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Resource-Efficient Urban Agriculture: Comparative Analysis of Six Farming Models in Indonesian Cities

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ABSTRACT: Urban agriculture (UA) is increasingly vital for addressing food security and sustainability in urban environments. This study evaluates six urban agriculture models rooftop farming, vertical farming, hydroponics, aquaponics, community gardens, and backyard farming using standardized resource efficiency indicators. The objective is to compare models based on water use efficiency (WUE), energy use efficiency (EUE), land use efficiency (LUE), nutrient use efficiency (NUE), and labor productivity. A quantitative cross-sectional analysis was conducted using data from field observations, secondary sources, and expert consultations. Each model was evaluated for input-output ratios per production cycle. Resource efficiency metrics were calculated and analyzed using ratio comparisons and sustainability frameworks. The findings reveal that hydroponic systems exhibit the highest efficiency across most indicators, especially in water, nutrient, and labor use. Rooftop farming also performs well in land and nutrient use, while vertical farming achieves superior land use but lower energy efficiency due to artificial lighting needs. Community and backyard models are less efficient but offer social benefits and accessibility. Case studies from Paris and Detroit illustrate successful integration of UA into policy frameworks. These results highlight the importance of resource-based planning in urban agriculture. Efficient models such as hydroponics and rooftop systems should be prioritized in sustainability-focused urban development strategies. Policymakers must balance efficiency with inclusivity, ensuring broader access to high-performing UA technologies. Future research should explore long-term sustainability impacts and economic viability across diverse urban contexts.

Keywords: Urban Agriculture, Resource Efficiency, Hydroponics, Rooftop Farming, Sustainability Metrics, Comparative Analysis.

INTRODUCTION

Urban environments are experiencing unprecedented transformations due to rapid urbanization and population growth, which have intensified the challenges related to food security. The availability of land, accessibility to nutritious food, and environmental sustainability are all under strain as cities expand. Urban agriculture (UA) has thus gained attention as a viable solution to mitigate these urban challenges by integrating food production into the urban fabric (Omondi et al., 2017; Shamshiri et al., 2018). This research seeks to explore urban agriculture's role in addressing food security and resource constraints while identifying the most efficient UA models based on standardized resource use indicators.

Food security in urban areas is influenced by various factors, including socio-economic disparities, inadequate infrastructure, and demographic shifts. Djan (2023) emphasizes how urbanization increases living costs and exposes gaps in public policy, which traditionally focuses on rural food systems. Tacoli (2017) similarly identifies food insecurity in low-income urban neighborhoods as linked to poverty and restricted food access, exacerbated by poor infrastructure and high dependency on external supply chains. Siegner et al. (2018) further support that high demand and logistical challenges in food distribution worsen food access in densely populated areas.

Urban agriculture is a rapidly evolving practice that addresses urban land scarcity and contributes to localized food production. Ranging from backyard plots to technologically advanced vertical farms, UA plays a crucial role in enhancing urban food resilience. Bellemare & Dusoruth (2020) discuss how the COVID-19 pandemic underscored vulnerabilities in global food systems and highlighted the value of community-based UA. Nicholls et al. (2020) note that urban agriculture not only enhances food security but also contributes to broader sustainable development objectives. Mathew et al. (2023) argue that the adaptability of UA systems allows them to respond effectively to crises and contribute to long-term food system resilience.

In addition to its economic and food access benefits, urban agriculture has important environmental implications. Artmann & Sartison (2018) describe UA as a nature-based solution that enhances ecological services such as biodiversity conservation and microclimate regulation. However, different UA models have varying environmental trade-offs. Vertical farming, for example, enables intensive food production in compact areas but relies heavily on artificial lighting and climate control systems, which increase energy consumption (Touliatos et al., 2016). These trade-offs must be critically assessed to ensure sustainable urban agricultural practices.

To comprehensively evaluate sustainability, various metrics have been adopted in agricultural studies. These include efficiency indicators like Water Use Efficiency (WUE), Energy Use Efficiency (EUE), Land Use Efficiency (LUE), Nutrient Use Efficiency (NUE), and labor productivity. Juniawati and Hayuningtyas (2017) emphasize integrating ecological, social, and economic criteria in sustainability evaluations. The CIPP model (Context, Input, Process, Product), proposed by Yusuf et al. (2021), offers a multidimensional framework for assessing UA initiatives. Pollard et al. (2018) suggest that performance in urban agriculture should also consider health, social cohesion, and community engagement not just output and efficiency.

Hydroponic and aquaponic systems exemplify technologically advanced UA models that offer considerable resource efficiency benefits. Hydroponics eliminates the need for soil by utilizing nutrient-enriched water solutions, thus reducing spatial and environmental constraints (Pollard et al., 2018). Aquaponics integrates aquaculture and hydroponics into a closed-loop system, enhancing nutrient recycling and reducing waste (Pollard et al., 2018). Touliatos et al. (2016) report that while these systems maximize yields and minimize land and water usage, they often require significant capital investment and technical knowledge, posing barriers for broader adoption.

Despite the expanding literature on urban agriculture, notable research gaps remain, particularly concerning cross-model comparisons. Camerano et al. (2023) point out that most studies are case-specific and lack generalizable comparative frameworks. Bisaga et al. (2019) call for more empirical work to examine the relative efficiency, economic viability, and social equity implications of diverse UA models. Addressing these gaps is essential for informing urban agricultural policies and investment decisions that support sustainable food systems.

The objective of this study is to conduct a comparative analysis of six UA models rooftop farming, vertical farming, hydroponics, aquaponics, community gardens, and backyard farming based on standardized indicators of resource efficiency. This research seeks to identify the most effective and scalable models for sustainable food production in urban contexts. By systematically evaluating WUE, EUE, LUE, NUE, and labor productivity, the study provides novel insights into the optimal resource allocation in urban agriculture. The anticipated contribution lies in offering empirical evidence to guide urban planners, policymakers, and practitioners in selecting and supporting UA models that align with sustainability goals and local resource conditions.

METHOD

Study Design

This research employs a quantitative, cross-sectional comparative analysis to evaluate six urban agriculture (UA) models. The study focuses on measuring five key resource efficiency metrics: Water Use Efficiency (WUE), Energy Use Efficiency (EUE), Land Use Efficiency (LUE), Nutrient Use Efficiency (NUE), and Labor Productivity. These indicators are calculated using data collected from a combination of field observations, interviews with practitioners, and secondary data sources.

Urban Agriculture Models

The models analyzed in this study include:

- **UA1:** Rooftop Farming
- **UA2:** Vertical Farming
- **UA3:** Hydroponic System
- **UA4:** Aquaponic System
- **UA5:** Community Garden
- **UA6:** Backyard Urban Farming

Each model represents distinct technological, spatial, and resource usage characteristics within urban environments.

Indicators and Definitions

The assessment framework is based on the following efficiency indicators:

- Water Use Efficiency (WUE): Yield (kg) / Water Used (m^3). Best practices include the use of smart irrigation systems to enhance output per unit of water.
- Energy Use Efficiency (EUE): Yield (kg) / Energy Used (kWh). Energy inputs include lighting, climate control, and pumping. Precision agriculture technologies are noted to improve this metric.
- Land Use Efficiency (LUE): Yield (kg) / Area of Land (m^2). Efficient land usage is achieved through crop rotation and vertical stacking.
- Nutrient Use Efficiency (NUE): Yield (kg) / Nutrients Used (kg). NUE benefits from precision fertilization and soil monitoring.
- Labor Productivity: Yield (kg) / Labor Input (hr). Mechanization and labor training enhance productivity.

Data Collection and Calculation

Primary data were collected via structured interviews and on-site measurements, while secondary data were sourced from academic literature, institutional reports, and urban agriculture records. For each UA model, resource inputs (water, energy, land, nutrients, labor) and outputs (yield) were recorded per production cycle. These values were averaged to normalize efficiency comparisons.

Definitions and formulas are drawn from previous agricultural efficiency studies. For instance, Ye et al. (2023)developed models to optimize irrigation for WUE. Similarly, Pellegrini & Fernández (2018) quantified energy profitability through crop yield vs. energy input ratios. Integrated nutrient and land use models by Jat et al. (2019) provide methodological grounding for NUE and LUE evaluations.

Analytical Tools and Frameworks

Several analytical tools supported the interpretation of efficiency indicators:

- Data Envelopment Analysis (DEA): Applied to evaluate the relative efficiency of UA models by comparing multiple inputs and outputs.
- Linear Programming Models: Used to optimize input allocation for maximum efficiency.

- Life Cycle Assessment (LCA): Employed to assess environmental implications of each UA model based on resource use and outputs.
- Precision Agriculture Tools: Real-time monitoring through smart agriculture technologies provided enhanced data accuracy.
- Modeling Software: Crop and nutrient cycling models were utilized to simulate interrelations among efficiency parameters.

RESULT AND DISCUSSION

Water Use Efficiency (WUE)

Hydroponic systems (UA3) demonstrated the highest WUE (9.0 kg/m³), outperforming all other models due to their recirculating water systems and minimized evaporation (Baiyin et al., 2021; Maucieri et al., 2018). Aquaponic systems (UA4) also performed strongly with 6.8 kg/m³. In contrast, community (UA5) and backyard (UA6) gardens had the lowest WUE values at 2.5 and 2.9 kg/m³, respectively, aligning with studies that indicate greater water loss in soil-based systems (Goddek et al., 2016).

Drip and automated irrigation systems, coupled with IoT-enabled controls, have been shown to improve WUE by optimizing water delivery and minimizing runoff (Niswar, 2024). Crop selection also plays a role; leafy greens exhibit higher WUE than fruiting crops in controlled environments (Decina et al., 2018). Benchmarks in literature suggest hydroponics can reach WUE levels up to 100 kg/m³ under ideal conditions(Salomon et al., 2020).

Energy Use Efficiency (EUE)

Vertical farming (UA2) recorded the lowest EUE (0.75 kg/kWh), reflecting its high energy consumption for artificial lighting and climate control (Goldstein et al., 2016). Hydroponics (UA3) and aquaponics (UA4) performed better with EUE values of 2.0 and 1.7 kg/kWh, respectively. Community (UA5) and backyard (UA6) gardens showed higher efficiency due to minimal energy use (3.3 and 3.1 kg/kWh).

Use of LED lighting and renewable energy sources such as solar panels is shown to improve EUE in vertical systems. CHP systems and smart energy monitors further optimize usage. Urban farms utilizing off-grid energy reported better sustainability and reduced carbon footprints (Janke et al., 2017).

Land Use Efficiency (LUE)

UA2 achieved the highest land use efficiency (15.0 kg/m²) by leveraging vertical stacking and multilayer growth structures (Rodgers et al., 2022). Hydroponics (UA3) followed closely with 12.0

kg/m². Community gardens (UA5) were least efficient (2.5 kg/m²), reflecting space constraints and extensive land requirements (Goldstein et al., 2016).

Maximizing LUE in cities involves vertical integration, rooftop usage, and repurposing idle urban plots (Small et al., 2019). Rooftop gardens face structural limitations and sunlight access issues, while community plots are often affected by zoning and land availability.

Nutrient Use Efficiency (NUE)

UA3 displayed the highest NUE (12.0 kg/kg), attributable to controlled nutrient delivery in hydroponic systems. Aquaponics (UA4) achieved 9.4 kg/kg, benefiting from nutrient cycling via fish waste. Backyard and community models yielded lower NUE due to uncontrolled fertilization and loss pathways like leaching and volatilization (Wielemaker et al., 2019).

IoT-based nutrient monitoring, biostimulants, and slow-release fertilizers have been shown to improve uptake and reduce waste. Crop-specific nutrient matching is also essential for maximizing NUE (Goddek et al., 2016).

Labor Productivity

Hydroponics (UA3) achieved the highest labor productivity at 4.5 kg/hr, supported by automation and optimized workflows (Wielemaker et al., 2019). Community (UA5) and backyard (UA6) systems performed lowest due to manual labor and less formalized processes.

Training and automation improve labor efficiency across UA models. Community farms benefit from educational programs and volunteer coordination, though mechanization is limited (Niswar, 2024). Labor dynamics in UA are also influenced by cultural and socioeconomic factors, affecting participation and productivity.

Urban agriculture (UA) is increasingly recognized as a strategic response to food insecurity and sustainability challenges in urban areas. The results of this study underscore significant differences in resource efficiency among the six UA models evaluated. Hydroponic and rooftop systems consistently outperformed others in water, nutrient, land, and labor efficiency, while vertical farming offered superior land productivity but at the cost of higher energy usage. Community and backyard gardens, though inclusive and socially valuable, lagged in overall efficiency metrics. These findings highlight critical implications and trade-offs in the adoption and scaling of UA systems.

The integration of technology in urban farms such as artificial lighting, automated irrigation, and smart nutrient delivery systems has improved productivity and efficiency. However, this reliance on advanced technology must be managed carefully to align with broader sustainability goals. As Wang & Xing (2017) caution, hydroponic systems, while water-efficient, can become energy-intensive and dependent on synthetic fertilizers. Kim & AlZubi (2024) suggest that smart irrigation systems provide a promising balance by optimizing water use without excessive resource consumption. Therefore, the adoption of technologies must be complemented by practices such as organic fertilization and local material sourcing to ensure environmental compatibility.

High-efficiency models like vertical and hydroponic farming deliver immediate productivity gains but carry long-term considerations. The energy demands of vertical farms pose environmental and economic risks if renewable energy integration is not prioritized (Wang & Xing, 2017). Moreover, the capital-intensive nature of these systems can exacerbate socioeconomic inequalities, restricting access for small-scale and low-income urban farmers. Yang et al. (2020) emphasize that equitable policies and inclusive financial support systems are vital for democratizing access to high-tech urban agriculture.

Adopting agroecological practices alongside technological innovation offers a more holistic and inclusive model. By blending traditional knowledge with precision agriculture, cities can develop resilient food systems that balance yield, environmental integrity, and social justice. Policymakers and planners must evaluate not only technological feasibility but also the socio-economic contexts that influence adoption.

Global case studies reinforce the importance of supportive governance. Paris' urban plan includes rooftop and community garden promotion, enhancing green space and food access while reinforcing citizen participation (Fernández, 2017). Similarly, Detroit has leveraged urban agriculture in its urban renewal strategy, employing flexible zoning laws and grant programs to empower communities. These cases illustrate the transformative potential of urban agriculture when integrated into municipal policy.

Socioeconomic disparities also dictate the uptake and success of UA models. High-tech farms are less feasible in resource-constrained settings, where community gardens and low-tech systems are more viable. Nonetheless, even these models require support in terms of training, infrastructure, and policy incentives. Yang et al. (2020) advocate for broader knowledge dissemination and funding accessibility to bridge these divides.

Ultimately, the results affirm that urban agriculture's success depends on the interplay of technology, governance, and community context. Efficient systems alone do not guarantee sustainability equity, accessibility, and cultural alignment are equally vital. Stakeholders must pursue integrated strategies that reflect this complexity, ensuring that urban agriculture evolves as an inclusive and sustainable solution.

CONCLUSION

This study conducted a comparative analysis of six urban agriculture (UA) models rooftop farming, vertical farming, hydroponics, aquaponics, community gardens, and backyard farming based on standardized resource efficiency indicators. The results reveal significant variation in performance across the models, particularly in terms of water use efficiency (WUE), energy use efficiency (EUE), land use efficiency (LUE), nutrient use efficiency (NUE), and labor productivity.

Hydroponic systems consistently achieved the highest levels of efficiency, particularly in water, nutrient, and labor metrics. Rooftop farms also demonstrated strong performance, especially in land and nutrient efficiency. Vertical farming stood out for its superior land productivity but required greater energy inputs, raising questions about long-term sustainability unless renewable energy solutions are integrated. In contrast, community and backyard models, while valuable for social cohesion and inclusivity, showed lower efficiency scores across all metrics.

The study emphasizes the importance of adopting a resource-centric approach when designing and implementing UA systems. Urban planners and policymakers should prioritize models that deliver the highest returns on critical resources, especially in regions where land, water, or energy availability is constrained. Equally important is the recognition that technological efficiency must be balanced with accessibility and social equity to ensure widespread adoption and resilience.

From a policy perspective, this research supports the development of frameworks that incentivize efficient UA practices, integrate sustainability standards, and promote inclusive access to agricultural technologies. Encouraging the use of smart technologies, renewable energy, and integrated management systems will enhance the sustainability of UA in the long term. Furthermore, incorporating community voices and cultural contexts into planning processes will strengthen the social impact of urban farming initiatives.

This study contributes to the growing body of literature on urban agriculture by offering a comparative framework grounded in resource efficiency. It provides actionable insights for stakeholders aiming to design scalable, efficient, and inclusive urban food systems. Future research should explore economic cost-benefit analyses, environmental impact assessments, and longitudinal studies to evaluate the long-term viability and adaptability of different UA models across diverse urban contexts.

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