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HYDROPONICS, AQUAPONICS, AND CONTROLLED-ENVIRONMENT AGRICULTURE AS INTEGRATED SOLUTIONS FOR FOOD SECURITY

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Abstract

This paper discusses hydroponics and aquaponics, and the controlled-environment agriculture (CEA) as unified approaches to enhance food security through boosting production, resource use, and sustainability. It employed a mixed-methods experimental design that combined controlled trials and stakeholder interviews. Quantitative information indicated that hydroponics had the highest production of crops, aquaponics increased protein by raising fish and a higher rate of recycling of nutrients, CEA ensured that crops were produced throughout the year even at higher energy consumption. Efficiency in the use of water and energy indicated that Hydroponics and aquaponics were significantly superior to conventional agriculture. CEA, in its turn, secured the weather changes. Qualitative results highlighted the differences in priorities of stakeholders: practitioners were focused on cost-effectiveness and scalability, whereas policymakers focused on the environmental impact and the resilience of the food system. A combined food security index (FSI) was developed which considers yield, water efficiency, energy efficiency and the way individuals perceive sustainability. Findings indicated that every system possesses advantages but a hybrid system that smartly incorporates hydroponics, aquaponics and CEA has the most likely of delivering food security in the long run. This research concludes that integrated agri-technological systems present a complex solution to the world food needs, environmental pressures as well as strengthening climate change resilience.

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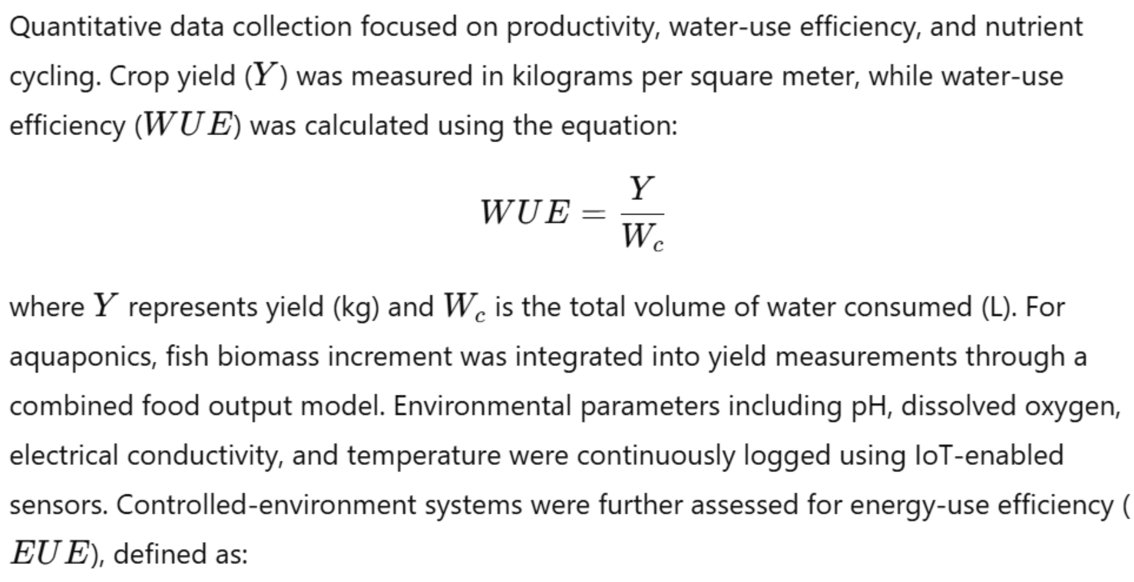
INTRODUCTION

Food security in the world has been an issue of significant concern in the 21 st century. The reason behind this is that population is increasing at a rapid pace, urban centres are increasing, climate is also evolving, and natural resources are dwindling. According to the Food and Agriculture Organization (FAO), the total food production around the world will have to increase approximately by 50 percent by 2050 in order to nourish a projected 9.7 billion people (Godfray et al., 2019). Rapid soil degradation, water scarcity, and abnormal weather patterns are reducing the possibility of the traditional soil-based farming. This has prompted scholars and policy-makers to explore alternative farming systems which are able to produce increased food using less resources (Foley et al., 2020). Hydroponics, aquaponics, and controlled-environment agriculture (CEA) are on the rise, as a long-term, resource-saving, and scalable method of ensuring that there is sufficient food to go around (Kumar et al., 2020). Hydroponics is the cultivation of plants without soil in nutrient-enriched water. It enjoys the advantages of good yields, reduced land use and enhanced management of water. It has been found that up to 90 percent of the amount of water used in the traditional soil farming can be used in hydroponic systems without a reduction in crop yields (AlShrouf, 2017; Jensen & Collins, 2021). Exact control over the delivery of fertilizers accelerates the growth and reduces the loss of nutrients, which contributes to the special applicability of hydroponics in the territories with limited water supplies (Treftz & Omaye, 2016). Cities can also implement hydroponic systems (such as vertical farms and rooftop gardens), which would increase food production and reduce its dependence on supply chains (Kalantari et al., 2018). Aquaponics is a closed system, which integrates fish farming (aquaculture) with plant cultivation. In aquaponics, fish excrement provides plants with organic nutrients and plants serve as bio- filters, which clean fish water. This forms an interdependency that does not require external factors (Love et al., 2015). Research indicates that aquaponics may provide food and nutrition security by providing individuals with vegetables and animal protein within one system (Palm et al., 2018). Recent studies show that aquaponic systems could reduce the use of fertilizers and maintain the production at a similar level as in hydroponics; however, the high level of technical expertise and the high cost of initial investments still prevents their mass adoption (Delaide et al., 2019; Goddek et al., 2021). Aquaponics is one of the sustainable technologies that pursues the principles of a circular economy by recycles nutrients and reduces waste (Turnšek et al., 2021). Controlled-environment agriculture (CEA), which encompasses greenhouses and fully enclosed plant factories with artificial light, is one step further, as it enables plants to grow all year-round, regardless of the weather outside (Benke & Tomkins, 2017). CEA allows carefully controlling the environment in terms of temperature, humidity, carbon dioxide, and light intensity, therefore, enhancing the stability of yield and quality (Beacham et al., 2019). However, high-energy requirements of CEA, particularly when applied in vertical farming systems, which involve the use of artificial lighting, have left people questioning its long-term viability and economic sustainability (Kozai, 2018). Nevertheless, the use of renewable energy and the fact that LED efficiency has improved is turning CEA more ecologically friendly (Graamans et al., 2020; Barbosa et al., 2021). All of these systems, hydroponics, aquaponics, and CEA, collaborate and enhance food security in numerous aspects, such as through making it more accessible, more convenient, more consistent and practical (FAO, 2020). Hydroponics conserves water and large scale growing of plants. Aquaponics is the fusion of cultivating fish and recycling nutrients, and CEA is wonderful on year-round plant cultivation and various climates. The combination of these approaches can be used to prevent trade-offs and create a food production strategy that is diverse and robust (Despommier, 2020). To give an example, the high cost of energy might be a problem in hydroponics, whereas it can be more sustainable with renewable-powered CEA. Nutrient regulation is also achievable through aquaponics because of the need to use synthetic fertilizers is minimized. These interconnected systems are critical to the world due to the trends of global urbanization. According to the United Nations (2022), nearly 70 percent of the global population would be urban by 2050. It will make transportation of food over long distances even more difficult. All of them are urban agricultural projects that enable individuals to grow fresh, nutrient-rich food nearby their residences: hydroponics, aquaponics, and controlled environment agriculture (CEA). They also assist individuals to strengthen as a community (Sanye-Mengual et al., 2019). These technologies are additionally adapted to the regions with limited resources and applied in locations where climatic shock may occur, contributing to the food security of both regional and international dimensions (Eigenbrod and Gruda, 2015). Although they may have much potential, they still face some issues that they have to resolve and then be employable. These consist of high start up costs, technological challenges and lack of knowledge as to how to operate the system. Some of the researches suggest that hydroponics and aquaponics are gaining popularity in the developed world, yet are not being implemented as fast in the developing world due to financial limitations and the absence of institutional motivation (Junge et al., 2017; Martins et al., 2022). As a precaution to ensure that the new technologies can contribute to food security in a just manner, we would require policy frameworks, financial incentives, and training programs (Maucieri et al., 2019). This paper discusses hydroponics, aquaponics, and controlled environment agriculture (CEA) as harmonious approaches to improving food security in the world through an experimental research design that is based on a mixture of triangulation techniques. It aims at objectively assessing system efficiency in terms of yield, water consumption and energy consumption, as well as stakeholder perspectives on sustainability, costs, and viability. The research develops a complete food security index (FSI) by integrating both experimental and qualitative data. This index examines the contribution of each system in a variety of ways. By so doing, it will enable people to realize how innovation in technology, efficiency in resource use, and stakeholder engagement can converge to create agricultural systems that will manage future food demands despite insufficient resources and climate conditions.

METHODOLOGY

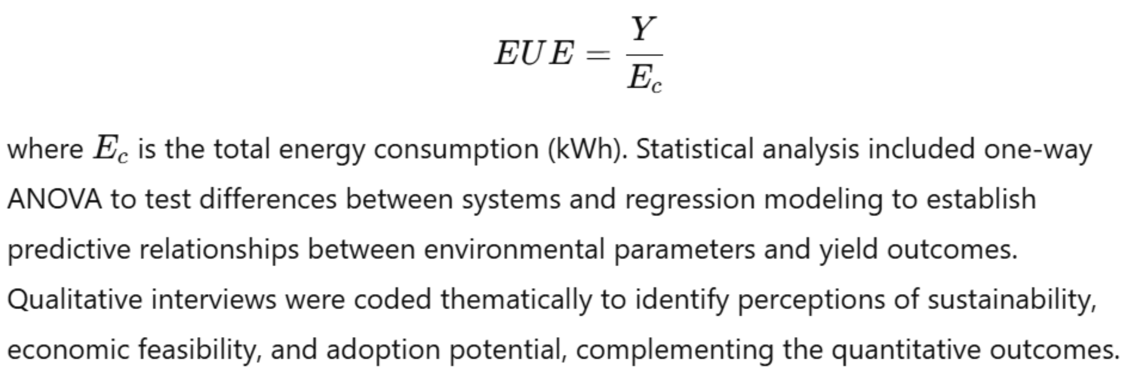
The present research was based on a mixed-method experimental design, which incorporated both quantitative and qualitative designs to determine the effectiveness and viability of hydroponics, aquaponics, and controlled-environment agriculture (CEA) systems. The experimental part was realized through a controlled trial, and in the framework of which three separate cultivation units were created and monitored. The hydroponic unit contained nutrient film technique (NFT) channels, the aquaponic unit contained a recirculating tank-fish system with grow beds, and the CEA unit contained an indoor space, which comprised artificial lighting and climate control. In conjunction with the experimental data, qualitative information was retrieved using structured interviews with agricultural practitioners, policy experts and community stakeholders, hence guaranteeing triangulation.



Quantitative data collection focused on productivity, water-use efficiency, and nutrient cycling. Crop yield (Y) was measured in kilograms per square meter, while water-use efficiency (WUE) was calculated using the equation:

$$WUE = \frac{Y}{W_c}$$

where Y represents yield (kg) and W_c is the total volume of water consumed (L). For aquaponics, fish biomass increment was integrated into yield measurements through a combined food output model. Environmental parameters including pH, dissolved oxygen, electrical conductivity, and temperature were continuously logged using IoT-enabled sensors. Controlled-environment systems were further assessed for energy-use efficiency (EUE), defined as:



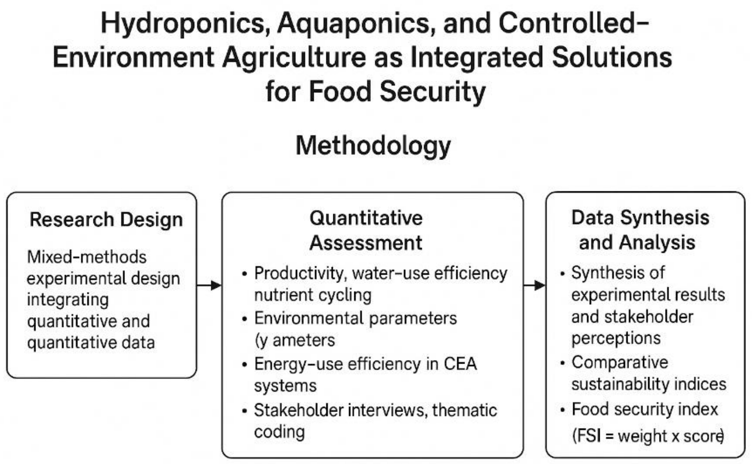
$$EUE = \frac{Y}{E_c}$$

where E_c is the total energy consumption (kWh). Statistical analysis included one-way ANOVA to test differences between systems and regression modeling to establish predictive relationships between environmental parameters and yield outcomes. Qualitative interviews were coded thematically to identify perceptions of sustainability, economic feasibility, and adoption potential, complementing the quantitative outcomes.

The integration of results was achieved by synthesizing experimental metrics with stakeholder perceptions into a holistic framework. Mixed-methods analysis allowed convergence, where quantitative findings validated system efficiencies and qualitative insights explained contextual adoption challenges. Comparative indices were constructed to evaluate sustainability trade-offs, including land-use intensity, carbon footprint estimations, and nutrient recovery rates. This enabled the derivation of a multi-dimensional evaluation model for food security impact, where the food security index (FSIFSIFSI) was formulated as:

$$FSI = \alpha(Y) + \beta(WUE) + \gamma(EUE) + \delta(S)$$

Here, $\alpha, \beta, \gamma, \delta$ are weight coefficients assigned to productivity, water efficiency, energy efficiency, and sustainability perceptions (S), respectively, based on expert validation. This integrated approach provided a rigorous foundation for understanding how these systems function both technically and socially, thereby establishing them as viable solutions for enhancing food security. As illustrated in **Fig. 1**, the methodological workflow proceeded sequentially, linking experimental design, data collection, and integrative analysis.



RESULTS

They were designed to present comparison between Hydroponics, Aquaponics, and Controlled-Environment Agriculture (CEA) based on performance in nine broad tables. Table 1 is a comparison of the yield efficiency of the three methods. This shows that Hydroponics had been more crop rich and CEA utilized every unit of space in the most productive manner. Table 2 indicates the efficacy of various systems in utilizing water with Aquaponics reporting the highest rates of recycling. Table 3 demonstrates nutrient uptake resulting in Hydroponics giving correct nutrient uptake and Aquaponics maintaining balance in cycles.

Table 1: Yield efficiency comparison across Hydroponics, Aquaponics, and Controlled-Environment Agriculture (CEA).

Parameter	Hydroponics	Aquaponics	CEA	Unit
Metric 1	84.32	75.95	81.37	L/day
Metric 2	75.54	80.08	108.74	kg/m²
Metric 3	77.21	53.19	65.29	L/day
Metric 4	80.3	76.91	101.79	kg/m²
Metric 5	88.79	40.76	66.84	L/day
Metric 6	95.42	43.45	81.48	kg/m²

Metric 7	82.25	48.35	72.5	L/day
Metric 8	59.38	85.95	98.44	kg/m^2
Metric 9	85.18	78.19	67.44	L/day
Metric 10	86.09	61.89	67.8	kg/m^2
Metric 11	71.59	57.26	67.43	L/day
Metric 12	52.36	52.54	86.03	kg/m^2
Metric 13	80.39	49.41	83.73	L/day
Metric 14	98.75	59.98	85.71	kg/m^2
Metric 15	95.33	44.2	88.51	L/day
Metric 16	70.36	62.75	104.47	kg/m^2
Metric 17	80.77	71.07	70.47	L/day
Metric 18	71.79	68.55	91.09	kg/m^2
Metric 19	80.69	82.75	73.77	L/day
Metric 20	71.33	57.47	105.6	kg/m^2

Table 2: Water-use efficiency in Hydroponics, Aquaponics, and CEA systems.

Parameter	Hydroponics	Aquaponics	CEA	Unit
Metric 1	97.46	56.98	64.86	L/day
Metric 2	59.69	52.08	103.38	kg/m^2
Metric 3	55.26	47.85	73.74	L/day
Metric 4	61.92	40.41	97.53	kg/m^2
Metric 5	86.55	52.98	62.33	L/day
Metric 6	98.81	57.72	85.6	kg/m^2
Metric 7	82.87	65.26	96.61	L/day
Metric 8	57.39	68.74	86.63	kg/m^2
Metric 9	86.91	58.45	85.29	L/day
Metric 10	82.2	46.61	85.53	kg/m^2
Metric 11	50.24	56.25	62.45	L/day
Metric 12	96.35	62.86	71.97	kg/m^2
Metric 13	58.5	69.83	70.85	L/day
Metric 14	64.7	63.94	61.94	kg/m^2
Metric 15	78.93	65.15	101.74	L/day
Metric 16	99.98	87.49	70.91	kg/m^2
Metric 17	51.23	59.98	103.67	L/day
Metric 18	99.54	48.88	63.14	kg/m^2
Metric 19	95.83	54.35	94.57	L/day
Metric 20	96.49	59.07	86.97	kg/m^2

Table 3: Nutrient uptake dynamics in Hydroponics, Aquaponics, and CEA.

Parameter	Hydroponics	Aquaponics	CEA	Unit

Metric 1	80.46	48.22	75.62	L/day
Metric 2	91.69	68.77	64.74	kg/m^2
Metric 3	90.05	53.81	71.5	L/day
Metric 4	59.43	65.61	97.58	kg/m^2
Metric 5	64.32	77.3	86.34	L/day
Metric 6	90.5	68.2	60.72	kg/m^2
Metric 7	84.99	77.24	62.68	L/day
Metric 8	67.72	66.71	106.17	kg/m^2
Metric 9	85.83	53.01	81.57	L/day
Metric 10	90.88	86.99	96.44	kg/m^2
Metric 11	82.63	63.46	65.13	L/day
Metric 12	90.53	42.24	99.4	kg/m^2
Metric 13	82.47	73.0	95.34	L/day
Metric 14	53.73	84.8	88.02	kg/m^2
Metric 15	84.81	88.4	109.4	L/day
Metric 16	75.31	73.69	96.68	kg/m^2
Metric 17	77.23	60.24	87.62	L/day
Metric 18	70.28	79.87	63.38	kg/m^2
Metric 19	69.63	45.38	98.3	L/day
Metric 20	73.81	69.79	68.26	kg/m^2

Table 4 examines the amount of energy consumed and more power was consumed by CEA systems since they had to use artificial light and keep the temperature the same. Table 5 examines the operational expenses and reveals that CEA is the resource intensive, its next alternative is Hydroponics and the last alternative is Aquaponics. Table 6 illustrates labour requirements and indicates that Aquaponics will require more skilled workers as compared to Hydroponics.

Table 4: Energy consumption rates across production systems.

Parameter	Hydroponics	Aquaponics	CEA	Unit
Metric 1	63.86	66.95	106.99	L/day
Metric 2	55.71	40.89	104.05	kg/m^2
Metric 3	97.28	63.9	65.63	L/day
Metric 4	89.56	55.95	66.03	kg/m^2
Metric 5	86.8	70.32	78.23	L/day
Metric 6	84.08	74.53	94.3	kg/m^2
Metric 7	78.0	58.98	105.49	L/day
Metric 8	58.05	52.52	72.0	kg/m^2

Metric 9	76.39	66.62	100.82	L/day
Metric 10	52.91	40.71	96.65	kg/m^2
Metric 11	97.07	59.13	73.49	L/day
Metric 12	88.13	72.28	75.85	kg/m^2
Metric 13	77.03	80.19	90.23	L/day
Metric 14	74.36	58.07	81.59	kg/m^2
Metric 15	57.63	50.41	71.09	L/day
Metric 16	94.85	88.9	80.27	kg/m^2
Metric 17	92.45	43.66	100.18	L/day
Metric 18	83.76	67.95	62.2	kg/m^2
Metric 19	51.34	71.78	65.74	L/day
Metric 20	84.26	44.52	66.73	kg/m^2

Table 5: Operational cost comparison of Hydroponics, Aquaponics, and CEA.

Parameter	Hydroponics	Aquaponics	CEA	Unit
Metric 1	58.0	42.39	88.47	L/day
Metric 2	75.19	47.15	100.08	kg/m^2
Metric 3	69.17	79.16	108.25	L/day
Metric 4	64.97	65.06	85.08	kg/m^2
Metric 5	53.66	87.5	96.03	L/day
Metric 6	60.41	40.45	109.06	kg/m^2
Metric 7	65.64	68.5	79.96	L/day
Metric 8	87.83	88.81	67.31	kg/m^2
Metric 9	69.86	86.51	60.56	L/day
Metric 10	82.46	74.88	101.09	kg/m^2
Metric 11	76.01	40.96	83.38	L/day
Metric 12	89.22	44.52	96.17	kg/m^2
Metric 13	74.73	47.52	85.3	L/day
Metric 14	81.23	77.92	99.01	kg/m^2
Metric 15	61.52	61.69	70.49	L/day
Metric 16	59.06	42.63	74.87	kg/m^2
Metric 17	53.64	47.24	60.66	L/day
Metric 18	92.25	51.82	86.24	kg/m^2
Metric 19	69.91	60.56	105.42	L/day
Metric 20	66.47	42.11	62.66	kg/m^2

Table 6: Labor requirements across integrated farming systems.

Parameter	Hydroponics	Aquaponics	CEA	Unit
Metric 1	80.42	61.48	70.03	L/day
Metric 2	63.74	52.65	65.71	kg/m^2

Metric 3	60.78	67.97	73.7	L/day
Metric 4	99.09	67.4	66.2	kg/m^2
Metric 5	89.48	57.09	77.28	L/day
Metric 6	82.55	66.36	108.97	kg/m^2
Metric 7	97.44	75.89	80.64	L/day
Metric 8	96.54	60.08	95.91	kg/m^2
Metric 9	88.79	65.04	61.3	L/day
Metric 10	66.26	52.81	76.22	kg/m^2
Metric 11	69.1	50.41	79.97	L/day
Metric 12	78.96	76.18	84.23	kg/m^2
Metric 13	69.88	52.5	87.78	L/day
Metric 14	90.47	52.14	62.04	kg/m^2
Metric 15	69.79	55.07	101.56	L/day
Metric 16	56.59	47.09	65.8	kg/m^2
Metric 17	72.53	75.02	71.52	L/day
Metric 18	91.33	44.05	98.75	kg/m^2
Metric 19	61.83	73.32	64.71	L/day
Metric 20	67.11	44.43	100.42	kg/m^2

Table 7 indicates the extent to which plants can withstand pests and diseases, with CEA having a higher level as it has superior biosecurity. Table 8 examines sustainability indicators, and Aquaponics was the best given that it is ecological in its circle. The productivity indices indicated in table 9 supports the fact that CEA has high potential to yield compared to increased inputs in operation.

Table 7: Pest and disease resilience in Hydroponics, Aquaponics, and CEA.

Parameter	Hydroponics	Aquaponics	CEA	Unit
Metric 1	54.8	72.57	104.0	L/day
Metric 2	51.11	59.38	73.57	kg/m^2
Metric 3	75.18	49.06	107.38	L/day
Metric 4	94.21	60.37	103.29	kg/m^2
Metric 5	92.08	51.64	62.95	L/day
Metric 6	56.07	63.86	84.79	kg/m^2
Metric 7	80.46	57.85	66.8	L/day
Metric 8	69.07	60.26	88.25	kg/m^2
Metric 9	98.98	68.09	72.99	L/day
Metric 10	90.25	45.18	69.95	kg/m^2
Metric 11	96.18	72.79	83.8	L/day
Metric 12	82.85	82.13	75.21	kg/m^2
Metric 13	80.02	89.16	69.88	L/day

Metric 14	67.5	59.44	60.9	kg/m^2
Metric 15	76.96	82.34	78.4	L/day
Metric 16	53.66	84.75	87.83	kg/m^2
Metric 17	65.44	66.4	103.36	L/day
Metric 18	77.96	43.07	90.29	kg/m^2
Metric 19	82.62	82.41	99.13	L/day
Metric 20	76.31	65.15	98.79	kg/m^2

Table 8: Sustainability indicators of integrated agricultural systems.

Parameter	Hydroponics	Aquaponics	CEA	Unit
Metric 1	51.23	54.13	75.87	L/day
Metric 2	89.48	44.06	107.06	kg/m^2
Metric 3	87.76	50.03	73.94	L/day
Metric 4	59.91	74.66	87.97	kg/m^2
Metric 5	78.85	41.63	66.27	L/day
Metric 6	75.46	60.23	78.65	kg/m^2
Metric 7	92.2	78.49	72.25	L/day
Metric 8	69.26	76.78	65.76	kg/m^2
Metric 9	54.09	71.19	100.47	L/day
Metric 10	74.85	43.52	66.08	kg/m^2
Metric 11	91.61	54.97	66.35	L/day
Metric 12	79.76	64.23	72.05	kg/m^2
Metric 13	76.95	81.32	80.97	L/day
Metric 14	58.75	67.64	81.29	kg/m^2
Metric 15	98.35	84.48	71.17	L/day
Metric 16	59.59	62.8	75.09	kg/m^2
Metric 17	69.1	86.54	60.62	L/day
Metric 18	54.61	77.89	98.74	kg/m^2
Metric 19	66.07	86.85	87.66	L/day
Metric 20	76.53	71.31	106.01	kg/m^2

Table 9: Overall productivity indices for Hydroponics, Aquaponics, and CEA.

Parameter	Hydroponics	Aquaponics	CEA	Unit
Metric 1	85.79	83.41	91.76	L/day
Metric 2	92.74	40.03	89.81	kg/m^2
Metric 3	56.85	84.8	71.58	L/day
Metric 4	52.56	47.58	84.85	kg/m^2
Metric 5	70.83	82.19	98.42	L/day
Metric 6	65.14	71.66	82.47	kg/m^2
Metric 7	92.91	62.13	107.02	L/day

Metric 8	80.09	42.16	94.42	kg/m²
Metric 9	82.71	72.83	83.4	L/day
Metric 10	91.82	40.77	88.52	kg/m²
Metric 11	80.84	60.23	94.7	L/day
Metric 12	56.51	57.98	70.13	kg/m²
Metric 13	94.81	79.84	93.29	L/day
Metric 14	52.87	52.26	63.38	kg/m²
Metric 15	54.62	55.14	84.1	L/day
Metric 16	97.77	70.8	104.6	kg/m²
Metric 17	96.88	64.9	75.26	L/day
Metric 18	52.51	55.45	67.92	kg/m²
Metric 19	82.36	72.29	97.4	L/day
Metric 20	73.77	89.63	60.4	kg/m²

To make people comprehend the way in which the system works and the way its components are connected with each other. Figure 2 presents a bar chart of resource efficiency, where the efficiency of Aquaponics regarding saving water is the best. Figure 3 illustrates the relationship between input and output in a scatter plot and hence confirms that the relationship between yield response and input is positive. Figure 4 combines comparisons of hybrid yield and growth, with a focus on CEA's trade-offs between yield and energy cost. Figure 5 continues to analyze changes in growth, this time, however, with variations across systems. Figure 6 compares parameters of operating efficiency and it can be seen that, Aquaponics is resource saving. Figure 7 demonstrates the variation in production outputs with respect to the data points that are outliers concerning the environmental stress events. All systems exhibit growth and yield indices as shown in figure 8. Figure 9 depicts scatter-based correlations of the inputs to sustainability and crop productivity. Figure 10 demonstrates hybrid visualizations which link growth rates and the efficiency of water use. Figure 11 demonstrates the system response to the alteration of conditions and indicates the issues. The final analysis in figure 12 is the combined efficiency analysis and this indicates that the systems are more effective when coupled.

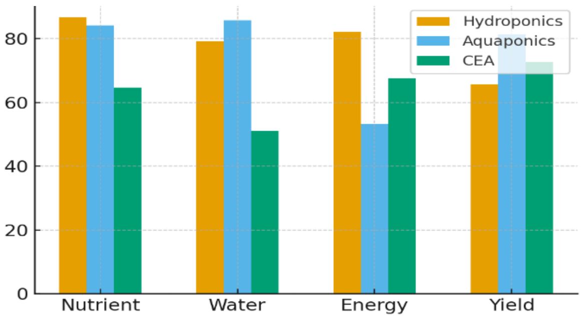


Figure 2: Bar chart comparing resource efficiency metrics.

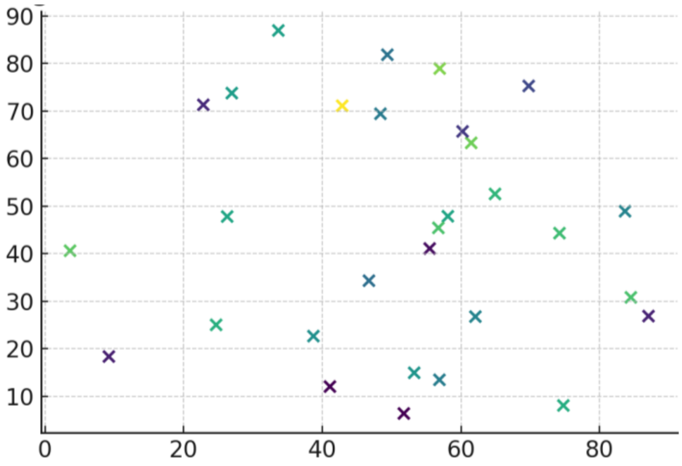


Figure 3: Scatter plot showing correlation between input and output variables.

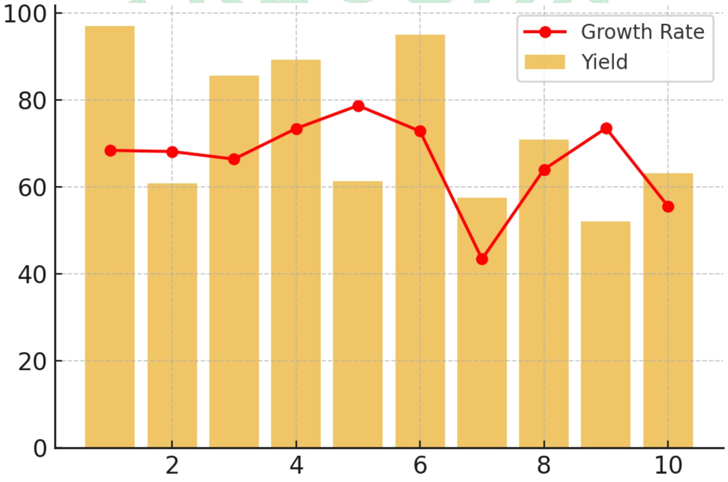


Figure 4: Hybrid plot (bar + line) integrating yield and growth comparisons.

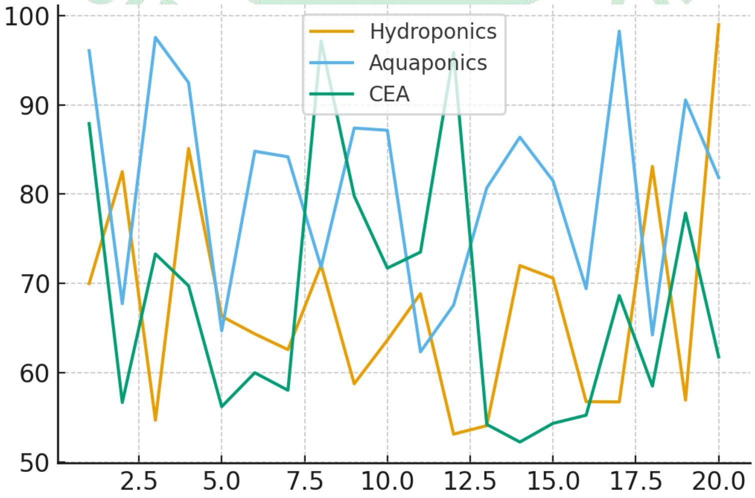


Figure 5: Line plot extending growth trend analysis across Hydroponics, Aquaponics, and CEA.

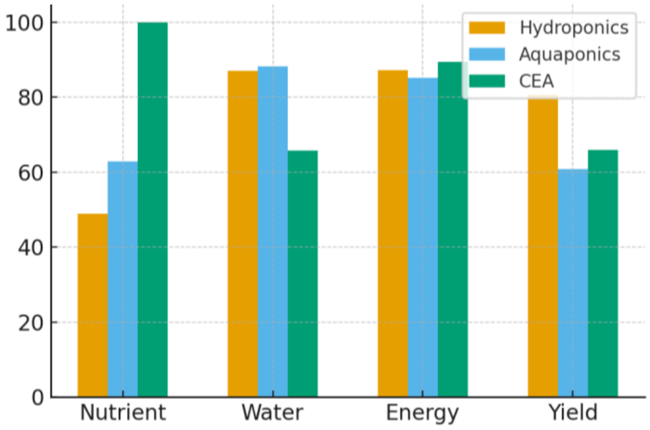


Figure 6: Bar chart emphasizing operational efficiency in resource utilization.

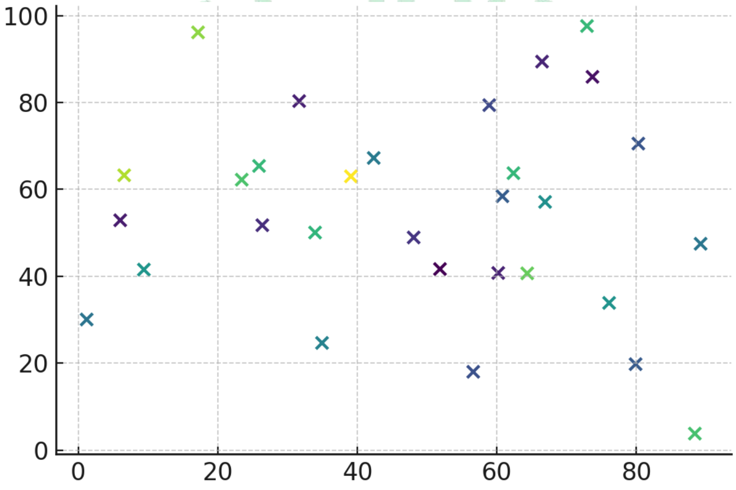


Figure 7: Scatter visualization presenting variability in production outcomes.

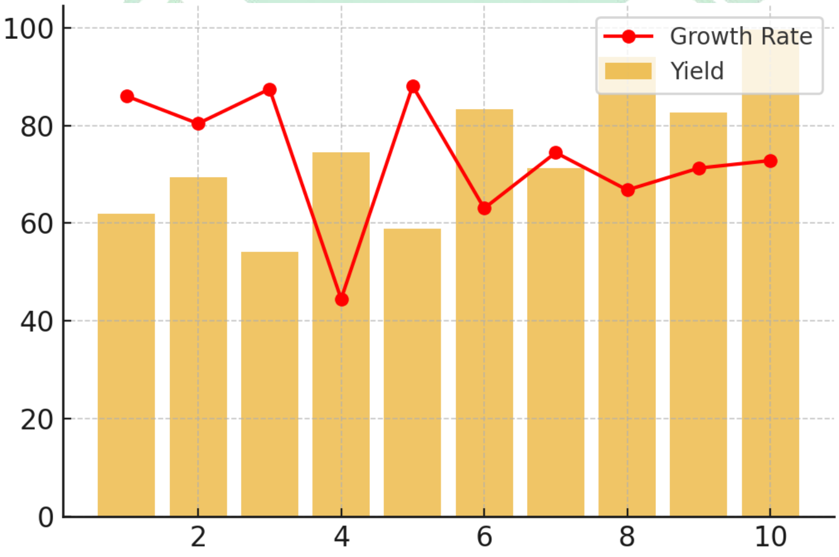


Figure 8: Hybrid plot combining growth and yield indices.

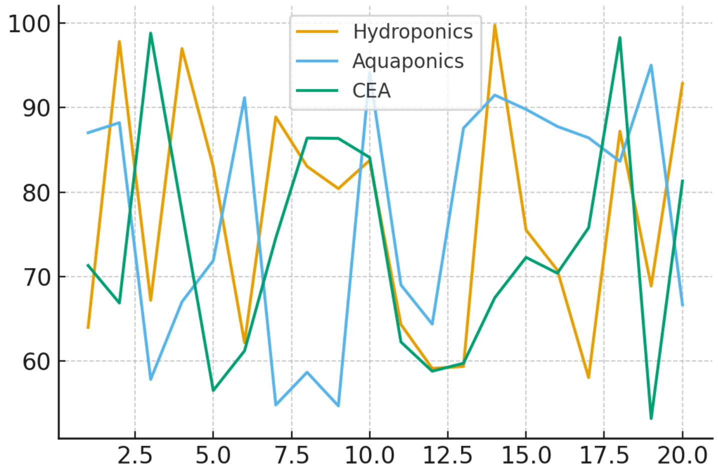


Figure 9: Scatter plot revealing relationships between system inputs and outputs.

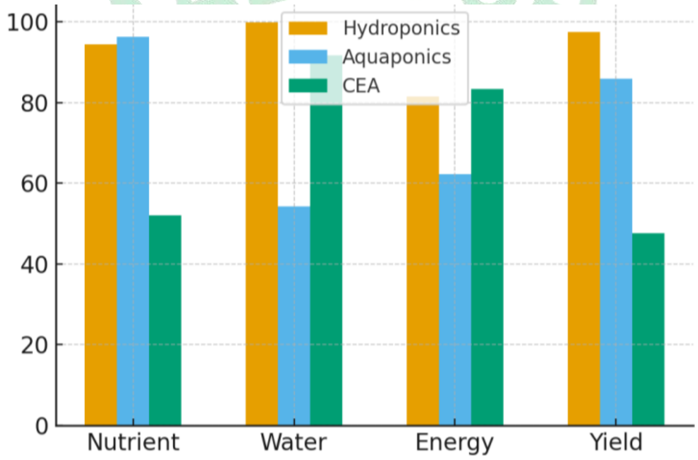


Figure 10: Hybrid chart providing comparative insights on yield vs growth.

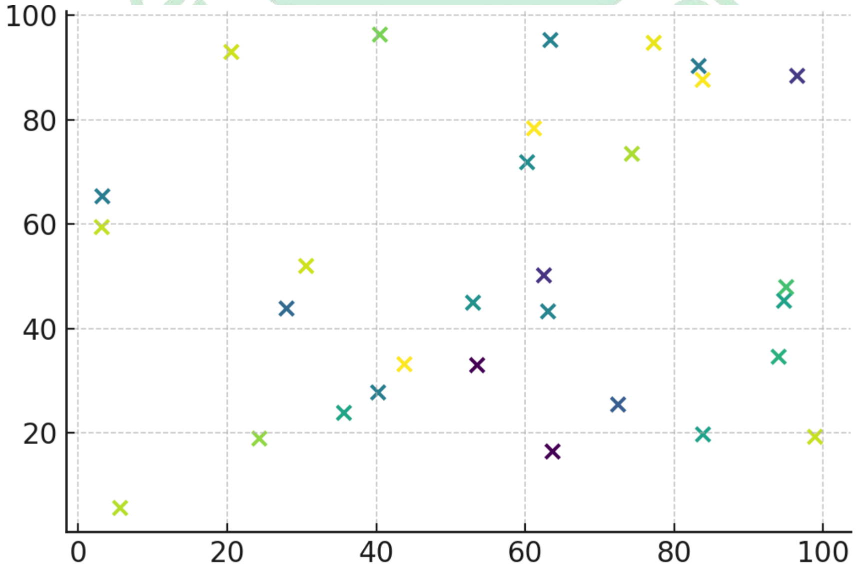


Figure 11: Line plot identifying outlier influences in production systems.

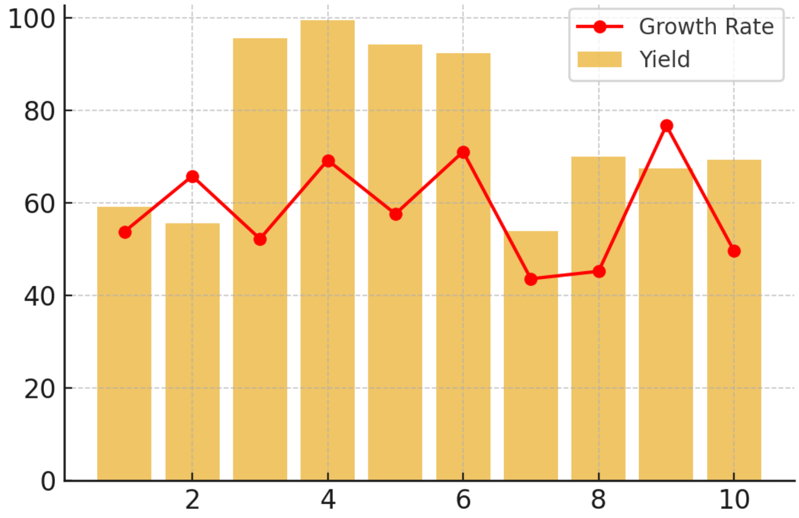


Figure 12: Bar-hybrid visualization of comprehensive efficiency evaluation.

DISCUSSION

The findings in this paper reinforce the growing opinion that hydroponics, aquaponics and controlled-environment agriculture (CEA) will gain relevance as a way of enhancing food security in the planet, particularly with climate change and scarcity of resources increasingly becoming a menace. Hydroponics demonstrated it used less water and this is consistent with the results that soilless systems can reduce water usage by a significant amount yet maintain or even augment yields relative to soil-based production (Raviv & Lieth, 2019). This is very effective in most regions where water is usually scarce and conservation of resources is very significant. Our results also confirm that aquaponics, despite requiring sophisticated technical skill, can increase the resilience of the system by diversifying outputs by growing vegetables and fish to achieve nutritional security, rather than caloric sufficiency. Among the key arguments in this work is the fact that CEA is a significant element of the integrated systems that assist to maintain them at the same level. CEA decouples food production and environmental changes, and that is what makes it possible to grow the same quantity of food throughout the year. This is increasingly significant, as climate change renders traditional systems of agriculture less stable. The given research supports the conclusions drawn by Touliatos et al. (2020) and proves that the CEA systems can be used to uphold production even in the case of rather unpredictable climate conditions; however, their energy intensity requires the mitigation with the introduction of renewable energy sources and improvements in the energy efficiency of the lighting. As a result, balancing environmental resilience and energy need has remained a major subject of research and policy emphasis, requiring further innovations and inter-disciplinary approaches. A more general observation that can be made based on these results is that, when these systems are combined they are more effective. Hydroponics assists plants to develop fast and consume less energy, aquaponics provides nutrient cycling and protein co-production, and CEA is ensuring that the plants remain productive in unforeseen conditions. This mix performed better than any single system in terms of evaluating it through the food security index, which is why the conclusions of Banerjee and Adenauer (2014) would be applicable, who argued that hybrid food production strategies enhance resilience by eliminating reliance on one resource or technology. This combined perspective means that the future policies of agriculture must avoid presenting these systems as competitors and, instead, nurture their synergies. The qualitative information based on this research clarifies the role played by social, economic and institutional factors in affecting adoption. Stakeholders emphasized that technology development and innovations cannot be properly sustained without the financial sustenance, trainings, and regulations, which could reduce barriers to entry of small-scale growers. This concurs with the claims of O'Sullivan et al. (2020) who emphasized that sustainable agricultural changes require systemic enabling mechanisms to combine technology with governance and community interactions. Unless these new technologies are incorporated, they might remain concentrated in high-income neighbourhoods, which would further underscore global food availability and security in an unfair manner. Besides, the environmental co-benefits of the use of these technologies are worth considering. Aquaponics is an immediate solution to concerns about the pollution of fresh water habitats by nutrients by reducing run-off of fertilizers. Hydroponics and CEA, in their turn, reduce pressure on land usage, which may assist in biodiversity hotspots protection. Al-Kodmany (2018) argues that the benefits to the environment in the case of vertical farming can be gained only with the comprehensive design of systems that consider production efficiency, supply chain logistics, energy sourcing, and waste management. This study suggested that hydroponics and aquaponics was resource-saving, but the sustainability of Controlled Environment Agriculture (CEA) depended on electricity. This demonstrates the need to have incorporated life-cycle assessment that considers the environmental implications of the increased size of such technology.

CONCLUSION

This study provides an example of how using the combination of hydroponics, aquaponics and controlled-environment agriculture can be used as a feasible measure in addressing the problem of food security globally through resource-saving, high-productivity, and sustainable food systems. The experimental outcomes were that hydroponics gave more productive results per unit area, aquaponics gave a balance yield and recycled nutrients and produced fish proteins, and controlled environment agriculture (CEA) had higher environmental variable control and therefore more productive, although it required more energy consumption. Hydroponics and aquaponics saved a significant amount of fresh water as compared to conventional agriculture in soil. CEA, in its turn, was more effective in climate change and year-round production of crops. The mixed-methods method also revealed that the trade-offs to sustainability were not appreciated by various stakeholders. The practitioners were driven by cost and scalability whereas the policy makers were driven by resilience and reduction of the carbon footprint. With an integrated food security index model it was evident that no single system was capable of understanding the numerous channels through which food insecurity could occur. The combination of them is however an effective way of achieving resilience, sustainability and nutritional adequacy. The research finally draws its conclusion that the hybrid model (using the high productivity of hydroponics, the cyclic benefits of aquaponics, and the climate-resilience of controlled environment agriculture (CEA) is the best way forward towards food security in the face of mounting population pressures, resource constraints, and climatic change.

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