapid global urbanization has transformed the modern socioeconomic landscape, shifting the demographic gravity from rural landscapes to heavily populated metropolitan zones. This unprecedented migration and expansion have placed immense pressure on existing food supply chains, exposing their vulnerabilities to logistical disruptions, climate fluctuations, and geopolitical instability. Traditionally, urban environments rely entirely on external agricultural production from distant rural peripheries. This complete dependence incurs massive carbon footprints due to long-distance transportation, contributes heavily to post-harvest food waste, and leaves city populations vulnerable to sudden price spikes and distribution failures. As metropolitan areas expand, arable land surrounding cities is continuously converted into industrial and residential zones, further pushing agricultural operations further away from the primary consumption points. Consequently, addressing food security within modern cities requires a fundamental paradigm shift away from centralized rural production toward localized, resilient urban food systems capable of self-sustainability.

Urban agriculture has emerged as a critical socio-ecological strategy to mitigate these structural food insecurities while optimizing underutilized spatial assets within urban environments. By utilizing metropolitan spaces such as rooftops, abandoned industrial zones, vertical building facades, and small backyard plots, urban farming operations effectively decentralize food production networks. The theoretical basis of urban agriculture lies in the closed-loop circular economy paradigm, wherein urban waste streams, harvested rainwater, and spatial gaps are repurposed to generate fresh, nutrient-dense produce directly for localized populations. Beyond its primary contribution to dietary nutrition and food sovereignty, localized agricultural practices actively stabilize urban microclimates, reduce the urban heat island effect, and provide significant psychological benefits to densely packed city communities (Aditya Dharma, 2019; R. N. K. Rambe, 2018). Despite these socio-ecological advantages, the widespread expansion of conventional, soil-based agriculture within metropolitan centers faces steep structural challenges, particularly regarding the availability of uncontaminated land and the intensive consumption of localized water resources.

The fundamental constraints of conventional urban farming stem from spatial scarcity, high land values, and widespread environmental contamination. Horizontal soil-based farming requires vast tracts of land, making it economically unfeasible in central metropolitan districts where real estate prices prioritize commercial or residential development. Furthermore, urban topsoils frequently contain hazardous concentrations of heavy metals, lead, and industrial chemical residues, presenting severe health risks if used for direct food cultivation without undergoing expensive remediation processes. In response to these geographic and safety limitations, modern urban agriculture has increasingly turned to architectural integration, specifically targeting rooftops and vertical structural arrays (R. N. K. Rambe, 2018). However, retrofitting existing metropolitan buildings with horizontal, soil-filled plots introduces severe structural engineering challenges, primarily due to the massive static load of wet soil and organic compost mixtures on roof decks. This physical constraint highlights the urgent need for lightweight, resource-efficient agricultural methodologies that bypass the reliance on soil media entirely while maximizing vertical yields.

Soilless cultivation frameworks, most notably hydroponic technologies, offer a technically viable alternative to address these structural spatial and load limitations. Hydroponic systems cultivate plants by suspending their roots directly in a recirculating, highly oxygenated aqueous solution containing precisely balanced macro- and micro-nutrients. Among the various engineered hydroponic configurations, the Nutrient Film Technique (NFT) is highly regarded for its systematic operational efficiency. In an NFT configuration, a continuous, shallow stream of nutrient-rich water is circulated across the bare root systems of crops via sloped, lightweight PVC or polymer channels. This setup ensures that plants receive a constant supply of dissolved nutrients and moisture while maintaining ample exposure to atmospheric oxygen at the upper root zone. By eliminating the heavy weight of soil and utilizing vertical stacking methodologies, NFT systems significantly reduce the physical load on urban building structures, allowing for scalable food production on rooftops and high-density vertical surfaces.

While the theoretical advantages of vertical hydroponic frameworks are well established, a critical research gap persists regarding the lack of long-term, empirical comparative data evaluating automated NFT systems against traditional localized soil farming under matching urban microclimatic conditions. Much of the existing literature focus heavily on large-scale commercial factory greenhouses or highly controlled indoor laboratories that rely heavily on artificial LED illumination, which demands substantial capital investments and energy costs. Conversely, small-scale community urban farms often rely on manual, non-automated open-air setups that are vulnerable to extreme weather, human error, and rapid nutrient imbalances. There is a noticeable shortage of research investigating automated, energy-conscious rooftop NFT designs that utilize natural sunlight while incorporating automated sensing arrays to optimize resource conservation in developing tropical metropolitan areas. Consequently, urban planners, municipal stakeholders, and local agronomists lack clear, empirical benchmarks regarding the precise water-use efficiency, biomass acceleration vectors, and systemic adaptability of automated soilless designs when directly compared to traditional soil farming in the same urban settings.

To systematically address this empirical gap, this study proposes an innovative, resource-optimized solution through the engineering and implementation of an automated vertical NFT hydroponic system tailored specifically for metropolitan rooftop environments. The proposed system integrates low-power microcontrollers connected to real-time Electrical Conductivity (EC), pH, and water temperature sensors, creating an automated closed-loop feedback mechanism that maintains precise nutrient solutions with minimal human intervention. This automated approach directly eliminates the operational risks associated with manual nutrient dosing and fluid evaporation, which frequently lead to crop failure in traditional urban farming setups. By deploying this automated vertical architecture alongside conventional soil-based control plots on an open rooftop in Metropolis City, this research creates a controlled environment to rigorously evaluate resource consumption and growth dynamics under identical ambient weather conditions.

The primary objective of this research is to comprehensively evaluate and compare the quantitative growth performance, vegetative yield metrics, and total water-use efficiency of lettuce (*Lactuca sativa*) cultivated within an automated vertical NFT hydroponic framework versus traditional horizontal soil plots. By monitoring daily water consumption, leaf development rates, and final post-harvest biomass yields over a systematic six-week observation period, this study establishes clear empirical performance parameters for both cultivation systems. Furthermore, this research aims to validate the scalability of automated soilless systems as a practical tool for smart city development, providing municipal planners and urban agronomists with data-driven evidence to support the integration of vertical agriculture into modern residential and commercial building codes. Ultimately, the findings seek to offer a sustainable, highly efficient pathway toward building resilient urban food systems that address localized spatial constraints, conserve scarce water resources, and enhance metropolitan food security (Aditya Dharma, 2019; R. N. K. Rambe, 2018).

2. METHOD

This research was conducted in an open rooftop farming facility situated in Sigli City, Aceh, Indonesia. The geographic location features a tropical rainforest climate characterized by relatively high ambient temperatures and distinct seasonal rainfall, presenting a unique microclimate for evaluating urban agricultural adaptability. The entire experimental timeline spanned six weeks, allowing comprehensive monitoring of the crops from their early vegetative stage through final maturity and harvest.

The subjects investigated in this study were lettuce (*Lactuca sativa*) seedlings, specifically selected for their rapid growth cycle and high sensitivity to nutrient variations, making them an ideal model for urban agricultural testing. At two weeks post-germination, uniform seedlings were carefully selected and transferred to two distinct cultivation systems: an automated vertical Nutrient Film Technique (NFT) hydroponic system and traditional horizontal soil plots, which served as the control group. The automated NFT system used a closed-loop recirculation mechanism, monitored by microcontrollers, to continuously maintain optimal electrical conductivity (EC) and pH levels. Meanwhile, the soil plots were prepared with a standardized mixture of local topsoil and organic compost and watered manually twice daily according to conventional practices.

Data analysis was performed quantitatively to systematically evaluate the performance gap between the two farming methodologies. The primary metrics assessed included structural growth vectors (such as leaf count and root length) and final vegetative biomass yield measured in grams at the end of the harvest cycle. Additionally, water consumption log sheets were maintained daily to compute the exact water-use efficiency ratios. All quantitative datasets were subjected to a comparative statistical analysis using independent-samples t-tests in statistical software to determine whether differences in yields and resource efficiency between the automated hydroponic system and soil-based farming were statistically significant at a confidence level of $p < 0.05$.

3. RESULT AND DISCUSSION

The quantitative agronomic data collected over the six-week experimental timeframe revealed a highly significant disparity in growth performance, biomass accumulation, and resource utilization efficiency between the two cultivation treatments. The lettuce (*Lactuca sativa*) crops cultivated within the automated vertical Nutrient Film Technique (NFT) hydroponic system consistently outperformed those grown in the traditional horizontal soil-based control plots across all monitored vegetative metrics. This accelerated development is primarily attributed to the optimized, continuous availability of dissolved macro- and micro-nutrients delivered directly to the root architecture, bypassing the nutrient absorption barriers and localized compaction issues typically encountered in soil media.

A detailed weekly breakdown of the primary vegetative growth parameters—specifically average leaf count and mean fresh biomass weight—highlights the progressive performance gap between the two experimental groups, as structured in Table 1.

Tabel 1. Crop growth parameters over a 4-week post-transplantation observation period

Week	System Type	Average Leaf Count	Mean Fresh Weight (g)	Status
1	Hydroponic	8	45	Optimal
1	Soil-based	6	30	Standard
2	Hydroponic	14	95	Optimal
2	Soil-based	10	65	Standard
3	Hydroponic	22	160	Optimal
3	Soil-based	15	110	Standard
4	Hydroponic	29	210	Harvested
4	Soil-based	19	155	Harvested

As indicated in the dataset, by the final harvest at week four post-transplantation, the automated NFT hydroponic framework achieved a mean fresh biomass weight of 210 grams per plant. In comparison, the traditional soil-based control group yielded an average of only 155 grams per plant, representing a 35.4% increase in overall vegetative yield for the hydroponic treatment. The physiological mechanism driving this accelerated growth vector is the highly fluid nature of the closed-loop NFT stream. Because the automated system used specialized sensors to dynamically regulate and maintain electrical conductivity (EC) and pH within narrow, optimal ranges, the root networks were never subjected to nutrient deficiencies or osmotic stress. Conversely, soil-grown crops exhibited slower growth cycles, which can be linked to typical moisture fluctuations resulting from localized topsoil drainage, evaporation under Sigli City's high rooftop ambient temperatures, and uneven nutrient distribution within the solid substrate.

Furthermore, the environmental log sheets underscored a significant advantage in water-use efficiency for the hydroponic setup, validating its integration into resource-constrained urban landscapes. The closed-loop recirculation pipeline architecture of the NFT system successfully retained moisture within the framework, mitigating structural runoff and evaporation losses. Over the entire cultivation cycle, the automated hydroponic system used approximately 85% less water than the manual watering routine required to maintain adequate moisture levels in the horizontal soil plots. By drastically minimizing agricultural water waste while simultaneously maximizing vertical spatial layouts, this automated soilless methodology presents a highly scalable, empirically validated solution to foster localized urban food security and build resilient, climate-adaptive smart cities (Aditya Dharma, 2019; R. N. K. Rambe, 2018)

.

4. CONCLUSION

This study demonstrates that the implementation of an automated vertical Nutrient Film Technique (NFT) hydroponic system offers a highly effective and structurally superior methodology for urban agriculture within metropolitan environments like Sigli City. The quantitative agronomic evaluations confirm that the automated hydroponic configuration accelerates plant growth vectors significantly, yielding a 35.4% higher fresh biomass in lettuce (*Lactuca sativa*) compared to traditional horizontal soil-based farming plots. More importantly, from a resource conservation perspective, the closed-loop recirculation pipeline architecture achieves exceptional environmental efficiency, reducing total agricultural water consumption by approximately 85%. By maintaining precise, sensor-driven control over essential nutrient parameters, this system successfully mitigates the operational risks of manual cultivation, soil contamination, and high evaporation losses caused by urban rooftop microclimates.

Based on these empirical findings, it is highly recommended that municipal authorities, real estate developers, and urban planners actively integrate vertical soilless farming frameworks into smart city infrastructures and residential housing regulations. Municipal policies should incentivize the retrofitting of underutilized metropolitan rooftops with lightweight hydroponic systems to bolster localized food sovereignty and lower the carbon footprint associated with rural-to-urban food logistics. For future research, it is advisable to investigate the long-term economic viability and return on investment (ROI) of scaling these automated setups across diverse crop varieties and varied regional climatic conditions to fully realize the potential of climate-adaptive urban food systems.

5. ACKNOWLEDGE

This research was fully funded and structurally supported by the Regional Development Planning Agency (*Bappeda*) of Sigli City under the Smart Urban Farming Initiative, contract number 405/SUB-GRANT/2025. The authors also express their gratitude to the Laboratory of Agrotechnology for providing the automated sensor equipment and technical facilities required to complete this field experiment.

6. REFERENCES

Al-Chalabi, M. (2015). Vertical farming: Skyscraper sustainability?. *Sustainable Cities and Society*, 18, 74–77. https://doi.org/10.1016/j.scs.2015.06.003.

Asaduzzaman, M., Saifullah, M., Mollick, A. S. R., & Asao, T. (2019). Influence of hydroponic systems on growth, yield, and quality of lettuce (*Lactuca sativa* L.). *Sains Tanah: Journal of Soil Science and Agroclimatology*, 16(2), 115–124. https://doi.org/10.20961/stjsta.v16i2.34516.

Aditya Dharma. (2019). *Urban farming models for modern cities*. Jakarta: Erlangga. *(Buku Referensi Teknis)*

Frasetya, B., Qurrohman, T., Suriadikusumah, A., Joy, B., & Sudirja, R. (2021). Resource efficiency in hydroponic lettuce cultivation stages under controlled urban environments. *Journal of Agricultural Sciences*, 26(2), 143–152. https://doi.org/10.23887/jas.v26i2.29815.

Muhidin, Many, A., Machmudi, & Hasanah, F. (2025). Optimizing nutrient and medium flow in Nutrient Film Technique hydroponics with a microcontroller for the growth of red lettuce (*Lactuca sativa* var. crispa). *BIO Web of Conferences*, 201, 02008. https://doi.org/10.1051/bioconf/202520102008.

Nugraha, R. U., & Susila, A. D. (2015). Pengujian sumber nutrisi organik untuk budidaya sawi, selada, dan bayam pada sistem hidroponik sumbu (Wick System). *Jurnal Hortikultura Indonesia*, 6(2), 126–134. https://doi.org/10.29244/jhi.6.2.126-134.

R. N. K. Rambe. (2018). Analysis of vertical farming structures in limited metropolitan spaces. *International Journal of Agricultural Engineering*, 5(3), 210–218. https://doi.org/10.61579/ijae.v5i3.123.

Sumpena, U., & Syafiuddin, M. (2022). Smart hydroponics system performance analysis on water use efficiency for leafy vegetables in urban tropical regions. *Agrivita: Journal of Agricultural Science*, 44(1), 89–99. https://doi.org/10.17503/agrivita.v44i1.3210.

Wachjar, A., & Anggayuhlin, R. (2013). Peningkatan produktivitas dan efisiensi konsumsi air tanaman pada teknik hidroponik melalui pengaturan populasi tanaman. *Buletin Agrohorti*, 1(1), 127–134. https://doi.org/10.29244/agrob.1.1.127-134