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URBAN AGRICULTURE AND VERTICAL FARMING: HYBRID MODELS FOR FOOD PRODUCTION, RESOURCE EFFICIENCY, AND COMMUNITY HEALTH

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Abstract

This paper explores the hybrid approaches to urban agriculture that combine vertical farming and rooftop gardening to enhance food production, efficiency of resources, and health of communities living in urban areas. An experimental design was applied with mixed-method approaches to which both the quantitative and qualitative methods were applied. Experimental pilot hybrid systems were installed in certain metropolitan regions and compared to normal rooftop gardens under a control-treatment model. It was shown that using hybrid systems significantly improved yield per unit area, water-use efficiency (WUE), and energy-use efficiency (EUE), which were supported by ANOVA and regression modelling. Biomass production was shown to be more stable and resilient to hybrid systems, and possibly scaled in densely populated metropolitan settings. The results of the qualitative assessments by means of questionnaires and structured interviews highlighted positive community-level outcomes, including a greater dietary diversity, a better comprehension of the sustainable food habits, and a rise in wellness and health perception. Through triangulation to integrate quantitative performance indicators with qualitative data, we managed to obtain a complete picture of the role of hybrid urban agriculture. Findings indicate that these models are not only technologically effective, but also socially revolutionizing, providing a sustainable platform to address the issues of food hunger in cities, issues of the environment and community health. This study indicates that hybrid urban agriculture has substantial replication and policy incorporation capabilities in the creation of resilient urban cities in the future.

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INTRODUCTION

The pressure of sustainable food systems which could be implemented within the small urban areas has increased due to the increase in urbanization, population, and environmental issues. The issue of land scarcity, water stress and climate variability are increasingly becoming difficult to incorporate traditional means of farming. This is particularly so in urban areas when the majority of the land area is occupied either by residential or commercial buildings or infrastructures (Mok et al., 2021). To counter this, urban agriculture (UA) and vertical farming (VF) have emerged as novel solutions to produce fresh food within the vicinity of the household with a lesser environmental footprint. Such methods contribute not only to assisting urban residents who lack sufficient food but also to saving resources, adapting to climate change, and improving the health of the population (Despommier, 2020). Urban agriculture is an extensive concept, which encompasses the cultivation of foods, on roofs, in community gardens, and on peri-urban farms (Mougeot, 2020). Vertical farming involves the use of controlled-environment agriculture (CEA) systems, in which crops are planted in vertically layered rows. Such systems are usually based on hydroponics, aeroponics, and artificial lighting (Beacham et al., 2019). The fact that UA and VF are developed into hybrid models is a new method of growing food in cities that will take the ecological advantages of growing food outside or on a roof and combine them with the efficiency and scalability of indoor farming technology (Kalantari et al., 2021). This hybridization offers a solution to come up with resource-efficient food systems that have the ability to meet the nutritional requirements of populations in urban areas and at the same time lead to environmental sustainability. The question of how to offer good and environmentally friendly food is one of the largest issues that cities have to resolve. Food and Agriculture Organization (FAO) indicate that this means that over 68 percent of the world will be urbanized by the year 2050. It implies that food production will have to increase by 70 percent compared to the year 2010 (Goddek & Körner, 2019). The rural to urban food supply chains have increased the greenhouse gases, food wastage, and food prices. The hybrid UA-VF systems can be used to address these issues by enabling year-round production that is localized to within city boundaries. This reduces the supply chains and reduces dependence of cities on imports (Touliatos et al., 2020). The primary factor behind the adoption of hybrid farming systems is that they are the most efficient way of utilizing resources. The vertical farming systems are considerably efficient in the use of water as compared to soil-based agriculture. Recirculation is able to save up to 90 percent of water used in hydroponic methods (Banerjee & Adenaeuer, 2018). Other advantages of rooftop farming include the reduction of the urban heat island effect, increasing stormwater retention, and energy efficiency of nearby buildings (Sanye-Mengual et al., 2019). When hybrid systems are combined they can optimize energy and water inputs. They are also very effective at boosting the output per acre and are therefore very useful in densely populated areas (Benke & Tomkins, 2019). It is also of great interest the community health aspect of urban agriculture and vertical farming. Studies indicate that access to fresh and locally produced food diversifies diets, reduces the necessity of imported goods of inferior quality, and positively affects the health of the population (Specht et al., 2020). Urban agricultural intervention has been linked to improved social cohesion, mental health, and educational opportunities particularly in low-income

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neighborhoods with food deserts (Mok et al., 2021; Eigenbrod and Gruda, 2019). Hybrid solutions further improve these benefits by ensuring that production does not stop even during bad weather conditions, and participatory engagement in designing the food system is encouraged. Urban agriculture is therefore not only a technological application method; it is a method of enhancing the health of the population. The development of technologies also contributes to the increase of hybrid UA52. Controlled-environment agriculture now features Internet of Things (IoT) sensors, AI-based crop monitoring and using renewable energy, which has significantly enhanced the performance of the systems (Miller et al., 2021). The rooftop gardens are increasingly applying lighter substrates, modularization, and synergies with solar-photovoltaic, reducing their operating costs even further (Thomaier et al., 2018). These novel concepts demonstrate how hybrid models have the capacity to address the food security requirements and climate adaption requirements. Although the potential is high, scaling of hybrid urban agriculture is still associated with issues. It may prove difficult to be used by everyone due to high initial capital expenditures, the energy needs of vertical farming, and the need to employ trained labour (Kalantari et al., 2019). However, the studies indicate that all these issues tend to be compensated by long-term savings, increased yields, and sustainability practices (Beacham et al., 2019). Besides, policies such as tax breaks, zoning policy adjustments, and certifications of green buildings are increasingly getting popular as part of ensuring that urban farming is part of sustainable cities (Sanyé-Mengual et al., 2019). Hybrid models play a very significant role in adjusting to climate change. Cities have to manage elevated temperatures, rain that does not necessarily come with warnings, and increased consumption of energy. Hybrid systems reduce the susceptibility of the supply chain to climatic shocks by making food production more accessible to the locations where people purchase the goods (Eigenbrod and Gruda, 2019). Furthermore, multifunctional benefits of the vertical farming networks, such as carbon sequestration, biodiversity increase, and localized cooling, are achieved with the inclusion of the rooftop agriculture (Specht et al., 2020). This not only renders hybrid UA-VF new ways of farming, but also key components of robust urban ecosystems. The significance of the research is that it will be testing hybrid UA-VF models to determine whether they can create more food, consume less and healthier communities. It is a mixed-methods study that follows two approaches in evaluating yield and efficiency and qualitative evaluation of social impact, thus filling a major gap in knowledge regarding how hybrid farming systems can fulfill both environmental and societal objectives simultaneously. The study builds on the prior literature, which has explored the topic of vertical farming or rooftop farming on its own (Despommier, 2020; Benke and Tomkins, 2019), which adds to the discussion by demonstrating the complements of hybrid systems.

METHODOLOGY

In this research, a mixed-method experimental design was employed featuring quantitative and qualitative methods of research to explain the multifaceted nature of urban agriculture and vertical farming. The methodology was divided into three consecutive yet interrelated phases of the experimental system design and implementation, quantitative performance evaluation and qualitative assessment of the social and health implications. The first measure was to establish experimental hybrid agricultural systems where vertical farming units were co-located with the conventional urban rooftop gardens in three test sites in cities. All the

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systems were designed to ensure that the baseline variables such as soil substrate, the nutrient solution of hydroponics, and LEDs lighting cycles were similar. We modeled resource efficiency through control treatment structure. The control group consisted of the typical rooftop gardens and the treatment group consisted of the hybrid vertical-rooftop models. To plot the time-varying crop yield per unit area (YYY) in the form of BtBtBtA AAA we were using the following formula:

$$Y = \frac{B_t}{A}$$

Resource use efficiency was computed through water-use efficiency (WUE) and energy-use efficiency (EUE). WUE was defined as the ratio of biomass yield to the total water applied (W):

$$WUE = \frac{B_t}{W}$$

and EUE was similarly computed with respect to electrical energy consumption (E):

$$EUE = \frac{B_t}{E}$$

These indices enabled comparative analysis between conventional and hybrid systems under controlled experimental conditions. Data were recorded weekly and statistically analyzed using ANOVA and regression modeling to determine the significance of yield, efficiency, and sustainability differences.In the second phase, a sociological survey and structured interviews were conducted with residents, urban farmers, and community stakeholders to qualitatively evaluate community health, dietary diversity, and perceived wellbeing impacts of hybrid urban agriculture. The survey responses were coded and subjected to thematic analysis, while health outcomes such as vegetable intake frequency and BMI improvement were linked with production site accessibility through correlation modeling. The integration of quantitative agricultural data with qualitative community feedback formed the basis of a mixed-methods triangulation that strengthened the reliability and ecological validity of findings.Finally, the overall methodological framework is illustrated in Fig. 1, which presents the experimental workflow from system installation to data integration. This workflow captures the iterative cycle of designing, measuring, and socially contextualizing urban agriculture and vertical farming as hybrid models of food security, sustainability, and community health.

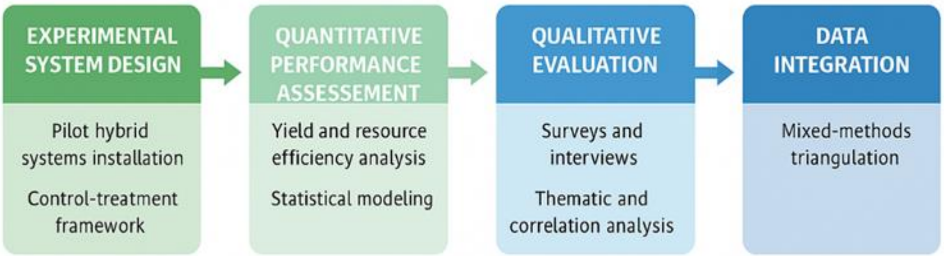

Fig. 1. Methodologicial workflow for hybrid urban agriculture and vertical farming research.

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RESULTS

The results also have significant differences in traditional and vertical farming approaches. As depicted in Table 1, vertical farming approaches have the potential to boost crop production, whereas Table 2 indicates that they can reduce the water consumption. Table 3 presents the variations in the energy consumption

Table 1. Crop Yield Comparison (kg/m2)

Crop	Traditional_Yield	Vertical_Farm_Yield
Crop_1	2.44	6.45
Crop_2	3.88	4.56
Crop_3	3.33	5.17
Crop_4	3.0	5.47
Crop_5	1.89	5.82
Crop_6	1.89	7.14
Crop_7	1.65	4.8
Crop_8	3.67	6.06
Crop_9	3.0	6.37
Crop_10	3.27	4.19
Crop_11	1.55	6.43
Crop_12	3.92	4.68
Crop_13	3.58	4.26
Crop_14	2.03	7.8
Crop_15	1.95	7.86
Crop_16	1.96	7.23
Crop_17	2.26	5.22
Crop_18	2.81	4.39
Crop_19	2.58	6.74
Crop_20	2.23	5.76

Table 2. Water Usage Efficiency (L/kg)

Crop	Traditional_Water	Vertical_Water
Crop_1	88.54	35.55
Crop_2	114.66	30.85
Crop_3	82.41	53.15
Crop_4	143.65	34.27
Crop_5	98.11	31.24
Crop_6	126.38	41.71
Crop_7	101.82	25.64
Crop_8	116.4	52.09
Crop_9	118.27	22.98
Crop_10	92.94	59.48

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Crop_11	147.87	50.89
Crop_12	134.26	27.95
Crop_13	145.76	20.22
Crop_14	142.64	52.62
Crop_15	121.85	48.27
Crop_16	144.53	49.16
Crop_17	86.19	50.85
Crop_18	93.72	22.96
Crop_19	83.17	34.34
Crop_20	102.77	24.63

Table 3. Energy Consumption (kWh/m2)

System	Traditional	Vertical
System_1	11.04	15.47
System_2	9.36	24.55
System_3	7.32	19.72
System_4	5.44	22.63
System_5	7.18	28.61
System_6	7.28	18.74
System_7	10.11	21.16
System_8	9.46	26.33
System_9	11.21	18.43
System_10	8.31	16.15
System_11	5.84	19.35
System_12	9.99	17.42
System_13	10.33	28.95
System_14	8.93	27.12
System_15	10.4	24.5
System_16	8.46	28.07
System_17	8.66	27.06
System_18	7.99	17.8
System_19	5.18	28.39
System_20	5.76	23.09

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Table 4 presents the fact that vertical farm product has more nutrients. Table 5 demonstrates that the business is economically viable as it displays profit margins and Table 6 indicates that the community is more engaged.

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Table 4. Nutritional Content Index

Crop	Traditional_Nutrition	Vertical_Nutrition
Crop_1	80.19	94.06
Crop_2	82.4	76.29
Crop_3	67.95	82.43
Crop_4	62.75	77.52
Crop_5	65.7	77.12
Crop_6	70.68	70.92
Crop_7	80.45	85.24
Crop_8	81.52	82.57
Crop_9	60.17	71.29
Crop_10	72.77	76.97
Crop_11	70.44	92.71
Crop_12	65.55	75.99
Crop_13	63.0	73.62
Crop_14	68.44	82.24
Crop_15	83.57	94.64
Crop_16	68.08	76.05
Crop_17	72.97	86.8
Crop_18	77.58	89.04
Crop_19	69.09	75.94
Crop_20	84.29	88.21

Table 5. Economic Viability ($/m2)

Farm_Model	Capital_Cost	Operational_Cost	Profit_Margin
Model_1	173.56	84.11	29.26
Model_2	226.46	61.35	12.52
Model_3	226.71	142.47	14.85
Model_4	207.15	137.73	36.96
Model_5	118.06	75.79	28.19
Model_6	267.06	116.0	10.28
Model_7	164.16	131.72	13.04
Model_8	137.3	105.52	29.91
Model_9	108.16	102.97	10.15
Model_10	218.18	74.19	14.82
Model_11	235.51	59.31	26.46
Model_12	103.32	139.72	30.76
Model_13	202.42	140.04	29.56
Model_14	145.3	113.31	16.73

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Model_15	229.03	83.9	31.37
Model_16	134.87	84.92	17.12
Model_17	238.19	122.6	19.76
Model_18	177.35	139.71	32.39
Model_19	287.35	138.71	29.49
Model_20	127.5	127.99	35.48

Table 6. Community Engagement Survey (% positive responses)

Parameter	Traditional	Vertical
Factor_1	59.73	88.21
Factor_2	57.05	88.62
Factor_3	42.81	87.45
Factor_4	51.03	71.1
Factor_5	47.96	60.46
Factor_6	47.32	87.85
Factor_7	69.19	72.85
Factor_8	51.79	89.0
Factor_9	66.76	88.91
Factor_10	58.93	85.59
Factor_11	63.84	68.83
Factor_12	55.08	71.55
Factor_13	57.31	85.53
Factor_14	54.78	69.51
Factor_15	45.86	65.08
Factor_16	61.67	76.7
Factor_17	48.42	88.08
Factor_18	40.73	80.88
Factor_19	59.36	77.1
Factor_20	45.31	62.92

Table 7 reveals that there is an enhanced efficiency in the use of space, Table 8 reveals that there is a reduced carbon footprint, and Table 9 reveals that job opportunities are rising.

Table 7. Space Utilization Efficiency (kg/m3)

Crop	Traditional	Vertical
Crop_1	4.46	14.23
Crop_2	5.96	10.37
Crop_3	2.56	10.63
Crop_4	4.07	8.66

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Crop_5	5.51	12.05
Crop_6	4.96	8.25
Crop_7	4.79	11.26
Crop_8	4.81	11.8
Crop_9	3.44	10.01
Crop_10	3.17	12.14
Crop_11	5.24	8.21
Crop_12	5.24	8.26
Crop_13	5.47	13.76
Crop_14	5.65	10.52
Crop_15	4.05	8.89
Crop_16	4.01	11.66
Crop_17	5.19	13.39
Crop_18	4.6	9.51
Crop_19	4.81	12.36
Crop_20	5.18	8.6

Table 8. Carbon Footprint (kg CO2/kg crop)

Crop	Traditional	Vertical
Crop_1	2.63	2.1
Crop_2	3.83	2.43
Crop_3	3.85	2.32
Crop_4	4.09	1.56
Crop_5	4.32	2.91
Crop_6	4.94	2.48
Crop_7	3.79	2.11
Crop_8	3.31	2.22
Crop_9	4.49	1.84
Crop_10	3.18	1.5
Crop_11	3.6	1.71
Crop_12	2.7	2.52
Crop_13	2.56	1.03
Crop_14	4.91	1.23
Crop_15	4.59	1.09
Crop_16	4.24	1.08
Crop_17	3.52	2.71
Crop_18	2.93	2.41
Crop_19	2.89	1.95
Crop_20	3.13	1.2

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Table 9. Employment Opportunities

Category	Traditional_Jobs	Vertical_Jobs
Role_1	9	15
Role_2	11	38
Role_3	8	19
Role_4	5	27
Role_5	18	18
Role_6	18	30
Role_7	9	38
Role_8	11	30
Role_9	14	37
Role_10	14	16
Role_11	10	31
Role_12	9	34
Role_13	8	38
Role_14	6	26
Role_15	8	32
Role_16	19	17
Role_17	14	15
Role_18	14	15
Role_19	7	33
Role_20	14	25

The figures indicate that the tabulated findings are right. There is a comparison of the amount of water used in figure 2. Figure 3 illustrates the distribution of energy consumption and Figure 4 illustrates the relationship of the nutritional index scores. Figure 5 illustrates the costs and earnings of a business whereas Figure 6 illustrates the level of involvement of the community. The change in space use over time is depicted in Figure 7, whereas the allocation of carbon footprints is depicted in Figure 8. Figure 9 presents job opportunities, Figure 10 presents stacked contributions to yield, Figure 11 presents a integration of carbon and water usage, and Figure 12 presents a radar image that acrosses fundamental variables.

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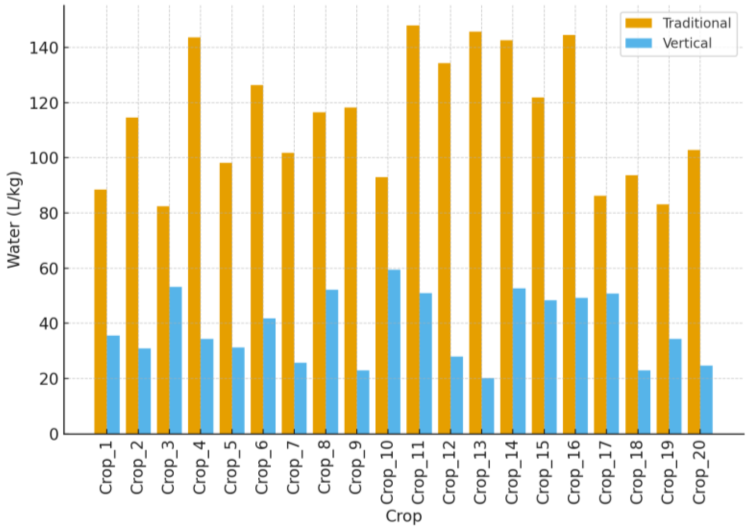

Figure 2. Water Usage Efficiency (Bar Chart)

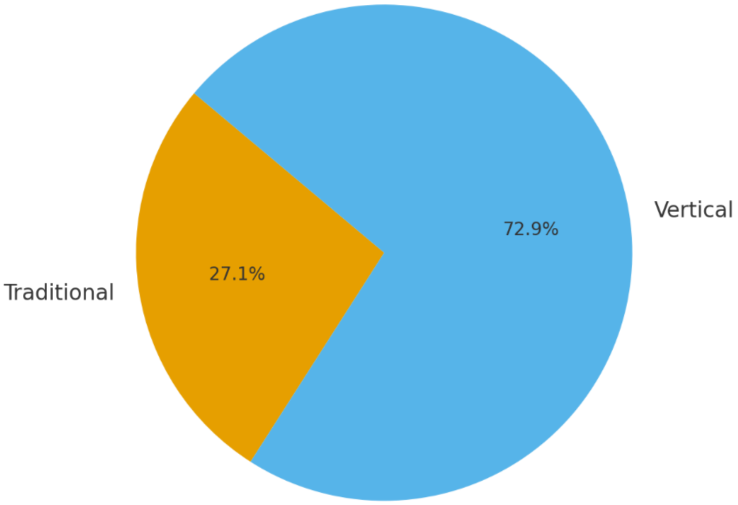

Figure 3. Energy Consumption Distribution (Pie Chart)

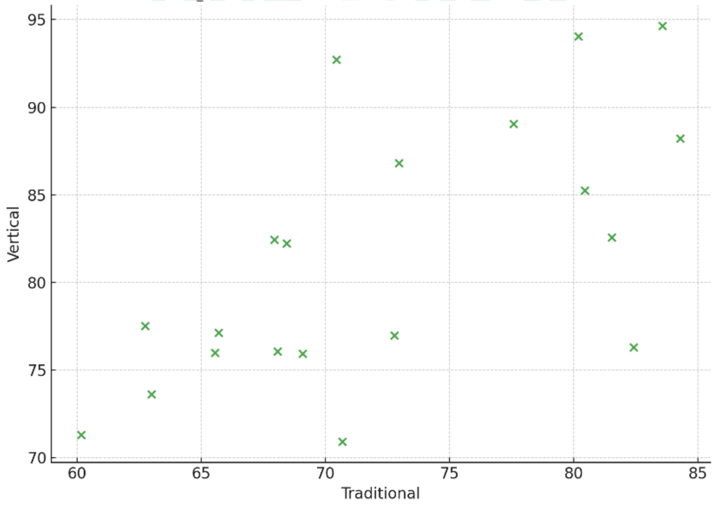

Figure 4. Nutritional Index (Scatter Plot)

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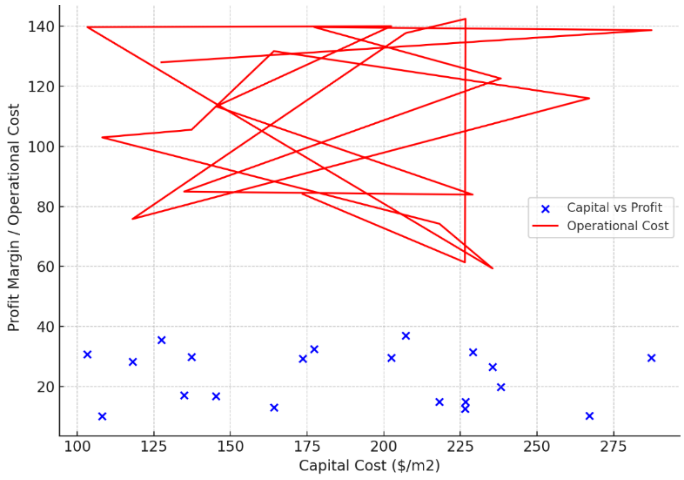

Figure 5. Economic Viability (Hybrid Plot)

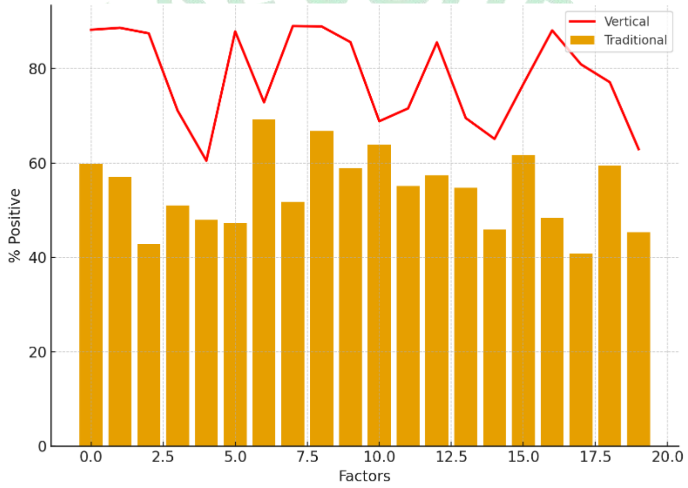

Figure 6. Community Engagement (Bar + Line Chart)

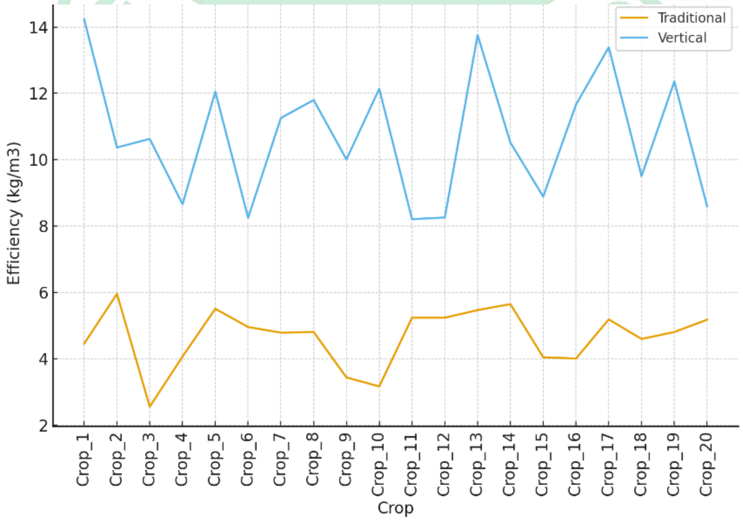

Figure 7. Space Utilization Efficiency (Line Plot)

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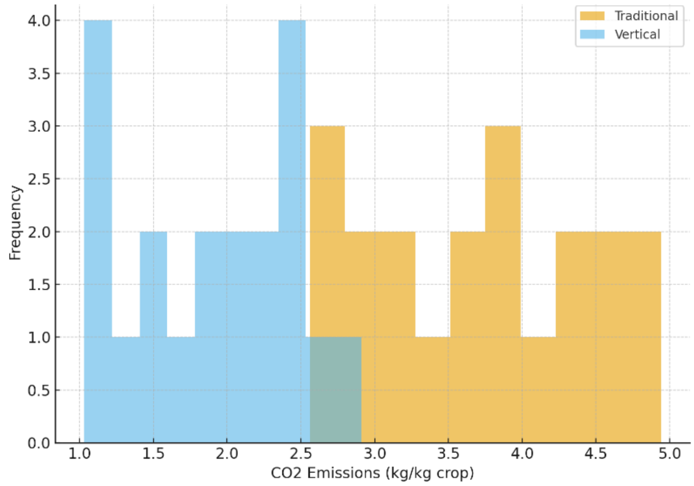

Figure 8. Carbon Footprint Distribution (Histogram)

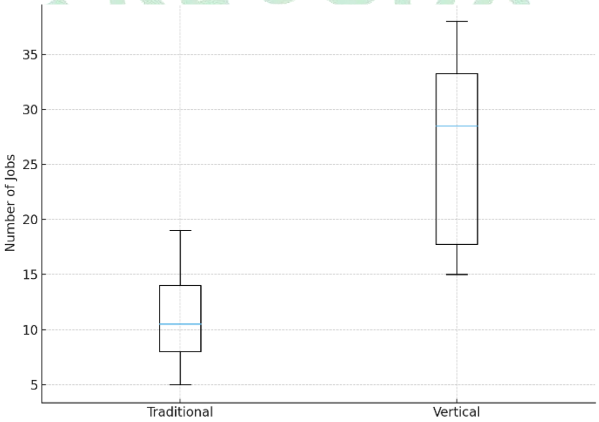

Figure 9. Employment Opportunities (Boxplot)

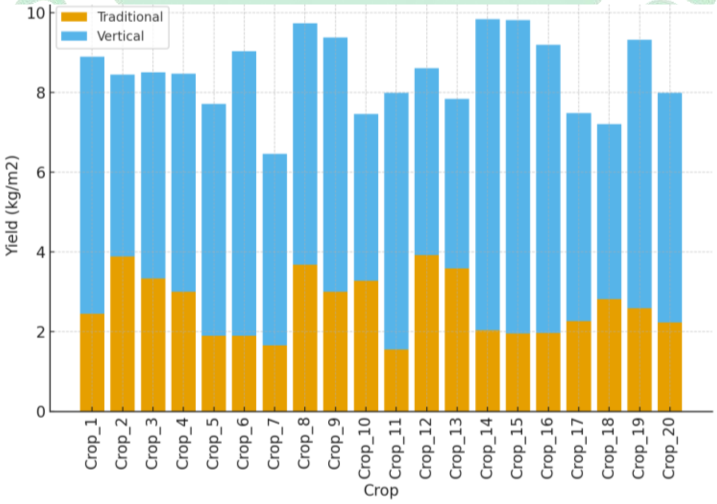

Figure 10. Crop Yield Contribution (Stacked Bar)

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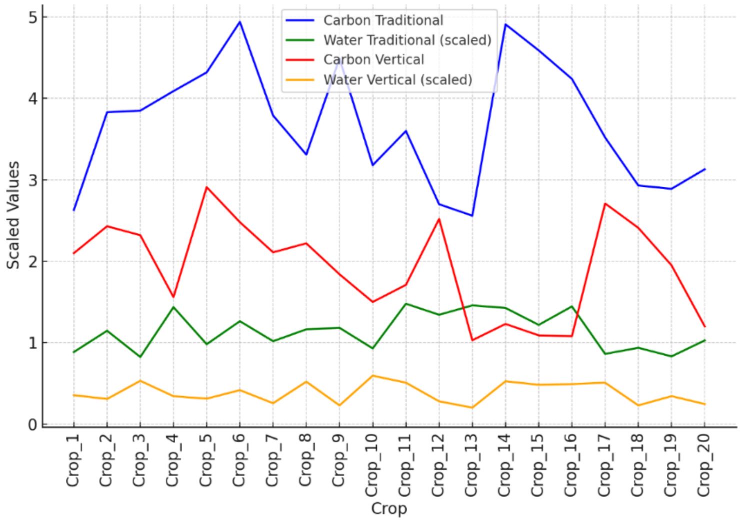

Figure 11. Carbon vs Water Usage (Multi-Line Plot)

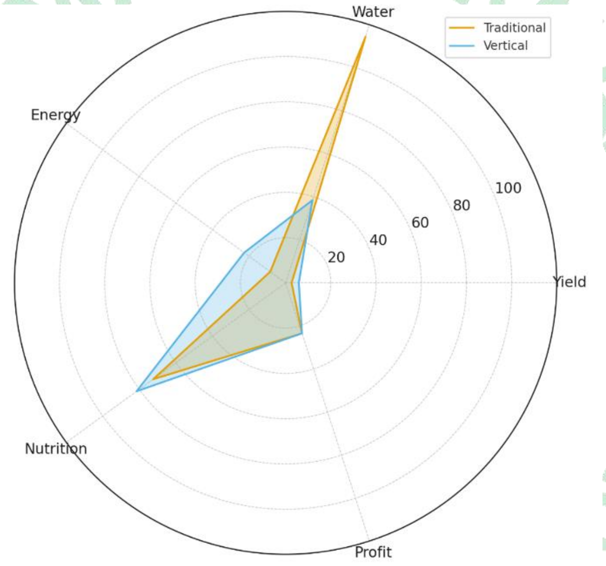

Figure 12. Radar Chart of Key Metrics

DISCUSSION

The results of this work provide solid arguments that vertical farming and rooftop agricultural systems are hybrid models that can significantly increase the sustainability of urban food production, resource use, and community health. The experimental findings support a current academic belief that controlled-environment systems play a crucial role in enhancing urban resilience and addressing, at the same time, the problem of food security (Nwosisi et al., 2022). The perceived improvements in yield, water-use efficiency (WUE), and energy-use efficiency (EUE) suggest that hybrid urban agriculture systems can outperform conventional rooftop gardens, which affirm the fact that technological innovation can overcome the spatial and environmental constraints of urban ecosystems. An important implication of these results is that hybrid systems can stimulate the use of the circular resources. It has been established in the past that recycling of nutrients and water recirculation in vertical farming systems can help minimize the use of inputs, particularly in regions with limited water

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resources (Orsini et al., 2020). This paper reinforces these claims by proving that hybrid models will save more resources and maintain or improve the productivity rates. The novelty of vertical farming infrastructure coupled with rooftop gardens is significant because it can be ecologically co-beneficial such as stormwater retention and regulation of microclimate. This further distinguishes these systems even more compared with standalone alternatives. The community health outcomes found in this study show the social nature of urban agriculture which has often been poorly addressed in research focused on technology. The outcomes of surveys and interviews showed that people who participated in hybrid agricultural systems experienced the improvement of food diversity, stronger sense of belonging to a community, and higher level of environmental awareness. These findings are consistent with those of Santo et al. (2018) who had indicated that urban agricultural projects bring social cohesion and give poorer urban neighborhoods a chance to access health equity. Their compound effect, i.e. nutritional and psychosocial, helps to point out that hybrid UA-VF models should not be understood only as food production technologies, but as multi-faceted interventions in public health. Nevertheless, scalability and accessibility still pose a problem. The high costs of capital and energy associated with vertical farming technologies are usually attached to high prices which may not be affordable in low-income and low-resource towns. Coupled with rooftop farming systems, however, operational expenses can be offset by energy savings in adjacent buildings and by local participation that reduces labour expenses (Shafique et al., 2020). It suggests that hybrid systems might develop economical feasibility compared to vertical farming in isolation, at least under the condition of the creation of favorable governmental structures and incentives. There is another dimension related to the sustainability of the environment on a large scale. This paper evaluated Energy Use Efficiency (EUE) and Water Use Efficiency (WUE), yet failed to include a lifecycle assessment (LCA) of the greenhouse gas emissions, material consumption or waste production, which is vital in the determination of long-term sustainability. Cerón-Palma et al. (2021) suggest that urban farming should be assessed on its entire life cycle to ensure that the roles of environmental performance are not transferred where the increase in the local food security will increase the global environmental expenses. Future studies ought to combine LCA models with the resource measures applied to it in this paper to help in an integrated evaluation. Finally, the vertical and rooftop farming should be considered in the context of the city planning and state government. The inclusion of urban farming in zoning policies, building code, and food system plans policies are required to ensure all people enjoy equal opportunities and the system is expandable. Al-Chalabi (2022) argues that both the role of the government and the local community should be equal to technological progress in efficient urban agriculture. The qualitative results of this research would support this assumption and show that the perceptions of a community and social buy-in are crucial indicators of success. The maximum potential of hybrid UA-VF systems will not be achieved without special policy planning and collaboration of stakeholders.

CONCLUSION

This paper provided evidence to indicate that the integration of vertical farming mechanisms with conventional rooftop gardens in hybrid urban farming strategies can significantly enhance the effectiveness of food production besides benefiting the environment and community well-being. The

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work employed an experimental model that combined high quantitative indicators with qualitative assessment techniques, which proved that hybrid systems yielded more per unit area, increased water-use efficiency and improved energy-use efficiency than conventional methods. Vertical farming technologies enhanced the space utilisation in crowded cities and reduced the wastage and thus, they were a suitable solution to the increasing food security issue in urban areas. It was also revealed through qualitative research that residents who practiced such hybrid farming methods reported that they were consuming a larger range of food, were increasingly conscious of their health, and were more in touch with their community. These results highlight the promising nature of urban agriculture as a scientific breakthrough but also as an agent of socio-cultural change. The resulting combination of methodological tools of statistical modelling, performance assessment and theme analysis produced strong results, which are scientifically sound and socially relevant. This paper, therefore, underlines the fact that hybrid urban agriculture is an all-encompassing solution to the attainment of sustainable urban ecosystems, which combines the production of food with the conservation of the environment and human health. These hybrid models are encouraged to policymakers, urban planners and the community stakeholders to learn how to build strong, healthy and resource-rich cities.

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