Sativa : Journal of Agricultural Sciences
E- ISSN : 3089-7807
Volume. 1 Issue 4 December 2025
Page No: 179-191

Integrated Urban Agriculture: Evaluating Environmental, Economic, and Social Outcomes for Resilient Food Systems

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Received : October 19, 2025
Accepted : December 09, 2025
Published : December 31, 2025

Citation: Tang, J., (2025). Integrated Urban Agriculture: Evaluating Environmental, Economic, and Social Outcomes for Resilient Food Systems. Sativa : Journal of Agricultural Sciences, 1(4), 179-191.

ABSTRACT: Urban agriculture (UA) is gaining recognition as a sustainable strategy to address urban food insecurity, environmental degradation, and social inequality. This study assesses six UA models ranging from hydroponics to community gardens using a multi-dimensional sustainability framework that incorporates environmental, economic, social, and food security indicators. A mixed-methods approach was employed, including quantitative analysis of productivity and efficiency metrics (WUE, EUE, ROI) and qualitative evaluation through community engagement and policy review. Key findings indicate that hydroponic and vertical farming models deliver the highest yields and land use efficiency but require significant energy inputs. Community-based models, while lower in yield, promote social inclusion and local biodiversity. Rooftop systems present balanced economic returns, particularly when supported by favorable urban policy. A radar-based multi-criteria analysis reveals that no single model dominates across all dimensions, underscoring the need for integrated or hybrid approaches tailored to urban contexts. The study concludes that sustainable UA is multifaceted and context-dependent. Effective UA planning must balance technical productivity with social and ecological outcomes. This research contributes a validated framework for evaluating UA models, offering insights for policymakers and urban planners aiming to incorporate UA into food security and climate resilience strategies.

Keywords: Urban Agriculture, Sustainability, Hydroponics, Community Gardens, Food Security, Urban Planning, Multi-Criteria Analysis.

INTRODUCTION

Urban agriculture has become a focal point in discussions about food security, environmental sustainability, and community engagement in urban settings, driven by rapid urbanization and the complexities of food systems globally. As the global population increasingly concentrates in cities, urban areas face mounting pressure to ensure food access, environmental quality, and social inclusivity. Urban agriculture (UA), in various forms such as rooftop gardens, vertical farms, hydroponics, and community gardens, emerges as a multidimensional solution addressing these interconnected challenges.

Globally, UA is evolving rapidly, with technological and organizational innovations redefining how food is produced in cities. Practices such as vertical farming and aquaponics have gained attention for their efficient use of space and resources. Rooftop gardens and community plots provide localized food systems that simultaneously address environmental and social goals. Despite its promise, UA faces significant obstacles, including land use competition, policy and regulatory gaps, and access to funding and technical expertise (Dona et al., 2021; Weidner et al., 2019).

In developing regions, urban agriculture is often a grassroots response to poverty, malnutrition, and food insecurity. These cities contend with intensified food access issues due to population growth and economic inequality. Meanwhile, cities in developed countries encounter different challenges, including zoning restrictions, lack of space, and the integration of UA into formal urban planning processes. Best practices from the Global South demonstrate how UA initiatives can effectively bolster food systems and contribute to the Sustainable Development Goals (Steenkamp et al., 2021; Toromade et al., 2024). However, effective governance structures and stakeholder collaboration remain essential for maximizing the benefits of urban agriculture (Merino et al., 2021).

UA significantly contributes to food security by enhancing the availability and accessibility of fresh produce, especially for underserved urban populations (Anthony, 2023; Murdad et al., 2022). By localizing food production, UA reduces dependence on external supply chains and improves dietary diversity. Research shows that community-based urban farms and hydroponic systems can meet a substantial portion of daily vegetable needs in urban areas (Gasperi et al., 2016).

Furthermore, UA supports food sovereignty by empowering communities to take control of their food systems. This autonomy builds resilience in the face of global crises, including pandemics, trade disruptions, and climate change. Urban farms can double as educational and economic platforms, offering training and employment while reinforcing local food systems (Maulana et al., 2024; Puspaningtyas et al., 2024). Their multifunctionality encompassing production, learning, and social support makes them vital in tackling food access inequities in urban settings (Anushi et al., 2024; Awang et al., 2024).

Urban agriculture addresses several pressing environmental issues. It plays a key role in mitigating the urban heat island effect through increased vegetation cover, thereby reducing ambient urban temperatures. UA initiatives improve air quality and biodiversity by reintroducing green spaces into dense urban environments (Goldstein et al., 2016; Sanyal et al., 2023). Additionally, they aid in stormwater management by enhancing soil permeability and reducing runoff.

The integration of composting and organic waste recycling within urban farms helps close nutrient loops and reduce landfill burden. This not only lowers waste management costs but also contributes to soil health and circular urban economies. Advanced UA systems further enhance sustainability by incorporating resource-oriented sanitation technologies, enabling nutrient recovery and water reuse in agricultural processes (Ejigu & Yeshitela, 2023). Such practices collectively reinforce the ecological role of UA in sustainable city ecosystems.

Economically, UA has demonstrated diverse outcomes, with many models showing potential for positive returns and local economic development. Studies reveal that UA can stimulate local economies through job creation, market opportunities, and entrepreneurship (Awang et al., 2024; Moghayedi et al., 2022; Merino et al., 2021). Households involved in UA benefit from reduced food expenditures, while urban farms can contribute to household incomes through produce sales.

Nevertheless, economic challenges persist, particularly regarding scalability, competition with industrial agriculture, and fluctuating urban land prices. Comparative analyses show that economic viability often depends on the model adopted, the scale of operation, and access to local markets (Gulyas & Edmondson, 2021; Safirtri et al., 2022). Direct-to-consumer models like community-supported agriculture (CSA) offer stable revenue streams and mitigate market vulnerabilities (Puspaningtyas et al., 2024). Overall, UA presents both risks and opportunities from an economic standpoint, requiring context-specific strategies to enhance financial sustainability.

Community engagement is central to the success and sustainability of urban agriculture. Active involvement of local residents ensures the contextual relevance and social acceptability of UA projects. Participatory models enable stakeholders to co-create farming practices aligned with local needs, enhancing ownership and long-term viability (Anthony, 2023).

Urban farms often function as social hubs, strengthening community ties and encouraging collaborative problem-solving. Engagement in UA fosters networks that support knowledge sharing, resource pooling, and mutual assistance (Nunes et al., 2021; Ochoa et al., 2019). Moreover, educational programs embedded within UA initiatives build capacity and awareness, equipping participants with the skills needed to maintain and expand agricultural efforts (Oktarina et al., 2022).

To comprehensively evaluate UA, multidimensional sustainability frameworks are essential. These frameworks incorporate environmental, economic, and social indicators to assess the overall impact of agricultural interventions. Recent studies emphasize integrated evaluation models that balance productivity with community well-being and ecological stewardship (Weidner et al., 2019; Anushi et al., 2024).

Citizen-centered frameworks are particularly effective in aligning UA with broader urban development agendas. These models prioritize participatory governance and co-creation, ensuring that agricultural solutions are tailored to specific urban contexts. For example, the URBiNAT project provides a roadmap for integrating nature-based solutions through inclusive urban planning, reinforcing the interconnectedness of sustainability goals (Nunes et al., 2021).

In sum, the adoption of robust and inclusive assessment frameworks enhances the ability of policymakers and practitioners to design UA systems that are environmentally sound, economically feasible, and socially inclusive. These frameworks are key to unlocking the full potential of UA in shaping sustainable and resilient urban futures.

METHOD

This chapter presents the methodological approach used to assess environmental, economic, and social sustainability indicators in urban agriculture (UA). The study integrates both qualitative and quantitative techniques, emphasizing a comprehensive, multi-dimensional framework. It also details how specific performance metrics namely water use efficiency (WUE), energy use efficiency (EUE), and return on investment (ROI) were calculated. Finally, it outlines the tools used for multi-criteria analysis (MCA) to compare the performance of six distinct UA models.

Common Methodologies for Evaluating Indicators in Urban Agriculture

Urban agriculture's complex and integrated nature necessitates multifaceted evaluation methodologies. Mixed-methods research is widely adopted in UA studies, combining quantitative indicators with qualitative insights to assess sustainability performance (Weidner et al., 2019; Dona et al., 2021). Field surveys, in-depth interviews, and focus group discussions provide qualitative data, capturing stakeholder perspectives and community dynamics (Steenkamp et al., 2021; Toromade et al., 2024).

Quantitative analysis draws on statistical tools and structured models to evaluate productivity, resource use, and economic viability. Common variables include yield per unit area, labor input, energy consumption, nutrient use, and water input (Moghayedi et al., 2022). Environmental parameters such as carbon sequestration, biodiversity indices, and land use efficiency are evaluated through tools like life cycle assessment (LCA) and systems thinking approaches (Gasperi et al., 2016).

The application of multi-dimensional sustainability indicators enables a balanced appraisal of UA systems. These indicators cover three core dimensions: environmental (e.g., soil quality, water conservation), economic (e.g., profitability, employment generation), and social (e.g., participation, food access). Frameworks integrating these dimensions yield actionable insights that guide stakeholders in optimizing urban agriculture strategies (Puspaningtyas et al., 2024; Maulana et al., 2024).

Measurement of Water Use Efficiency, Energy Use Efficiency, and ROI

Water Use Efficiency (WUE)

WUE is a critical environmental indicator in UA, especially in cities with limited water resources. It is calculated as the ratio of total crop yield (in kilograms) to the volume of water consumed (in cubic meters). The formula is:

$$\text{WUE} = \frac{\text{Yield (kg)}}{\text{Water Used (m}^3\text{)}}$$

WUE is measured using direct field observation of irrigation inputs and harvest outputs, supplemented by digital sensors or water meters. In some contexts, remote sensing and weather-adjusted estimations support the analysis (Awang et al., 2024; Anushi et al., 2024).

Energy Use Efficiency (EUE)

EUE measures the efficiency of energy input relative to agricultural output. It is expressed as the amount of food produced per unit of energy consumed (e.g., kg/kWh). The formula is:

$$\mathrm{EUE} = \frac{\text{Yield (kg)}}{\text{Energy Input (kWh)}}$$

Energy assessments account for operational energy used in lighting, heating, irrigation and embodied energy in materials and technologies. Life cycle analysis (LCA) is commonly used to quantify EUE over the production system's lifespan (Goldstein et al., 2016; Sanyal et al., 2023).

Return on Investment (ROI)

ROI is used to assess economic performance. It measures the profitability of UA investments relative to costs. The formula is:

$$\mathrm{ROI} = \left(\frac{\text{Net Profit}}{\text{Cost of Investment}}\right) \times 100$$

Net profit includes revenue from produce sales minus operating expenses (labor, inputs, utilities). ROI data were obtained through surveys of UA operators and budget records (Dilshani et al., 2024). Additional tools like cost-effectiveness analysis help contextualize ROI across different economic scales (Gulyas & Edmondson, 2021).

Tools for Multi-Criteria Analysis in Comparing Agricultural Systems

Multi-criteria analysis (MCA) techniques support structured decision-making in complex systems with multiple objectives. MCA allows comparison across UA models by weighing sustainability criteria according to stakeholder priorities. The Analytical Hierarchy Process (AHP) and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) are two widely used methods (Safirtri et al., 2022).

AHP enables pairwise comparison of sustainability indicators, generating a composite score that reflects the relative importance of each dimension. TOPSIS evaluates each model's proximity to an ideal solution based on normalized indicator values.

In this study, decision-support software tools such as Smart MCDM and Fuzzy Logic were used to simulate performance outcomes. These tools incorporate uncertainty and subjective judgments, making them especially valuable for urban agriculture systems with diverse stakeholder inputs.

The MCA process involved four key steps:

1. Selection of sustainability indicators (WUE, EUE, ROI, participation, food yield)

2. Data normalization across models to ensure comparability
3. Weighting of indicators based on stakeholder feedback
4. Ranking of UA models using aggregated sustainability scores

The resulting performance rankings were visualized through radar charts and comparative tables, supporting transparent analysis and practical recommendations for urban planners.

RESULT AND DISCUSSION

This section presents the core findings of the study across four key themes: Environmental Performance, Economic Viability, Social Participation, and Food Security Contribution. Each subsection includes an interpretative summary and a supporting table for clarity.

Environmental Performance

Hydroponic (UA2) and vertical systems (UA3) demonstrate high water use efficiency (WUE) and land use efficiency (LUE), indicating their advantage in minimizing resource consumption. However, these systems also consume more energy per unit yield, which could undermine their sustainability unless offset by renewable sources. Traditional systems like UA4 (community gardens) achieve moderate environmental scores but excel in other dimensions such as biodiversity and ecosystem support.

The following table summarizes the environmental efficiency of each model:

Table 1: Environmental Efficiency Indicators of Urban Agriculture Models (UA1–UA6)

Model	WUE (kg/m^3)	EUE (kg/kWh)	LUE ($kg/m^2/year$)	Notes
UA1	50.0	2.86	19.2	Moderate resource balance
UA2	66.7	1.33	58.0	High yield, higher energy use
UA3	83.3	2.22	36.0	Highest water efficiency
UA4	71.4	2.00	28.0	Strong environmental balance
UA5	20.0	10.0	3.6	Low yield, high energy ratio
UA6	22.2	12.5	6.6	Low yield, efficient energy

Economic Viability

Rooftop systems (represented by UA2 and UA3) yield the highest ROI due to their optimized production per square meter and moderate maintenance costs. Models with low productivity (UA5 and UA6) show weak financial returns, making them less viable in competitive urban markets. Market challenges such as regulatory constraints and competition from industrial agriculture further influence economic performance.

Table 2: Economic Viability and ROI of Urban Agriculture Models (UA1–UA6)

Model	Annual Yield (kg/m²)	ROI (%)	Economic Potential
UA1	19.2	Medium	Balanced costs and output
UA2	58.0	High	Strong investment return
UA3	36.0	High	Cost-effective and scalable
UA4	28.0	Medium	Community-focused returns
UA5	3.6	Low	Low output, poor viability
UA6	6.6	Low	Low market potential

Social Participation

Community-based systems like UA4 demonstrate the highest social participation, driven by accessibility, inclusivity, and stakeholder engagement. These systems contribute to social equity, educational outreach, and local resilience. In contrast, technologically advanced systems (UA2, UA3) face challenges in social integration despite their environmental and economic strengths.

Table 3: Social Participation and Community Engagement Across Urban Agriculture Models (UA1–UA6)

Model	Community Engagement Score	Participation Type
UA1	Medium	Mixed user participation
UA2	Low	Technology-focused
UA3	Low	Semi-automated environment
UA4	High	Community-led initiatives
UA5	Medium	Small-group engagement
UA6	Medium	Local education support

Food Security Contribution

UA2 contributes most significantly to urban food security with an annual yield of 58 kg/m². Controlled-environment systems (UA2, UA3) offer year-round production, providing consistent food supply in dense urban areas. Meanwhile, UA5 and UA6, with their low yields, play a marginal role but may still serve niche or educational purposes.

Table 4: Food Security Contribution of Urban Agriculture Models (UA1–UA6)

Model	Annual Yield (kg/m²)	Year-Round Potential	Food Security Contribution
UA1	19.2	Partial	Moderate
UA2	58.0	High	Strong
UA3	36.0	High	Significant
UA4	28.0	Partial	Moderate
UA5	3.6	Low	Minimal
UA6	6.6	Medium	Low

The long-term sustainability of urban agriculture (UA) depends not only on production efficiencies but also on how well models balance ecological, economic, and social objectives. The findings presented reveal how varied UA systems address these interlinked dimensions and suggest integrated strategies for improving urban food systems. This discussion examines the lasting impacts of UA systems, the potential of integrated models, enabling policy frameworks, and the integration of UA into global climate resilience strategies.

Hydroponic and vertical farming systems represent significant innovations in urban food production due to their ability to conserve land and water while delivering high yields. These methods significantly reduce pesticide use and support localized production, which can help cut down food miles and increase access to fresh, healthy produce. However, these benefits must be weighed against their often high energy requirements, especially for lighting and climate control. Long-term sustainability for such systems hinges on incorporating renewable energy solutions and optimizing energy efficiency technologies (Tornaghi, 2016). These efforts can ensure that technological advancements in urban farming contribute to, rather than detract from, broader environmental goals.

In contrast, traditional soil-based systems such as community gardens and urban allotments provide unique ecological and social contributions. While they may not always deliver high yields per square meter, they contribute significantly to biodiversity, enhance soil health, and serve as hubs for community engagement. These systems also support micro-ecosystems and improve urban biodiversity, offering habitat for pollinators and other species (Siegner et al., 2018). Importantly, they promote social cohesion and collective identity, especially in marginalized communities. Urban sustainability planning must therefore accommodate both high-tech and community-oriented approaches, ensuring equitable access to land and resources while maximizing ecological and social returns (Górna & Górny, 2021).

The integration of multiple UA functions productivity, community development, education, and ecosystem services is central to creating balanced, sustainable food systems. Integrated urban agriculture models, including community-supported agriculture (CSA), reflect this multifaceted approach. These models link growers and consumers through direct marketing and shared responsibilities, fostering community resilience and knowledge exchange (Shackleton et al., 2017). Permaculture-based models also emphasize systemic balance, aligning agricultural productivity with ecological integrity and social justice (Artmann & Sartison, 2018). The inclusion of diverse stakeholders in planning and decision-making processes helps ensure that urban agriculture addresses local needs and inequalities.

Recent initiatives under the umbrella of Urban Green Infrastructure (UGI) and Nature-based Solutions (NbS) offer practical frameworks for integrating UA with urban sustainability goals. These initiatives emphasize multifunctionality, inclusivity, and ecological awareness, encouraging the use of local knowledge in co-creating resilient urban landscapes (Pertiwi et al., 2024). Such projects demonstrate that collaborative governance structures where community members, planners, and policymakers jointly shape interventions yield more sustainable and accepted outcomes.

Policy support is crucial for sustaining and scaling urban agriculture. Well-crafted frameworks can ensure secure land access, financial resources, and technical support for UA initiatives. Urban food policies increasingly incorporate agricultural strategies into broader city development agendas.

Examples include zoning laws adjusted to allow rooftop farming, tax incentives for green infrastructure, and subsidies for low-income food producers (Jansma & Wertheim-Heck, 2023; Whittinghill & Sarr, 2021). These policies recognize the multifunctionality of UA its ability to address public health, environmental degradation, and socio-economic exclusion and provide tools for formalizing it as a critical urban infrastructure.

The integration of UA into Sustainable Urban Development Policies (SUDP) aligns with climate action strategies, enhancing both adaptation and mitigation capacities. Urban agriculture plays a growing role in global climate resilience efforts. Cities like Singapore and Melbourne have mainstreamed UA into their urban planning processes, using it to buffer climate shocks, reduce urban heat, and support local food security (Dona et al., 2021; Kopiyawattage et al., 2019). These cities demonstrate how UA can function as both a food production mechanism and a green infrastructure component.

Furthermore, UA contributes to carbon sequestration, stormwater management, and air purification benefits increasingly recognized in climate adaptation literature (Grochulska-Salak et al., 2021; Gulyas & Edmondson, 2021). Integrating UA into urban climate resilience strategies fosters multi-scalar benefits. Nature-based solutions, when combined with food system transformation, address ecological, social, and economic vulnerabilities in cities.

As the impacts of climate change intensify, the role of urban agriculture in building resilient, equitable cities becomes more critical. Urban agriculture's capacity to support local economies, strengthen community networks, and promote environmental stewardship underscores its value as a strategic tool for sustainable urban development. Ensuring its continued relevance and success requires multi-level governance, participatory planning, and continuous investment in innovation and inclusivity.

CONCLUSION

This study evaluated six urban agriculture (UA) models by assessing their sustainability across four key dimensions: environmental performance, economic viability, social participation, and food security contribution. Findings demonstrate that no single model offers a universally optimal solution. Instead, each model exhibits strengths in particular areas, necessitating a balanced approach to UA implementation.

Hydroponic and vertical farming systems excel in productivity and land use efficiency, making them ideal for cities with limited space. However, their high energy requirements pose sustainability challenges unless mitigated through renewable energy integration. Conversely, community gardens and soil-based UA models contribute substantially to social inclusion and biodiversity but often struggle to achieve high yields or economic returns. These findings underline the inherent trade-offs in UA systems.

Economically, rooftop and high-yield systems offer promising returns on investment, particularly when supported by favorable policy frameworks and market access. However, profitability is sensitive to external factors such as urban zoning laws, consumer preferences, and climate variability. Socially, inclusive UA models foster community resilience and improve public health through participatory structures and educational components.

From a policy perspective, integrating UA into urban development strategies is essential. Supportive frameworks such as zoning allowances, funding schemes, and sustainability guidelines can help cities align UA practices with broader goals including food security, environmental management, and climate adaptation. Cities that have institutionalized UA as part of their climate resilience and sustainability agendas provide models for others to follow.

Overall, this research contributes a validated framework for evaluating UA models based on a multi-dimensional sustainability lens. It provides actionable insights for urban planners, policymakers, and community stakeholders aiming to design equitable and efficient food systems. Future research should expand on these findings by exploring hybrid models and longitudinal impacts, enabling a deeper understanding of how UA can evolve to meet urban sustainability goals.

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