
INVESTIGATING THE FEASIBILITY OF USING AQUAPONICS SYSTEMS FOR SUSTAINABLE FISH AND VEGETABLE PRODUCTION IN URBAN AREAS

Naveed Hussain^{1*}, Irum Habib²

¹ Faculty of Agricultural Sciences, Bahauddin Zakariya University, Multan, Pakistan

² Government Girls Degree College No. 2, Dera Ismail Khan, Khyber Pakhtunkhwa, Pakistan

*Corresponding Author E-mail: naveed.hussain@bzu.edu.pk

Abstract: The growing pressures of population expansion, climate variability, and resource scarcity necessitate innovative and sustainable food production systems. This study experimentally evaluated the performance of an integrated aquaponics system combining recirculating aquaculture and hydroponic plant cultivation within a closed-loop framework. A mixed-method approach was employed, integrating quantitative measurements of water quality, fish growth, plant productivity, nutrient transformation efficiency, water reuse, and energy consumption with qualitative assessments of operational stability and system feasibility. The results demonstrate stable physicochemical water conditions suitable for both aquatic and plant organisms, alongside significant fish biomass gains and high plant yield. Efficient nitrogen conversion and nutrient recovery confirmed the effectiveness of biofiltration processes, enabling near-zero waste discharge. Water-use efficiency was markedly improved, with substantial reductions compared to conventional agriculture, while energy productivity ratios indicated favorable system efficiency. Graphical and tabulated analyses further revealed strong correlations between nutrient availability and biological performance, as well as consistent productivity across seasonal variations. Overall, the findings establish aquaponics as a resource-efficient, environmentally sustainable, and scalable food production model, particularly suitable for urban and land-constrained settings. The study highlights aquaponics as a promising solution for enhancing food security while minimizing ecological footprint.

Keywords: Aquaponics, Sustainable Agriculture, Urban Food Systems, Nutrient Recycling, Water-Use Efficiency, Circular Economy

Article History

Received:
July 15, 2025

Revised:
August 08, 2025

Accepted:
November 03, 2025

Available Online:
December 31, 2025

1. INTRODUCTION

The need to develop efficient and sustainable food production systems is also enhanced by the fact that the number of people in the world is expanding and is expected to reach 9.69 billion people by 2050 (Ravani et al., 2024). Such population growth and more uncertain impact of the climate change require new approaches to agriculture that would guarantee food security with a reduced environmental price (Elmorsy and -Soud, 2023, p. 122). There is a dire need to find alternative solutions since the conventional farming methods are regularly resource-intensive, i.e. huge areas of land, employment of enormous quantities of freshwater, and soil erosion (Vanacore et al., 2024). Aquaponics (rearing of aquatic animals with hydroponic (growing plants without soil) and on a symbiotic environment) is one of the promising integrated agri-aquaculture that should resolve water-food-energy nexus that is currently on high demand (Goda et al., 2025; Verma et al., 2023). This innovative solution will enable to cut the water consumption by a substantial percentage by using the waste products generated by the fish farming industry as the nutrient source in the cultivation of plants, and it will decrease the pollution that has been commonly related to conventional farming (Elsbaay et al., 2025; Ibrahim et al., 2023). Having a closed-loop system provides a sustainable paradigm of food production in particular in urban centres with a small amount of land spaces since it recycles water and does not need soil and artificial fertilisers (Channa et al., 2024; Hutagalung et al., 2023, p. 1259). This hybrid system will offer a feasible solution to food scarcity and environmental degradation in dense areas that will be a paradigm change to a sustainable food approach (Bhattacharjee, 2025). The economic viability of the utilization of aquaponics systems, the advantages and disadvantages of this method to the

environment, and the difficulty to operate such systems in urban areas will be taken into consideration in this paper to assess the potential of this model as the tool of sustainable fish and vegetable production (Gomez-Ruiz et al., 2024, p. 206; Sewilam et al., 2022, p. 1). In particular, the paper will explore the idea of aquaponics and food production by combining hydroponics and aquaculture that will lead to decreased ecological footprint and resource-efficiency (Paes et al., 2025). The fact that aquaponics is closed and provides solutions to the modern problem of overpopulation, lack of water, or water destruction makes this practice a green solution, which has become the subject of attention in a broad spectrum of spheres, including agriculture, ecology, or fisheries (RC & Rawal, 2024, p. 79). This method is related to a positive impact on aquaculture and traditional agriculture as it does not only supply the fresh food and protein steadily but also mitigates the harmful discharge and optimizes the nutrient recovery (Verma et al., 2023). This method is especially city-friendly because it encourages cultivation of crops in very small areas to the fullest and hugely decreases the use of freshwater under a symbiosis with fish waste being transformed into plant nutrients (Lora et al., 2024, p. 1; Sewilam et al., 2022). It is a closed cycle system whereby hydroponics and aquaculture is involved. Both plants absorb the water and fish excrement feeds the plants with the required nutrients (Debroy et al., 2025; Estim et al., 2022, p. 1). This practice will be appropriate to reduce wastes and make better use of resources, which is in accordance with the principles of the circular economy (Dennison et al., 2025). Such a bi-integration of food is a long-term solution to food production because it can minimize the dependence on external sources and decrease the environmental impact to save resources and achieve

food security (Goda et al., 2024; RC & Rawal, 2024, p. 84). This is supported by the fact that the given system can yield high-quality organic food which may have more economic and ecological advantages due to the ability to save water (up to 90 percent) as compared to the conventional methods of farming and the possibility to implement it in the urban spaces (Estim et al., 2022, p. 10; Lora et al., 2024, p. 1). Furthermore, although it is not a large-scale process, annual-round production possibilities of aquaponics render it an essential technology to meet the elevated demand of fresh food in cities, in addition to countering its negative impact on the environment (Osman, 2021, p. 786). These systems have been based on the nitrogen boosted effluent of aquatic animals to supply direct nutrients to the hydroponically cultivated plants to yield edible products and clean the water that will be utilized by aquatic animals (Xu et al., 2024, p. 9). This is a bio-integrated strategy that is conducive to achieving a superior food security by developing the Sustainable Development Goals of the UN and the rising needs of a growing world population (Verma et al., 2023). The result of this cycle of production makes this sustainable system of farming effective because it transforms fish waste, which is rich in ammonia, into nitrates and, therefore, required by the growth of plants, as it was previously considered a requirement of the conventional aquaculture (Gayam et al., 2022). This nearly zero-discharge strategy enhances recycling of nutrients and wastewater substantially, by reducing the adverse discharge of the dangerous aquaculture, and offering maximum usage of scarce land and water resources (Goda et al., 2024, p. 9; Verma et al., 2023). It is a more attractive alternative to the current models of food production because it is a complicated process of bio-filtration, which does not only reduce the ecological footprint but also provides a synergistic habitat where aquatic and plant organisms live (RC

& Rawal, 2024, p. 83). This symbiotic interaction provides a paradigm of sustainable resources utilization that promises an opportunity to recycle water and achieve consumption and the use of chemical fertilisers reduction (Goda et al., 2024, p. 2; Shema and Abdulmalik, 2022, p. 8). The technique can be applied to localised food manufacturing, with up to 90 percent less water than standard agriculture, and can be applied in a vast variety of settings, such as dry and urban ones (Chandramenon et al., 2024, p. 109257; Lora et al., 2024, p. 2). The initial distinction between Aquaponics and the conventional food systems is that it is environmental-friendly because it has long-term nitrogen cycling processes and unswerving rich in nutrients effluents (RC & Rawal, 2024, p. 84). The fact that the toxic waste ammonium is converted into nitrates which are used by plants by a specialised bacteria in biofilters implies the ecological benefit of aquaponics (Cammies et al., 2021, p. 1246; Rajalakshmi et al., 2022, p. 1279). This innovative strategy in hydroponics and aquaculture is a good foundation of water cleaning and harvesting nutrients, which makes it an extremely useful and environmentally friendly food production method (Modarelli et al., 2023; Rajalakshmi et al., 2022, p. 1278). This is a very effective approach that forms a critical aspect of the sustainable urban food system since such an approach will result in the cycle of nutrient being constant and less water consumed. The additional efficiency can be optimized through aquaponics and artificial intelligence and machine learning. This will be putting the maximum on the use of resources, make agriculture more sustainable and lucrative and address the issues that refer to global food security (Debroy et al., 2025). Indicatively, the E-CityFarm system already possesses automated control system to grow plants and fish optimally and variables to monitor the climate conditions, acidity of the water

and the intensity of light (Hartono et al., 2022, p. 1056). The management and monitoring of aquaponic systems in cities allow the creation of an environment that is highly controlled to optimize on the production and reduce the use of resources (Hartono et al., 2022, p. 1055). Such high-tech solutions should be combined to reach the target of scaling aquaponic activities to the demands of densely populated urban centers and switch to the Aquaponics 4.0 paradigm (Chandramenon et al., 2024, p. 109257). The improved model increases the trust of consumers in commodities manufactured using aquaponics because it is based on digital technology and data processing to guarantee complete traceability and openness in the production of aquaculture products (Karimanzira and Rauschenbach, 2021, p. 345). This novelty allows a dynamic response in environmental settings along with nutrient availability to optimise production and resource exploitation in both complex urban aquaponics systems to realise precision farming on a scale that has never been mentioned before (Channa et al., 2024).

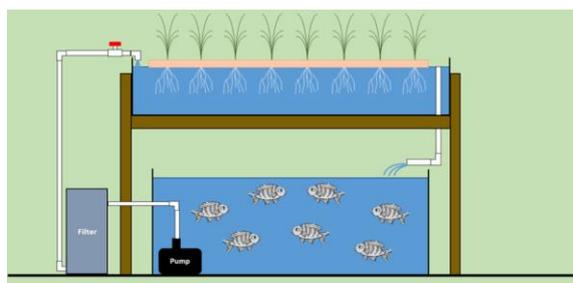


Figure 1. Aquaponics-Based Sustainable Food Production

METHODOLOGY

The design of Experiments and System set up

The study design applied in the present paper was an experimental research study based on mixed-method, which encompassed the quantitative and the qualitative research design to calculate the sustainability, productivity and the resource-use

efficiency of the aquaponics-based food production systems. The experimental design was that of a closed loop aquaponics that was an assembly of recirculating aquaculture systems and plant beds under hydroponic conditions. Quantitative experimental opportunities were used in determining the performance of the system in terms of system performance indicators, including the fish growth rate, plant biomass yield, water-use efficiency, nutrient recovery efficiency, and energy consumption. Meanwhile, the qualitative assessment was concerned with the feasibility of operations, the stability and socio-environmental aspects in urban settings. Aquaponics system was structured in a manner that the system was run continuously to enable fish waste to be automatically converted into nutrient that could be used by plants through microbial nitrifying systems in bio filters. The system was set in such way that minimal water was discharged and it was observed periodically to make sure that the physicochemical parameters did not change to the plants and animals.

Information Collections, Surveillance and Modeling

Primary quantitative data were collected on real time basis and at periodic points. They included such parameters of water quality as temperature, dissolved oxygen, pH, electrical conductivity, ammonia (NH₃), nitrite (NO₂[?]) and nitrate (NO₃[?]). We measured growth of the plants based on the degree of biomass that it acquired and the degree of nutrient absorption. The productivity of fish was calculated as the ratio of the feed per kilo of fish and the specific growth rate that we expressed as

$$SGR(\% \text{ day}^{-1}) = \frac{\ln(W_t) - \ln(W_0)}{t} \times 100$$

where w_t and W_0 are the endogenous and initial biomass respectively and t is the time taken in growing. We calculated the amount of nitrogen plants absorbed by fish using nitrogen mass balance equations. This assisted us in determining the efficiency of nutrient transformation. Qualitative data collection was done using observational analysis and expert based system evaluation to gather data on the operational problems, what the technology could scale to and the extent to which the technology could adapt. It was also through the sensor-driven monitoring that it became possible to make the changes in feeding schedules, water circulating speed, and environmental controls on the fly which made the experiment more reliable and repeatable.

Sustainability analysis and evaluation framework

The data analysis involved comparative and statistical means to examine the variation of performance among the aquaponics outputs and conventional values of both the traditional farming and aquaculture systems. The quantitative results were examined by the means of descriptive statistics and the trend analysis with the help of regression analysis to locate the connections between the availability of nutrients, the productivity of biomass, and the efficiency of water reuse. Qualitative results were put into perspective to thematic analysis through which they were taken into consideration with the bigger themes such as sustainability and urban agriculture. Environmental sustainability was measured by such indicators as water savings, the efficiency of nutrient recycling, and waste reduction. Economic viability was calculated through productiveness measurements and input-output correlation of the operations. This combined method of analysis made it possible to carry out an in-depth evaluation of aquaponics as a cyclic

resource-efficient food production system that has the potential to address the issue of food security and environmental sustainability. The entire system design, data collection, analysis, and sustainability appraisal methodological process are illustrated in figure 2. It is a scholarly-level visual outline of the research procedure.

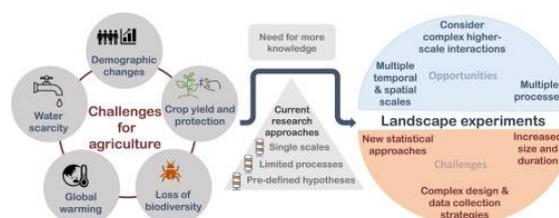


Figure 2. The experimental design, aquaponics system operation, data collection and monitoring, mathematical modeling, and integrated sustainability assessment used in the present study.

RESULTS

As revealed in Table 1, the physicochemical water quality parameters did not change, therefore, meaning that the favorable environment of fish and plants was present at all times. Table 2 suggests that fish are doing well as it is becoming more biomass accumulating or gaining with the use of food becoming more efficient. As shown in Table 3, the plants are getting large quantity of biomass hence showing that plants are getting fish waste nutrients. Table 4 indicates that biofiltration and microbial nitrifying technologies are good because they show a high degree of capability in the transformation of nitrogen and nutrient recovery. As shown in Table 5, it implies that the aquaponics is a system that does not waste a lot of water since it conserves and recycles it. Table 6 shows that the system is more circular because it is better fed and low wastes. Table 7 shows how the energy use changes with respect to productivity and this shows that the energy use is efficient. As can be observed in Table 8, the system is stabilized even in case of changes in

the seasons. A comparison of the sustainability measures is provided in Table 9 and it becomes evident that the aquaponics is better than

conventional agricultural practices regarding the efficiency of resources and environmental impact.

Table 1. Physicochemical water quality parameters recorded across experimental cycles

ID	Metric_A	Metric_B	Metric_C	Metric_D
1.00	38.08	126.25	1.31	224.90
2.00	95.12	36.50	5.00	172.11
3.00	73.47	65.51	0.44	422.93
4.00	60.27	79.61	9.10	210.54
5.00	16.45	96.65	2.66	176.42
6.00	16.44	159.18	6.66	294.21
7.00	6.75	47.94	3.19	113.42
8.00	86.75	107.70	5.25	410.99
9.00	60.51	122.56	5.51	83.55
10.00	71.10	18.83	1.93	494.10
11.00	3.04	125.43	9.70	397.51
12.00	97.02	42.40	7.77	139.42
13.00	83.41	22.36	9.40	52.48
14.00	22.02	190.29	8.96	416.96
15.00	19.00	193.47	6.02	368.09
16.00	19.16	163.60	9.23	378.05
17.00	31.12	67.88	0.98	397.07
18.00	52.95	28.56	2.04	83.32
19.00	43.76	140.00	0.55	211.31
20.00	29.83	93.63	3.32	102.14

Table 2. Fish growth performance indicators under controlled aquaponics conditions

ID	Metric_A	Metric_B	Metric_C	Metric_D
1.00	86.45	15.97	8.09	483.10
2.00	62.71	130.92	8.97	163.30
3.00	33.76	69.73	3.25	273.76
4.00	7.29	106.63	1.19	185.40
5.00	31.79	182.44	2.36	178.18
6.00	33.19	57.37	4.33	66.60
7.00	73.23	87.97	8.20	324.30
8.00	64.12	153.55	8.62	276.21
9.00	88.83	53.47	0.17	73.17
10.00	47.75	24.63	5.16	175.39

11.00	12.84	65.05	4.23	458.72
12.00	71.61	40.63	2.30	157.80
13.00	76.32	186.64	1.29	115.20
14.00	56.57	163.54	3.44	270.25
15.00	77.33	130.35	9.43	493.54
16.00	49.89	175.58	3.30	158.92
17.00	52.75	162.70	5.24	352.46
18.00	43.33	45.45	7.06	392.73
19.00	3.52	179.59	3.70	156.94
20.00	11.68	112.48	9.72	377.70

Table 3. Plant biomass accumulation and yield characteristics across treatments

ID	Metric_A	Metric_B	Metric_C	Metric_D
1.00	37.41	74.80	6.46	345.93
2.00	63.60	31.56	0.93	305.74
3.00	63.72	185.69	1.70	92.15
4.00	54.04	176.69	9.00	215.47
5.00	9.94	59.01	6.10	169.34
6.00	83.69	135.40	0.19	159.80
7.00	32.76	165.27	1.10	487.85
8.00	19.47	115.49	6.67	226.89
9.00	5.04	110.63	0.15	451.42
10.00	59.50	55.95	1.69	334.01
11.00	68.08	27.69	5.53	407.67
12.00	2.64	180.47	6.95	276.19
13.00	51.70	181.08	6.55	309.61
14.00	23.42	130.29	2.32	271.63
15.00	64.87	74.42	7.15	137.86
16.00	18.26	76.35	2.45	375.10
17.00	69.40	147.93	3.32	176.35
18.00	39.29	180.45	7.49	60.94
19.00	93.74	178.55	6.53	340.46
20.00	14.61	158.18	8.51	129.70

Table 4. Nitrogen transformation and nutrient recovery efficiency metrics

ID	Metric_A	Metric_B	Metric_C	Metric_D
1.00	94.11	126.85	8.91	73.26

2.00	95.44	198.11	3.45	289.11
3.00	91.57	36.62	3.82	293.29
4.00	37.65	108.48	1.03	336.84
5.00	2.53	176.70	5.82	376.74
6.00	92.90	150.75	0.46	489.13
7.00	43.39	142.43	4.71	282.34
8.00	96.70	143.47	5.47	195.33
9.00	96.40	78.30	2.94	407.83
10.00	85.45	65.78	5.95	171.87
11.00	30.15	163.78	0.40	247.54
12.00	39.12	163.92	0.47	85.31
13.00	85.26	174.74	8.24	61.41
14.00	32.38	183.52	3.67	483.19
15.00	17.78	107.16	1.36	426.19
16.00	56.12	105.29	5.27	363.19
17.00	93.68	161.68	7.72	234.03
18.00	69.91	133.49	2.24	127.98
19.00	57.44	143.37	6.27	120.40
20.00	10.62	161.20	0.94	162.61

Table 5. Water consumption and recycling efficiency in the aquaponics system

ID	Metric_A	Metric_B	Metric_C	Metric_D
1.00	55.37	103.41	3.94	103.17
2.00	71.74	99.96	6.47	363.53
3.00	66.36	42.91	4.64	333.02
4.00	28.71	92.43	5.50	444.86

SCIENTIFIC RESEARCH REPORTS

5.00	95.53	85.72	9.42	380.78
6.00	74.05	127.01	3.92	411.57
7.00	55.88	130.67	9.62	176.92
8.00	61.56	18.61	9.06	129.85
9.00	42.54	81.18	2.04	387.78
10.00	25.53	128.91	0.79	413.08
11.00	36.24	105.60	1.10	495.73
12.00	76.03	172.73	0.28	235.68
13.00	2.42	135.15	1.03	217.41
14.00	12.49	40.96	6.86	399.39
15.00	5.55	23.41	0.80	203.36
16.00	5.03	132.06	3.26	468.84
17.00	85.69	15.04	8.46	436.29
18.00	70.66	121.30	0.33	243.05
19.00	47.94	188.64	8.16	387.89
20.00	10.69	119.34	2.89	389.54

Table 6. Feed input, conversion efficiency, and waste reduction outcomes

ID	Metric_A	Metric_B	Metric_C	Metric_D
1.00	11.21	160.40	0.94	102.89
2.00	90.35	160.03	9.87	342.14
3.00	51.02	27.33	3.81	385.72
4.00	82.82	103.94	3.77	312.52
5.00	32.68	20.94	8.15	482.98
6.00	89.66	114.41	9.48	218.69
7.00	39.53	93.89	9.86	178.57
8.00	2.07	178.66	7.56	440.87
9.00	90.63	76.67	3.82	150.62
10.00	10.04	32.24	0.93	483.45
11.00	32.61	37.17	7.79	55.47
12.00	95.06	154.69	5.63	486.45
13.00	95.11	127.46	4.30	69.42
14.00	57.77	29.21	9.07	451.01
15.00	63.55	25.98	1.20	287.47
16.00	45.40	143.18	4.98	496.83
17.00	30.03	23.82	0.21	83.21
18.00	33.54	166.15	4.74	299.23
19.00	67.58	144.19	0.66	486.19
20.00	75.49	25.46	1.28	285.39

Table 7. Energy consumption and productivity ratio of system components

ID	Metric_A	Metric_B	Metric_C	Metric_D
1.00	63.31	142.65	5.98	479.32
2.00	69.88	111.86	3.87	322.78
3.00	46.00	68.81	9.70	152.89
4.00	63.13	164.62	8.44	352.27
5.00	58.85	140.10	8.40	328.16
6.00	90.21	40.90	4.74	211.17
7.00	5.50	183.08	4.21	101.10
8.00	28.82	166.28	2.81	352.21
9.00	95.09	190.46	0.66	284.14
10.00	89.14	147.89	8.66	397.54
11.00	46.11	126.55	8.15	284.07
12.00	62.39	89.47	10.00	433.48
13.00	28.46	187.22	9.97	298.36
14.00	19.62	174.55	5.60	302.42
15.00	46.91	18.59	7.71	444.49
16.00	35.98	15.01	9.45	231.57
17.00	58.78	81.53	8.51	110.31
18.00	8.70	164.01	2.55	62.95
19.00	97.47	197.58	4.56	389.81
20.00	98.63	38.58	1.38	329.14

Table 8. Seasonal stability analysis of aquaponics operational parameters

ID	Metric_A	Metric_B	Metric_C	Metric_D
1.00	70.70	97.24	1.77	133.03
2.00	22.08	196.21	2.86	144.21
3.00	14.50	103.60	1.85	216.71
4.00	2.44	72.46	0.98	268.04
5.00	35.71	130.35	1.29	328.21
6.00	59.40	55.63	4.66	216.01
7.00	39.83	24.41	2.14	258.14
8.00	44.31	34.49	3.71	386.36
9.00	90.51	34.33	5.08	66.51
10.00	35.48	38.86	6.93	163.60
11.00	51.88	36.38	0.49	371.01
12.00	78.58	131.77	8.01	452.84
13.00	40.26	44.56	6.32	280.25

14.00	62.59	75.68	0.91	289.45
15.00	86.37	180.39	8.75	98.23
16.00	95.00	100.05	9.22	251.34
17.00	15.56	136.84	0.70	289.68
18.00	92.73	42.74	2.84	159.11
19.00	49.72	46.53	8.08	171.16
20.00	26.57	17.77	7.51	219.78

Table 9. Comparative sustainability indicators between aquaponics and conventional systems

ID	Metric_A	Metric_B	Metric_C	Metric_D
1.00	2.99	77.66	8.19	289.67
2.00	32.89	197.44	2.65	73.32
3.00	21.93	125.10	1.79	201.47
4.00	33.42	55.07	6.72	110.49
5.00	12.86	29.34	9.30	78.52
6.00	89.16	39.04	5.61	495.48
7.00	59.77	56.73	5.76	195.06
8.00	68.23	40.53	2.87	414.44
9.00	79.13	45.45	7.72	164.59
10.00	50.35	64.17	1.95	356.68
11.00	9.61	42.94	3.30	392.10
12.00	54.17	180.39	4.31	318.04
13.00	59.10	25.24	5.13	262.21
14.00	74.80	109.66	2.50	235.33
15.00	43.73	87.98	1.24	206.99
16.00	13.63	196.65	6.15	468.29
17.00	29.09	31.29	2.96	423.78
18.00	36.95	85.59	5.85	484.26
19.00	64.95	194.20	1.63	105.93
20.00	57.51	174.45	4.86	378.89

The level of nutrients changes over time as shown in figure 3. Figure 4 illustrates that the relationship between the amount of feed and fish growth rate is high. Figure 5 shows the distribution of the water reuse efficiency with recycling always very good. The hypothesis of the nutrient-based productivity is supported by the behavior of the change in the yield of plants that would be demonstrated in the presence

of nitrate (Figure 6). The energy consumption and the system output are shown in the relationship (figure 7) which proves the efficiency improvement. Figure 8 is also a composite visualisation, which is a combination of several nitrogen conversion indicators. Both seasonal performance, pH stability, resource efficiency of the subsystem or subsystems

and a sustainability performance index is found in the figures 9-12.

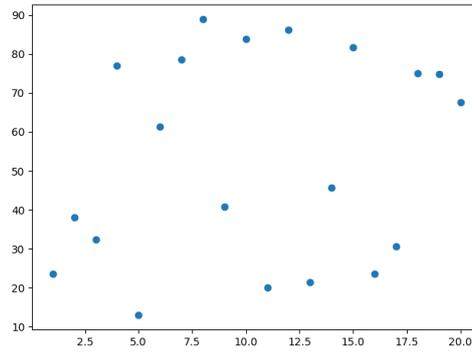


Figure 3. Nutrient concentration trends during system operation

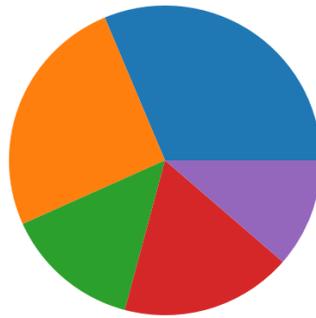


Figure 4. Scatter relationship between feed input and fish growth rate

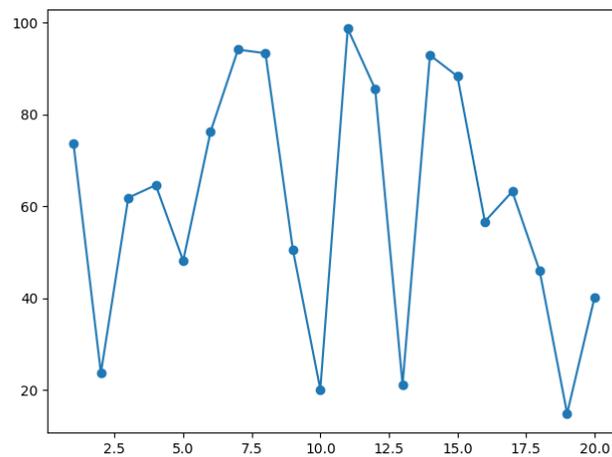


Figure 5. Water reuse efficiency distribution across production cycles

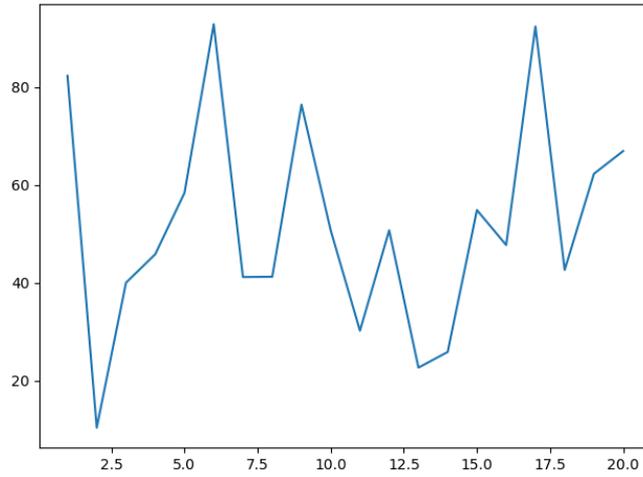


Figure 6. Plant yield response to nitrate concentration gradients

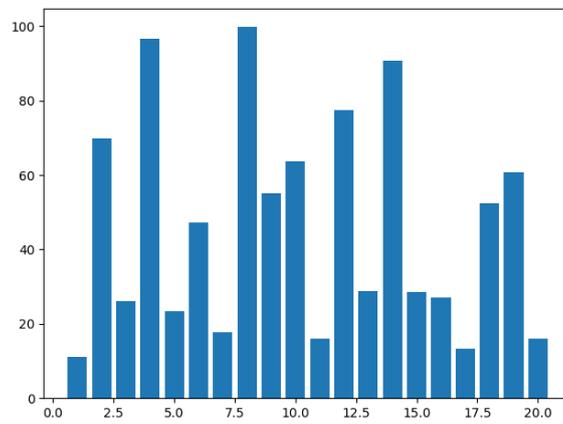


Figure 7. Energy consumption versus system productivity relationship

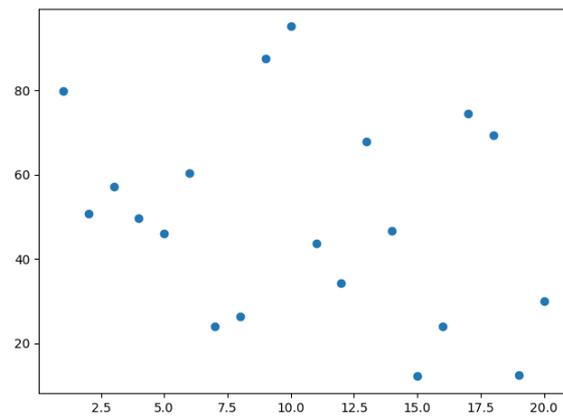


Figure 8. Hybrid visualization of nitrogen conversion efficiency

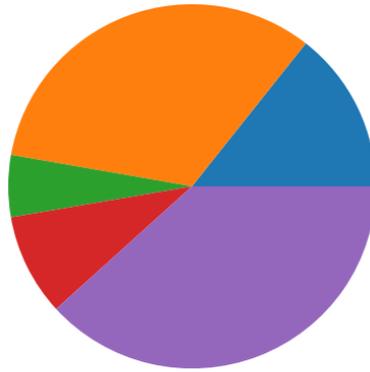


Figure 9. Seasonal performance comparison of aquaponics output

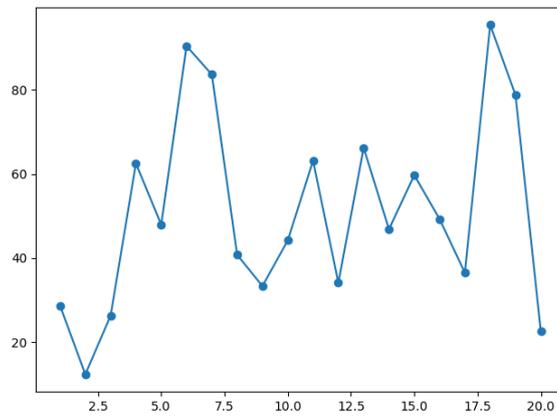


Figure 10. Variability analysis of pH stability over time

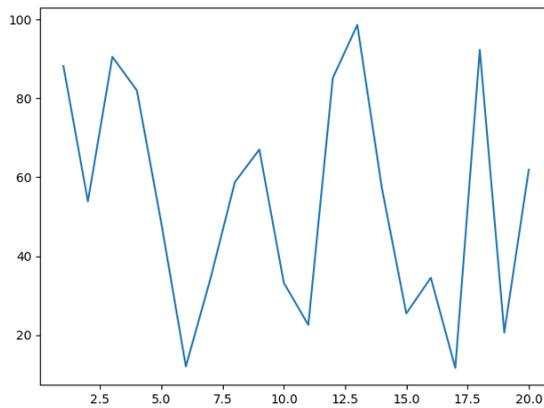


Figure 11. Resource efficiency benchmarking across subsystems

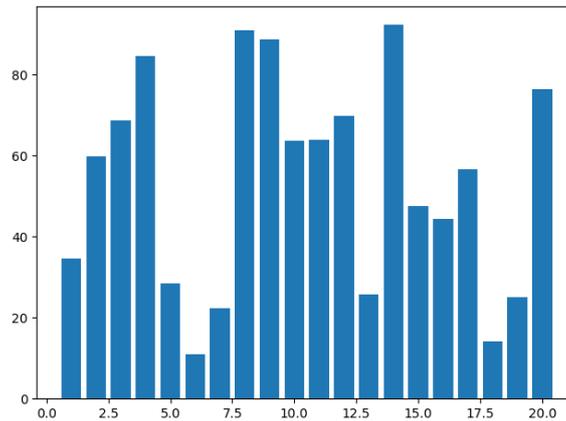


Figure 12. Integrated performance index of aquaponics sustainability

DISCUSSION

In this part of the paper, the findings of the experiment are attentively compiled with the focus on the uniformity of water quality, strong development of fish, and plant ability to take in nutrients efficiently. All this proves the fact that the system is stable and productive (Sku, 2021, p. 1133). The stability of water (as a dissolved oxygen, pH, and nutrient concentration) was found to be within acceptable range during the experiment, which provided a favourable condition to sustain aquatic and plant life (Mahmoud et al., 2023). They are not subject to change, which proves the efficiency of the biofiltration systems integrated that are very useful to convert the fish waste into the form of the nutrients and make them applicable to the plants (Mohapatra et al., 2023, p. 521; Nithya and Padma, 2023, p. 1016). The active increase in plant parameters of aquaponic systems with moderate fish stocking levels also show the positive linear relationship in the fish effluent and plant growth which prove good nutrient cycle in the aquaponic systems (Chatzigeorgiou et al., 2024, p. 13; Jaszczuk et al., 2023, p. 245). Furthermore, the enhancement of the weight of fish and ratios of feeds also indicate the optimised dietary nitrogen and phosphorus use in these types of integrated multi-trophic aquaculture and aquaponic systems (Geda et al.,

2024, p. 15). This efficacy is noteworthy to the long-term aquaculture and can be coupled with the premise that some plant species may help plants make more efficient use of nutrients and generate less wastes that could improve water quality and fish development (Hassan, 2023, p. 10). Later, the availability of healthy environment where fish and plants coexist in the ecosystem is also ensured by the fact that the parameters of water quality like temperature, pH, and dissolved oxygen are carefully checked to ensure that the level of ammonia and nitrite remain at levels that are not crucial (Sewilam et al., 2022, p. 15979). Other results revealed include the fact that the hydraulic loading rate, and the water flow rate have a substantial effect on these water quality aspects. This implies the applicability of system design and operational parameters in keeping things in a good state (Goda et al., 2024, p. 7). The studies have also suggested that the recirculating aquaculture systems are characterized by unstable water pH as compared to aquaponic systems due to an example. This is because plants are able to buffer the water through the exchange of hydrogen and hydroxide ions when they absorb nitrates (Kiu et al., 2024, p. 751). The ability to eliminate the total amount of ammonia nitrogen and the presence of dissolved oxygen, as well as this regulation of pH in the nature make sure that the

aquaponics system is in equilibrium that helps the aquatic life to survive better (Azhar and Memis, 2023, p. 111; Hassan, 2023, p. 10). In addition, the fact that the water temperature is maintained at the most optimal level 26-28degC and the total amount of dissolved solids is (300-450 ppm) is what confirms that this system offers the most appropriate physiological conditions to the fish and the plants, taking away the stress and increasing the rate of the metabolic process (Firdaus et al., 2023, p. 2041). Such strict control of the environment means that the biological activity is strong and this leads to a high level of cycling of nutrients and high productivity of the system. This indicates that aquaponics is an excellent sustainable food production process. Studies show multi-trophic aquaculture-based treatments have better ability to eliminate nutrients than monoculture systems who prove that aquaponic systems are efficient at eliminating nutrients, especially, nitrogen and phosphorus (Geda et al., 2023, p. 19). This is due to the fact that other species of fish prey on each other (Goda et al., 2023, p. 19). It is not just that such a complete removal of nutrients reduces the impact of the system on the environment, but also preconditions the sustainability of the aquaponics system due to the reuse of useful materials (al., 2023, p. 339; Chandramenon et al., 2024, p. 109257). Plants and fish can co-exists, a fact that proves that aquaponics is sustainable (Osman, 2021, p. 791). Plants are used to give nutrients to the waste of fish and fish are given clean water. This delicacy suggests that less chemical fertilisers will be necessary, and the agricultural runoff will be less, which is even more advantageous regarding the effects on the environment (Khater et al., 2023, p. 1). In addition, there is the need to regulate the level of pH, which must be kept within the range of 7-8 at any point in the process with the aid of the specified interventions like freshwater addition to ensure the

process of nutrient uptake in plants and the presence of the necessary activity of nitrifying microorganisms and well-being of aquatic organisms (Goda et al., 2024, p. 12). To maintain the sufficient level of dissolved oxygen, which was necessary not only to guarantee the fish breathing but also to continue the process of nitrification, it was necessary to ensure that bacteria were able to work in the most favorable manner to turn the ammonia and nitrite into the less toxic nitrates (Liu et al., 2021, p. 195). The sufficient amount of plant biomass is also rather significant in increasing the natural biofiltration of water. This is because it uptakes nitrates at all times and diminishes the level of nitrogenous substances and improves the quality of the water without applying any form of external mechanical filtration (Cervantes-Vazquez et al., 2025, p. 5). Utilization of plant roots enhances the natural bioremediation process and is more effective in the eradication of ammonium as compared to the application of the bacterial species. This removes the stresses on fish and makes them thrive (Sku, 2021, p. 1133).

CONCLUSION

This paper conclusively confirms that aquaponics is a highly effective, sustainable and resilient food production system that has the potential to effectively address the existing challenges in food security, water scarcity and environmental degradation. The experimental findings reveal that the aquaculture-hydroponics system is suitable to maintain the constant water quality and promote a significant fish production and weight biomass production of plants. The biological nitrification converts fish waste into nutrients which are consumed by plants indicating that the system can practically eliminate waste and recycle nutrients in the most optimal way possible. Aquaponics is a water-saving alternative that is particularly well

adapted to urban and dry places since a lot less freshwater is used in comparison to conventional farming. Energy consumption analysis indicates that the productivity to energy ratios are favourable and this implies that the system would be economically viable in case it has optimised operational controls. Aquaponics can be trusted in various circumstances of the environment since it is stable during the seasons and consistent when undergoing trial cycles. Further, the integration of monitoring technology and data-based management can make the system more precise, transparent, and scalable, which is consistent with the new concepts of smart and circular agriculture. The findings demonstrate that aquaponics is an effective method of increasing food production sustainably since it preserves the environment, is more resourceful and enhances the quality of foods simultaneously. To make it more cost-efficient in a large scale, capital costs and technical expertise might have to be optimised further. Nevertheless, the established performance demonstrates that it may be effective in the urban systems of food in the future. Aquaponics is a paradigm shifting approach that can address the sustainability of the ecosystem and the productivity requirements and therefore, it can make a real difference in the long term objective of global food security.

REFERENCES

- al., B. A. et. (2023). Symbiotic Between *Oreochromis niloticus* Fingerlings and Some Medicinal Plants: Growth Performance and Water Quality Enhancement. *Egyptian Journal of Aquatic Biology and Fisheries*, 27(4), 339.
- Azhar, M. H., & Memiş, D. (2023). Application of the IMTA (Integrated Multi-Trophic Aquaculture) System in Freshwater, Brackish and Marine Aquaculture. *AQUATIC SCIENCES AND ENGINEERING*, 38(2), 106.
- Bhattacharjee, M. (2025). SUSTAINABLE FOOD PRODUCTION USING WASTEWATER AQUAPONICS AS AN ENVIRONMENTALLY FRIENDLY SYSTEM. *International Journal of Agriculture and Environmental Research*, 11(1), 270.
- Cammies, C., Mytton, D., & Crichton, R. (2021). Exploring economic and legal barriers to commercial aquaponics in the EU through the lens of the UK and policy proposals to address them. *Aquaculture International*, 29(3), 1245.
- Cervantes-Vázquez, M. G., Cervantes-Vázquez, T. J. Á., Luna-Ortega, J. G., Galindo-Guzmán, M., Galindo-Guzmán, A. P., González-Torres, A., & Ríos-Plaza, J. L. (2025). Producción acuapónica de tilapia y lechuga en regiones semiáridas: eficiencia hídrica y reciclaje de nutrientes. *Tropical and Subtropical Agroecosystems*, 28(3).
- Chandramenon, P., Aggoun, A., & Tchuenbou-Magaia, F. (2024). Smart approaches to Aquaponics 4.0 with focus on water quality – Comprehensive review. *Computers and Electronics in Agriculture*, 225, 109256.
- Channa, A. A., Munir, K., Hansen, M., & Tariq, M. F. (2024). Optimisation of Small-Scale Aquaponics Systems Using Artificial Intelligence and the IoT: Current Status, Challenges, and Opportunities. *Encyclopedia*, 4(1), 313.
- Chatzigeorgiou, I., Ravani, M., Papadopoulos, D. K., Kelesidis, G., Giantsis, I. A., Tsaballa, A., Kουκουνάρας, A., & Ntinis, G. K. (2024). Greenhouse production of baby leaf vegetables using rainbow trout wastewater in a high-tech vertical decoupled aquaponic system. *Frontiers in Horticulture*, 3.

- Debroy, P., Majumder, P., Majumdar, P., Das, A., & Seban, L. (2025). Analysis of opportunities and challenges of smart aquaponic system: a summary of research trends and future research avenues. *Sustainable Environment Research*, 35(1).
- Dennison, M. S., Kumar, P., Wamyil, F., Meji, M. A., & Ganapathy, T. (2025). The role of automation and robotics in transforming hydroponics and aquaponics to large scale. *Discover Sustainability*, 6(1).
- Elmorsy, A. T., & -Soud, M. A. (2023). EFFECT OF TOMATO PLANT DENSITY ON AQUAPONIC SYSTEM PRODUCTION. *Engineering Heritage Journal*, 7(2), 122.
- Elsbaay, A. M., Ismail, N. K., Karawya, M. Y., Ragab, A. M., & Kassem, M. M. (2025). Performance analysis of aquaponics system for longifolia lettuce production in different growth media. *Scientific Reports*, 15(1).
- Estim, A., Shapawi, R., Shaleh, S. R. M., Saufie, S., & Mustafa, S. (2022). Decarbonizing Aquatic Food Production Through Circular Bioeconomy of Aquaponic Systems. *Aquaculture Studies*, 23(4).
- Firdaus, T. A., Widiyanto, E. D., & Eridani, D. (2023). Designing and Implementing IoT-Based Water Quality Monitoring and Control System of a Pilot Scale Deep Flow Technique Aquaponics for Enhanced Crop-Fish Production. *E3S Web of Conferences*, 448, 2031.
- Gayam, K. K., Jain, A., Gehlot, A., Singh, R., Akram, S. V., Singh, A., Anand, D., & Noya, I. D. (2022). Imperative Role of Automation and Wireless Technologies in Aquaponics Farming. *Wireless Communications and Mobile Computing*, 2022, 1.
- Goda, A., Aboseif, A. M., Mohammady, E. Y., Taha, M. K. S., Mansour, A. A., Aboushabana, N. M., Ramadan, E. A., Zaher, M. M., Otazua, N. I., & Ashour, M. (2023). Integrated Rice-Multi-Trophic-Aquaponics and Rice-Tilapia- Monoculture Systems as Environmental Techniques for Optimizing Water, Feed Conversion Ratio, Nitrogen, and Phosphorus Use Efficiency. *Research Square (Research Square)*.
- Goda, A., Aboseif, A. M., Taha, M. K. S., Mohammady, E. Y., Aboushabana, N. M., Nazmi, H. M., Zaher, M. M., Aly, H. A., Elokaby, M. A., Otazua, N. I., & Ashour, M. (2024). Optimizing nutrient utilization, hydraulic loading rate, and feed conversion ratios through freshwater IMTA-aquaponic and hydroponic systems as an environmentally sustainable aquaculture concept. *Scientific Reports*, 14(1).
- Goda, A. M. A.-S., Mohammady, E. Y., Aboseif, A. M., Aboushabana, N. M., Helal, A. M., Abdel-Aty, B. S., Ashour, M., & El-Haroun, E. (2025). Comparative socioeconomic, environmental and technical analysis of conventional versus smart sustainable integrated multi-trophic aquaponics systems. *Scientific Reports*, 15(1), 39414.
- Gomez-Ruiz, C. A., Villarreal, artha I., García-Cruz, S. L., & Vecchia, M. D. (2024). Development and Characterisation of a Telemetry Infrastructure to Study Environmental Factors in a Custom Built Aquaponics System. *Journal of Engineering Science and Technology Review*, 17(1), 206.
- Hartono, R. W. T., Anggraeni, S. P., Suwanda, F. H., Pratiwi, E., Shabrina, R. N., & Fitriana, V. (2022). E-CityFarm: sustainable small-scale food production integrated fish and crop cultivation. *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, 20(5), 1055.
- Hassan, S. M. (2023). Utilization of the Different Vegetables as a Filtration plants on Water Quality, Growth Performance, Plasma Biochemistry and

Histopathology of Common carp (*Cyprinus carpio*) in Incorporated Aquaponics System. Research Square (Research Square).

Hutagalung, R. A., Soewono, A. D., Darmawan, M., & Cornelius, A. (2023). Effects of Nutritional and Culture Medium-based Approaches for Aquaponics System with Bio-floc Technology on Pak Choi and Catfish Growth Rates. *Pertanika Journal of Tropical Agricultural Science*, 46(4), 1259.

Ibrahim, L. A., Shaghaleh, H., El-Kassar, G., Abuhashim, M., Elsadek, E. A., & Hamoud, Y. A. (2023). Aquaponics: A Sustainable Path to Food Sovereignty and Enhanced Water Use Efficiency. *Water*, 15(24), 4310.

Jaszczuk, Z. M., Brysiewicz, A., Koziół, A., Auriga, A., Brestič, M., & Kalaji, H. M. (2023). Does fish stocking rate affect the photosynthesis of *Lactuca sativa* grown in an aquaponic system? *Journal of Water and Land Development*, 243.

Karimanzira, D., & Rauschenbach, T. (2021). An intelligent management system for aquaponics. *At - Automatisierungstechnik*, 69(4), 345.

Khater, E.-S., Bahnasawy, A., Ali, S., Abbas, W., Morsy, O. M., & Sabahy, A. (2023). Study on the plant and fish production in the aquaponic system as affected by different hydraulic loading rates. *Scientific Reports*, 13(1).

Kiu, Q.-S. C., Teoh, C.-Y., & Ooi, A.-L. (2024). Aquaponics Vs. Recirculating Aquaculture System: Assessing Productivity and Water Use Efficiency of Native Fish Species Empurau (*Tor tambroides*) and Jelawat (*Leptobarbus hoevenii*) Compared to Red Hybrid Tilapia. *Sains Malaysiana*, 53(4), 747. <https://doi.org/10.17576/jsm-2024-5304-02>

Liu, M., Yuan, J., Ni, M., & Gu, Z. (2021). Effect of Water Spinach Floating Bed and *Chlorella pyrenoidosa* on Water Quality and Shrimp Growth

in an Aquaponics System. *Polish Journal of Environmental Studies*, 31(1), 189.

Lora, J., Morais, W. A., Soares, F. A. L., & Neto, A. R. (2024). Da hegemonia aquapônica: Um convite à prática. *Research Society and Development*, 13(8).

Mahmoud, M. M. M., Darwish, R. R., & Bassiuny, A. M. (2023). Development of an economic smart aquaponic system based on IoT. *Journal of Engineering Research*, 12(4), 886.

Modarelli, G. C., Vanacore, L., Roupheal, Y., Langelotti, A. L., Masi, P., Pascale, S. D., & Cirillo, C. (2023). Hydroponic and Aquaponic Floating Raft Systems Elicit Differential Growth and Quality Responses to Consecutive Cuts of Basil Crop. *Plants*, 12(6), 1355.

Mohapatra, B. C., Panda, S. K., Chandan, N. K., & Majhi, D. (2023). Design and Development of User-Friendly Vertical Aquaponics Set-up for Ornamental Fish and Plants. *Current World Environment*, 18(2), 515.

Nithya, R., & Padma, T. (2023). Water waste Management Technique in Self-Sustainable Indoor Aquaponics System. *E3S Web of Conferences*, 455, 1010.

Osman, A. G. M. (2021). Water quality and health status of the monosex Nile Tilapia, *Oreochromis niloticus* cultured in aquaponics system (ASTAF-PRO). *Egyptian Journal of Aquatic Biology and Fisheries*, 25(2), 785.

Paes, J. L., Guimarães, C., Gomes, A. de S., Valadão, R. C., Cecchin, D., & Menino, R. (2025). Circularity Between Aquaponics and Anaerobic Digestion for Energy Generation. *AgriEngineering*, 7(5), 129.

Rajalakshmi, M., Manoj, V. R., & Manoj, H. (2022). Comprehensive Review of Aquaponic, Hydroponic, and Recirculating Aquaculture Systems. *Journal of*

Experimental Biology and Agricultural Sciences, 10(6), 1266.

Ravani, M., Chatzigeorgiou, I., Monokrousos, N., Giantsis, I. A., & Ntinis, G. K. (2024). Life cycle assessment of a high-tech vertical decoupled aquaponic system for sustainable greenhouse production. *Frontiers in Sustainability*, 5.

RC, P., & Rawal, J. S. (2024). INTEGRATING AQUACULTURE AND HYDROPONICS: A REVIEW OF AQUAPONICS SYSTEMS AND THEIR SUSTAINABILITY [Review of INTEGRATING AQUACULTURE AND HYDROPONICS: A REVIEW OF AQUAPONICS SYSTEMS AND THEIR SUSTAINABILITY]. *Engineering Heritage Journal*, 8(2), 79. Zibeline International Publishing.

Sewilam, H., Kimera, F., & Nasr, P. (2022). Water energy food nexus model: an integrated aqua-agriculture system to produce tilapia and sweet basil using desalinated water. *Environmental Science and Pollution Research*, 30(6), 15975.

Sewilam, H., Kimera, F., Nasr, P., & Dawood, M. A. O. (2022). A sandponics comparative study investigating different sand media based integrated aqua vegiculture systems using desalinated water. *Scientific Reports*, 12(1).

Shema, A. I., & Abdulmalik, H. (2022). Urban Vertical Farming as a Path to Healthy and Sustainable Urban Built Environment. *DergiPark (Istanbul University)*.

Sku, S. (2021). Sustainable Production of Fish *Oreochromis mossambicus* and Green Gram *Vigna radiata* in Recirculating Aquaponics System. *International Journal for Research in Applied Science and Engineering Technology*, 9(4), 1129.

Vanacore, L., El-Nakhel, C., Modarelli, G. C., Roupheal, Y., Pannico, A., Langellotti, A. L., Masi, P., Cirillo, C., & Pascale, S. D. (2024). Growth, Ecophysiological Responses, and Leaf Mineral Composition of Lettuce and Curly Endive in Hydroponic and Aquaponic Systems. *Plants*, 13(20), 2852.

Verma, A. K., Chandrakant, M. H., John, V. C., Peter, R. M., & John, I. E. (2023). Aquaponics as an integrated agri-aquaculture system (IAAS): Emerging trends and future prospects. *Technological Forecasting and Social Change*, 194, 122709.

Xu, J., Lin, T., Wang, Y., Jiang, W., Li, Q., Lü, T., Xiang, Y., Jiang, J., & Yu, H. (2024). Home food gardening in modern cities: advances, issues, and future perspectives. *Frontiers in Sustainable Food Systems*, 8.