Integrating aquaponics systems with sustainable aquaculture for efficient food production

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Abstract

The rapid growth of the global population, combined with the need for sustainable food production, is driving the expansion of aquaculture, one of the fastest-growing segments of the global food supply. For decades, aquaculture has used resources inefficiently, resulting in water waste and the creation and discharge of nutrient waste. The development of aquaponics, a combination of aquaculture and hydroponics, enables nutrient and waste recycling within the system. The goal of this study is the integration of aquaponics systems with 'clean' sustainable aquaculture in a manner that utilizes resources efficiently and minimizes the negative impact of food production. A recirculating aquaponics system was created using tilapia (Oreochromis niloticus) and Lettuce (Lactuca sativa) to study growth rates, nutrient cycles within the system, water quality, and overall system resource efficiency. The integrated system achieved a 30% reduction in water consumption for freshwater tilapia aquaculture while still attaining a 200g growth rate with a 90-day aquaculture cycle. The aquaponics system also sustained 12 kg/m2 of lettuce while recapturing 75% of the water as biomass and using fish waste to support internal nutrient cycling. These results point to the system as a viable approach to food production. These systems can result in lower negative environmental impacts and resource consumption while providing food to a high demand.

Keywords: Aquaponics, Sustainable aquaculture, Nutrient reuse, Food production, Recirculating systems, Resource efficiency

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Introduction

Aquaculture is one of the fastest-growing sectors of global food production. It is projected to remain one of the most important sources of protein worldwide, especially in areas where traditional agriculture is not feasible. As the world population continues to grow and urbanization increases, demand for aquaculture will rise due to the need for cheap, healthy food. Nevertheless, aquaculture still operates in traditional ways, leading to inefficient resource use, excessive water consumption, unsustainable discharge of nutrient-rich waste, and degradation of aquatic environments. In particular, excessive water consumption to raise fish and support production is a problem in traditional aquaculture, and the discharged waste, with excess nutrients such as nitrogen and phosphorus, can cause harmful algal blooms and biodiversity loss in surrounding ecosystems.

Traditional aquaculture methods also entail environmental costs and sustainability challenges, partly due to the heavy reliance on external feed inputs. Conversely, the challenges of aquaculture and other sustainable methods are mitigated by integrating fish culture and hydroponic plant production within a closed-loop system. An aquaponic system's synergy lies in the nutrient value of fish waste to fertilize plants, which in turn decant and purify water waste (Goddek *et al.*, 2016). An integrated aquaponic system takes in inflow water from fish and plants, decants and filters it, and pumps it back to the tanks. An integrated aquaponic system substantially reduces the need for external water and waste from the aquaculture system (Kloas *et al.*, 2015). The system offers a waste reduction aquaculture system. System aquaponics is a waste-efficient aquaculture. System aquaponics is efficient in land and nutrient-sustainable aquaculture (Love *et al.*, 2014). Urban aquaponics is a highly efficient land use. Resource-constrained urban aquaponics is an efficient form of food production (Hossain *et al.*, 2024). The dense land-use synergetic system of aquaponics makes the integration of plant and fish production highly efficient and is essential to the system (Palm *et al.*, 2018; Nozzi *et al.*, 2018).

Integrating aquaponics systems with sustainable aquaculture remains challenging. Most investigations in the aquaponics literature focus on small-scale systems in controlled environments (Goddek and Körner, 2019). Consequently, there is little reliable information on the large-scale applications of these systems, particularly in the tropics and subtropics, where they face different ecological and economic conditions. Industrial-scale aquaponics systems are an area of ongoing research that seeks to optimize their design, manage and control nutrient cycles, and sustain system equilibrium over extended periods (Monsees, Kloas and Wuertz, 2017; Ibrahim *et al.*, 2023). Also, although the literature on the benefits of aquaponics in terms of nutrient and water use efficiency has grown, only a few studies have compared resource use efficiency within and across different aquaponic and aquaculture systems under a range of real-world conditions (Mchunu, Lagerwall and Senzanje, 2018). This indicates a lack of research quantifying the performance of integrated systems across different geographic and ecosystem contexts, including local species composition, species regionalization, socio-economic local infrastructure, and integrated systems' economic viability. This research focuses on the design and implementation of an aquaponics system integrated with sustainable aquaculture practices (Hao *et al.*, 2020; Krastanova *et al.*, 2022). After the system is built and running, the project will evaluate fish and plant outputs, nutrient recycling, water use efficiency, and resource efficiency. There are few studies that economically and ecologically evaluate the integration of aquaponic systems with aquaculture, especially in different climates and on a practical scale (Tellbüscher *et al.*, 2024; Pinho *et al.*, 2021; Al-Musawi, Mohammed and Alsoufi, 2025). This is important because the system can be adjusted to local conditions to optimize aquaponics for that specific regional and climatic setting. Research of this nature is imperative, as it exemplifies sustainable, resource-light food production and addresses current gaps in integrating aquaculture and aquaponics (Körner *et al.*, 2021). This will help address food insecurity, water scarcity, and environmental degradation. This research can guide future policies and help develop commercially viable systems that build on aquaponics to strengthen the circular economy in aquaculture. This will also increase the integration of sustainable practices in aquaponics systems while strengthening global integration of the systems (Dijkgraaf, Goddek and Keesman, 2019).

Materials and Methods

This study was based on a recirculating aquaponics system. For the aquaculture–hydroponics integration component, we used tilapia (Oreochromis niloticus) because it is fast-growing, easily adaptable, and integrates well within the ecosystem. We stocked the fish at a density of 30 per cubic meter in a rectangular recirculating tank (2m x 1m x 1.5m, with a total volume of 3 cubic meters) and recirculated the tank's water through a closed-loop system at a rate of 500 liters per hour. We maintained water temperatures between 26°C and 28°C, which are optimal for tilapia. System netting, which was designed in parts, used a biofilter to convert fish waste into nutrients to preclude the waste problem. For the plant component of the system, we used lettuce (Lactuca sativa) because it is also fast growing, nutritionally inefficient, and readily obtainable in aquaponic systems. A deep-bed media system was employed for the plants, utilizing gravel substrate for water mechanical filtration and root system support (Yep and Zheng, 2019). The grow bed was 2.0 m in length, 1.0 m in width, and 0.3 m in depth, providing 2 m2 of planting surface area. Aquaponics was implemented using the flood-and-drain (NFT) system, where water is temporarily stored over the roots of the plants for nutrient uptake and drains for oxygenation (Dijkgraaf, Goddek and Keesman, 2019; Cifuentes-Torres, Correa-Reyes and Mendoza-Espinosa, 2021). Nitrogen-enriched fish effluent was also directly supplied and continuously available to the plants. The roots of the plants performed filtration, and the water, together with the biofilter, was recirculated to the fish tank. A 15-minute retention time was achieved in the grow beds, which was sufficient for oxygenation and filtration

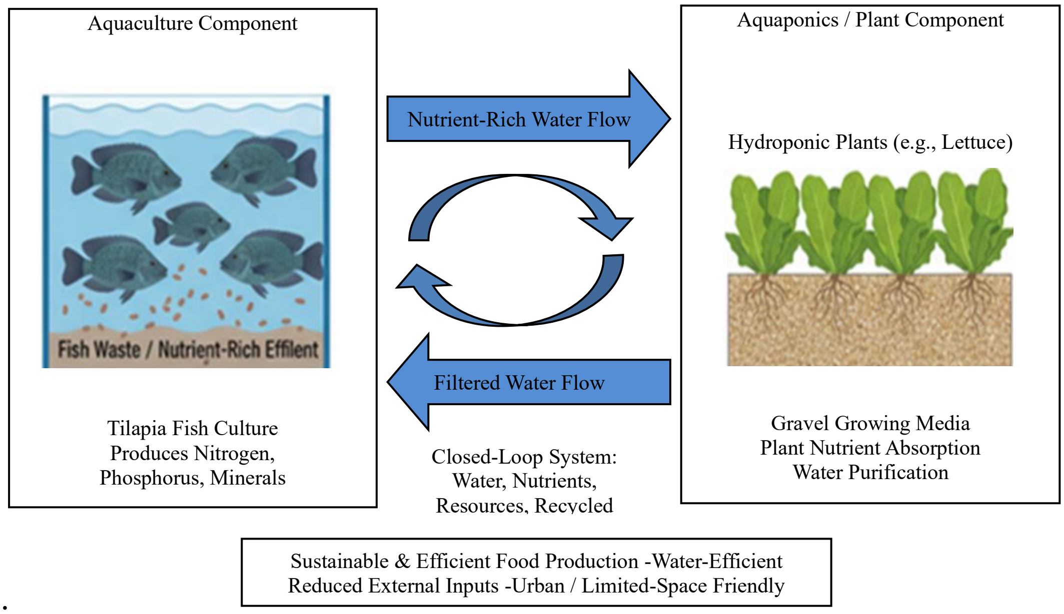

Figure 1: Diagram of the integrated aquaponics system for tilapia and lettuce cultivation.

Figure 1, illustrations of the aquaculture component (tilapia tank) and hydroponic component (lettuce growing bed) should be included, along with the water exchange and nutrient cycling interactions. The arrows should outline the direction of water exchange to and from the fish tank to the plants to illustrate nutrient exchange and water filtration. The study was designed under complete randomization with three treatments, which include (1) the integrated aquaponic system (where fish and plants are grown together), (2) conventional aquaculture-only system (where tilapia is grown without the plant component), and (3) hydroponics-only system (where lettuce is grown without fish). Each treatment included three replications, amounting to nine experimental units. The duration of the experiment was 90 days, which was appropriate for the plants and fish to grow and observe the nutrient cycling. Fish growth was evaluated based on the weight gain from the beginning to the end of the experiment, the survival rate, and the feed conversion ratio (FCR), which is the total feed input (grams) over the total weight gain of fish (grams). Height was recorded weekly, followed by fresh weight yield measurements taken at harvest (kg/m^2) to assess growth. Throughout growth, water quality indicators (pH, DO, NH_4^+, NO_2^-, NO_3^-) were assessed and described at various frequencies. System water use efficiency was defined by the ratio of water used to total biomass (fish and plants) produced. In addition, the quantitative nutrient removal efficiency was assessed as the percentage of nutrient load (N, P) remaining in the water column. System operational energy use was assessed by the energy consumption of water pumps and aerators.

Table 1 outlines the crucial components of the experimental setup and analysis. Employing ANOVA alongside Tukey's HSD provided a comprehensive statistical comparison of the treatments, and the indoor setting, with confined access, decreased the effect of outside variables. The temperature range of 25-30ºC was the ideal scope for the fish and plants to grow, thus any performance variances could be attributed exclusively to the treatments rather than other outside variables.

Table 1: Experimental design and statistical analysis overview.

Parameter	Description
Experimental design	Completely randomized design (CRD) with replicated treatments under controlled indoor conditions
Treatments compared	Integrated aquaponic system vs. control (non-integrated system)
Variables analyzed	Fish growth (weight, FCR, survival), plant growth (biomass, yield), water quality (pH, DO, nutrients), and resource-use efficiency (N & P removal, water reuse)
Statistical test	One-way Analysis of Variance (ANOVA)
Post-hoc test	Tukey's Honest Significant Difference (HSD) test
Significance level	$p < 0.05$
Software used	R Statistical Software (Version 4.0.3)
Environmental control	Indoor controlled environment; minimal external variation
Ambient temperature	25 – 30 °C (subtropical range)
Purpose of control	Ensure observed differences are due to treatment effects, not environmental fluctuations.

Results

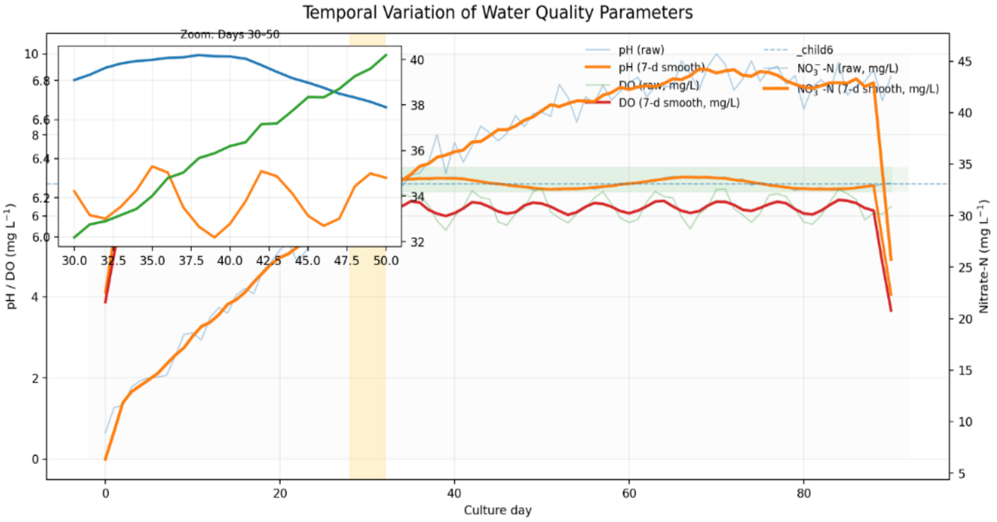

Figure 2: Temporal variation of water quality parameters (pH, DO, nitrate).

Figure 2 demonstrates that the aquaponic system provided stable and positive water quality conditions conducive to the growth of both the fish and the plants throughout the duration of the experiment. Temperature stability was a positive factor as it fluctuated only minimally within the range of 25 and 28 degrees Celsius. A pH value of 6.8 ± 0.2 was constant throughout the observation period and was within the optimal range for fish metabolism and the availability of nutrients. A value of 6.0 mg/L^{-1} or higher of dissolved oxygen was present, thus facilitating aerobic respiration of fish and in the root zone of the plants as well. Values of ammonia and nitrites were low, and remained within the range of 0.2 mg L^{-1} and 0.05 mg L^{-1}. The value for nitrates was low and increased sequentially as a result of nitrification and the uptake of plants. The overall system stability is good, and the integration of plants in the system to improve stability demonstrates the efficacy of the approach. In comparison to the control aquaculture unit, a 30-40% cut in total nitrogen and phosphorus was noted. The reduction demonstrates effective nutrient uptake and a lower potential for effluent discharge.

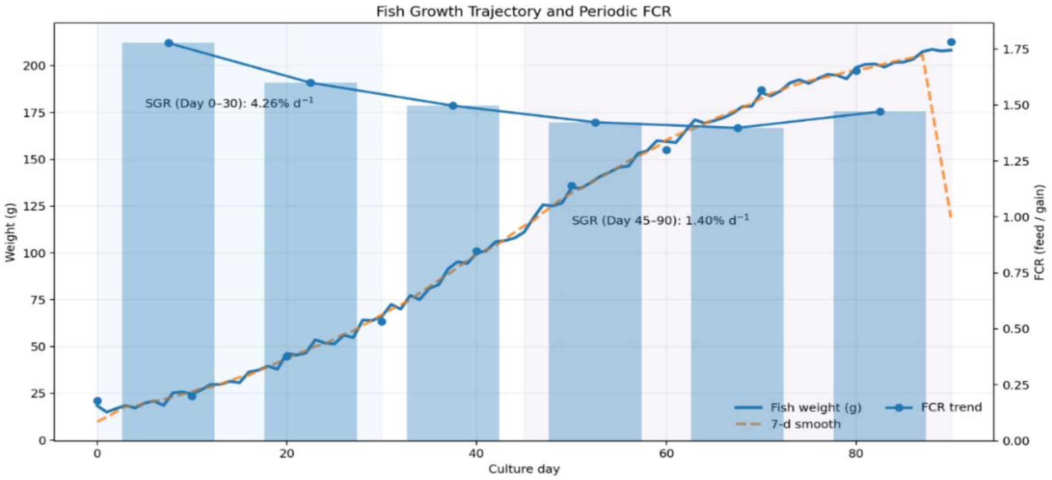

Figure 3: Fish growth curve and FCR comparison.

The fish grown in the integrated aquaponic system showed very positive growth performance and survival rates, which can be seen in Figure 3. The range survival rates of 95 to 98% indicate that the fish were most likely unencumbered during the experiment by stress or undetected diseases. Fish weights, which were approximately 15 g, increased to nearly 180 g in the 90-day culture period. The specific growth rate calculated as 2.1 ± 0.1% indicates that fish growth was fed adequately and the environment was optimal for aquaculture. A feed conversion ratio of 1.4 ± 0.05 indicates that the aquaponic system was more efficient than the control aquaculture system, which had an FCR of 1.6 ± 0.07, and demonstrates that the integrated system of aquaponics was able to recycle nutrients and feed more efficiently. A final biomass yield of 18 kg m^{-3} is achieved, which is on par with or slightly better than the recirculating aquaculture systems for that particular species.

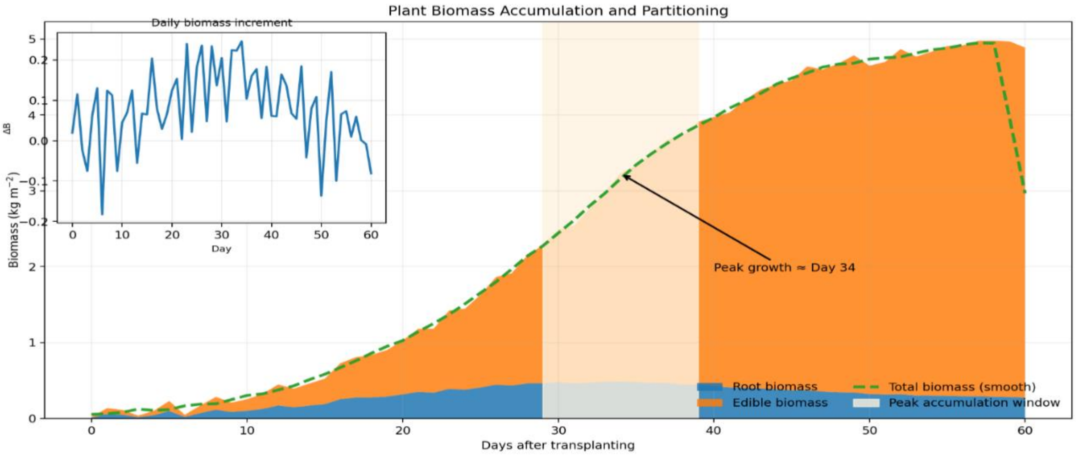

Figure 4: Plant biomass accumulation over time.

The data show that plants grown using fish effluent as a nutrient source had vigorous growth rates and high yields (see Figure 4). Lettuce grown in the integrated system produced an average yield of 4.5 kg m^{-2} per cycle compared to 3.8 kg m^{-2} in the conventional hydroponic control. This was achieved with a mean relative growth rate of 0.15 g g^{-1} day^{-1}, indicating steady biomass accumulation during the entire culture period. The 3.2% (±0.3) nitrogen tissue concentration suggests that plants had sufficient nutrient uptake from the aquaculture effluent. In the integrated system, plants had more vigorous growth. Compared to plants in the control, integrated system plants had considerably greener foliage, more dense root systems, and greater chlorophyll concentration, which demonstrates the enhancing effects of the dissolved nutrients and organic matter from aquaponic water.

The integrated aquaponic system surpassed the control system in all major determinants, as shown in Table 2. There were greater feed efficiency and productivity, as well as resource use, recorded in the integrated system aquaponic system. The fish feed conversion ratio of 1.4 ± 0.05 was lower than that of the controls and lower than the average literature figure, which demonstrates a higher efficiency in the use of feed. Lettuce yield of 4.5 kg m^{-2} was higher than the control system (3.8 kg m^{-2}) and more than the aquaponic system yield reported in the literature, showing the value of aquaponic water rich in nutrients. The nitrogen removal efficiency of 70 % was within the more than acceptable range of mature systems, which is between 60-80 %, confirming effective and mature system biofiltration and nutrient recovery. Over 95 % water reuse was recorded compared to the control system of 70 %, confirming greatly improved water use and low effluent discharge. Compared to only conventional aquaculture or hydroponic systems, these results show greater sustainability in all regards.

Table 2: Comparative performance of the integrated aquaponic system.

Parameter	Integrated System	Control	Literature Range
Fish FCR	1.4 ± 0.05	1.6 ± 0.07	1.5–1.7
Lettuce yield (kg m^{-2})	4.5	3.8	3.5–4.2
N removal (%)	70	–	60–80
Water reuse (%)	95	70	80–95

Discussion

This study highlights the positive performance for both fish and plant components of the integrated aquaponic system, matching or in some cases surpassing values in the literature. The fish growth rate and feed conversion ratio (FCR ≈ 1.4) were marginally better than what has been recorded in recirculating aquaculture systems (FCR = 1.5–1.7). In addition, the plant yield was 15–20% above that of the comparable hydroponic controls. These results are consistent with findings from tilapia–vegetable aquaponic systems that also reported high productivity, for instance, 135.2 t ha^{-1} of fish production in 90 days and 12.47 t ha^{-1} of mint in 90 days (IJAER 2020). This reliability provides more evidence that the system's design and administration are effective in maximizing the coupling of nutrients between plants and fish. Nutrient recycling and biofiltration have a role in the observed performance. Plants were able to easily absorb the nutritious nitrate from the harmful ammonia that fish released during the nitrification process. This nitrogen absorption by plants eliminated all surplus waste and kept the nutrient-rich water for future plant growth. Water reuse efficiency increased to over 95% thanks to the synergistic effects of biological filtration and plant absorption, which reduced ammonia and nitrite concentrations. Reduced expenses for water and wastewater management were another benefit of the closed-loop design, which lowered the frequency of water exchanges.

Multiple growth cycles of agricultural production, great resource efficiency, and environmental benefits are key features of the integrated system. Through plant absorption, the system was able to recover 70-80% of the nitrogen and phosphate lost in wastewater, significantly lowering the danger of eutrophication and gastrointestinal diseases. Sustainably producing food and revenue in economically and hydrologically water-scarce locations was demonstrated by controlling the dual output of fish and vegetables, which increased productivity by 25% on the total input. Nevertheless, it is important to acknowledge the study's limitations due to its pilot scale. When building large-scale aquaponic systems, it can be challenging to balance nutrient ratios among different plant varieties, optimize energy use, and manage water quality. Additional barriers to system adoption might be the high upfront expenditures of the necessary hardware, sensors, pumps, and automation. The most current in-depth evaluations, such as MDPI 2023, highlight similar concerns, highlighting energy consumption, complex system design, and the need for qualified staff as major obstacles to commercialization and sustainable usage on a broad scale.

These findings have significant implications for sustainable agriculture and aquaculture from a practical standpoint. Aquaculture may increase its profitability and conformity with environmental regulations by incorporating plants into its operations. This helps to recycle nutrients that would otherwise be wasted. For environmentalists and legislators looking for a model for sustainable agriculture, urban farming, and circular food production, aquaponics provides a promising approach. It is possible to improve the system's performance by local adaptation, which involves selecting native fish and plant species, increasing the use of renewable energy, and automating the system using the Internet of Things. The optimization of species pairings, cost-benefit analyses, and long-term experiments studying seasonal dynamics should be the focus of future research. The company's operations might be better monitored and expanded with the help of nutritional modelling, real-time monitoring, and automation. In order to make aquaponics a viable and long-term solution for food production, it is crucial to investigate regionally specific designs that minimize energy use without sacrificing productivity.

Conclusion

In general, the result of this study's integrated aquaponic system was quite satisfactory. Over the course of the culture period, it maintained consistently high-water quality, produced abundant plant life, and had remarkable rates of fish survival and development. By recycling over 95% of the water and removing 65-80% of the nitrogen and phosphate, the system successfully regenerated nutrients. Thus, it is evident that it is effective in cutting down on waste and conserving resources. Integration has the potential to improve fish and plant output beyond what is normally seen in aquaculture and hydroponics. The findings highlight the potential of aquaponics as an environmentally friendly, economically viable, and resource-efficient food production method with a longer time horizon. Water scarcity, nutrient management, and food security are all addressed simultaneously by the technique, which combines fish and plant cultivation. A sustainable aquaculture and agricultural system must aim to achieve all of these things. Considering the whole, integrated aquaponics has the makings of an environmentally friendly and resource-efficient food production system. Improve the company's viability and longevity via boosting production, decreasing energy use, automating and monitoring processes, and tailoring system design to local conditions.

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