# Innovative Approaches to Aquaponics: A Review of Current Practices, Strategies, and Impact Assessment

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**Abstract:** Aquaponics integrates aquaculture and hydroponics into a balanced, soil-less system, presenting a sustainable solution to modern agricultural challenges, particularly in the Philippines, where only 1/3 of the country's land is used for agriculture, with the rest being used for urbanization. This system efficiently recycles water while cultivating plants and fishes, optimizing resource use, and minimizing environmental impact. But despite its potential, aquaponics systems require more research with nutrient distribution, cost-efficiency, and adaptability. This study aims to cross-analyze existing research on aquaponics by focusing on three critical criteria: performance, value, and feasibility. Through a comprehensive literature review, the research combines insights from different aquaponics designs and practices, highlighting best practices, innovations, and areas needing further development. The findings explore various system configurations and their impacts on yield, general cost, and economic viability while also examining the potential benefits of renewable energy integration and automated monitoring systems. By providing practical recommendations for improving system efficiency, scalability, and sustainability, this study aims to contribute to advancing aquaponics as a viable agricultural practice. The research supports resilience in agricultural systems and addresses future food security needs by promoting aquaponics as an adaptable, resource-efficient alternative to traditional farming methods.

**Key Words:** aquaponics; aquaculture; hydroponics; sustainable agriculture

## 1. INTRODUCTION

The agricultural sector serves as one of the backbones of the Philippine workforce, providing a primary source of income for a significant portion of the population (Brown, 2020). As of January 2025, it accounts for 21.1 percent of the country's employment, highlighting its critical role in providing livelihoods for many Filipino households (Philippine Statistics Authority, 2024). The agricultural sector faces challenges in keeping up with the continuous urbanization throughout the country. In fact, out of the 30 million hectares of land in the Philippines, only one-third is currently utilized for agricultural purposes (Department of Agriculture, 2022; Statista, 2024). This has led to the widespread development of agricultural lands into residential subdivisions, commercial areas, and recreational facilities, leaving traditional farming methods unsustainable (Raihan, 2023).

In recent years, several solutions have been used to keep up with the rapid rate of urbanization, such as indoor urban farming (Alexander, 2022; Namkung, 2023), controlled environmental agriculture (UC Davis Continuing and Professional Education, 2025; World Bank, n.d.), and, most notably, aquaponics (Campanhola & Pandey, 2019). Aquaponics is an environmentally friendly system that combines plant and fish production by integrating aquaculture and hydroponics to cultivate plants and fish in a balanced, soil-less environment where water is recycled efficiently (Fernández-Cabanás et al., 2020; Shafahi & Woolston, 2015). This recirculating system transforms ammonia ($NH_3$) from fish waste into nitrate ($NO_3$), an absorbable nutrient for plants, through the process of nitrification (Bracino, 2023).

Aquaponics systems come in horizontal or vertical orientations; however, the vertical design is noted to be more space-efficient and reduces the need for extensive farmlands (Gustavsen et al., 2022). Vertical aquaponics allows crops to grow effectively in layers or stacks, a practical solution for urban areas with limited space (Mohapatra et al., 2023).

Despite being a promising field for further scientific inquiry, aquaponics lacks a systematic scientific foundation for its mechanics, symbiotic relationships, and cultivation methods, often relying on small-scale, trial-and-error approaches with limited species. For instance, in vertical aquaponics systems, higher-level stacks tend to receive higher concentrations of nutrients as the nutrient-rich water is supplied from the top than the ones below it (Touliatos et al., 2016). This highlights the necessity for systematic research to optimize these systems. In contrast, aquaculture and hydroponic plant production are well-established, widely commercialized fields supported by robust engineering and economic disciplines (Colt et al., 2021).

This paper aims to cross-analyze existing research on aquaponics systems, focusing mainly on their performance, value, and feasibility to understand their potential and limitations comprehensively. By consolidating and assessing the findings from multiple studies, this review provides comprehensive insights into best practices, emerging innovations, and future research directions in aquaponics systems.

As the trend of urbanization continues to grow, the expected projection suggests that 70 percent of the world's population will live in cities by 2050 (United Nations Statistics Division, 2023). However, in the Philippines, this rapid pace of modernization has caused the reduction of agricultural lands and has made traditional farming methods less viable and useless (Beckers et al., 2020). Urban residents also face the challenge of limited access to fresh produce due to the scarcity of arable land, compounded further by other issues such as water contamination (Beckers et al., 2020). This study also holds relevance for farmers, especially those transitioning to urban agriculture, as they can gain information regarding alternative ways to grow crops without needing large plots of land. Furthermore, this could also encourage future research and innovators to improve on this by integrating other strategies such as automated controls, machine learning, and environmental sensors, which can overall enhance the efficiency of vertical aquaponics systems.

## 2. METHODOLOGY

### *A. Research Strategy*

The methodology for gathering and analyzing information on aquaponics system design involves a comprehensive literature review of research articles from reputable sources such as ScienceDirect, SpringerLink, IEEE Xplore, and Wiley Online Library, among others. The keywords used for selecting relevant papers include "Aquaponics," "Hydroponics," "Aquaculture," "Urban Farming," and "Sustainable Agriculture." This ensures a thorough understanding of the latest practices, technological advancements, and challenges in these interconnected fields, providing a solid foundation for effective aquaponics system design.

The research process is visually depicted in Figure 1 and comprises five main steps: (1) Gathering Information, which collects relevant data and studies related to aquaponics. (2) Analysis of Aquaponics Information, where the gathered information is analyzed to identify critical factors that influence the performance of aquaponics systems. (3) Synthesis of Details combines strategies, current practices, challenges, and impact assessment. (4) Cross-Section Diagram evaluates the value, performance, and feasibility of different aquaponics system designs. (5) Aquaponics Design Discussion: this step includes discussions on findings and offers insights into future improvements and applications in aquaponics system designs.

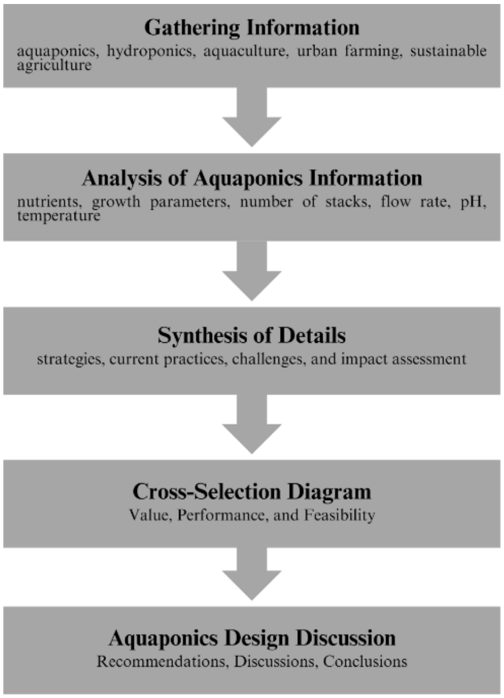

Fig. 1. Schematic Diagram Framework of the Analyses of Designs of Aquaponics System

*B. Data Extraction and Analysis*

To ensure data quality, paper selection was based on abstracts, data collection methods, and relevance to aquaponics, hydroponics, aquaculture, and sustainable farming practices. The evaluation of each system encompassed assessing performance, sustainability, and feasibility:

1) Performance: This is an evaluation and assessment of the system's yield.
2) Value: This is the measurement of the general cost of assembly of the system.
3) Feasibility: Determination of the technology's practicality and ease of integration in a real-world setting.

The references are somewhat limited due to the recent and experimental nature of the subject compared to its counterpart in hydroponics and aquaculture.

*C. Limitations*

Aquaponics is continuously evolving, and given its experimental nature, the available references are limited and may not cover certain aspects comprehensively. The performance, sustainability, and feasibility criteria are broad and subject to generalizations. The study is not localized to the context of the Philippines. Consequently, findings and recommendations may not directly apply to the country's environmental, social, or economic conditions. However, the study's findings offer valuable insights into current practices, challenges, and potential advancements in aquaponics systems and do not pose a hindrance to future research and development.

## 3. RESULTS AND DISCUSSION

Appendix A shows a cross-diagram of various designs currently used or implemented for aquaponics systems. The table gives the reference, design, and objectives of the setup, followed by an analysis of their performance, value, and feasibility, as described in the methodology.

*A. Performance*

The study of Fernández-Cabanás et al. (2020), showed a 160% increase in productivity per unit area in its vertical aquaponics system compared to the horizontal orientation. Going down the tiers, the average weight of the plants decreased up to 43% because of the lack of lighting and nutrient it receives. Researches, like that reviewed by Goddek et al. (2019), confirms this and suggests it that is essential to manage the shading effect properly to achieve complete uniformity in the growth of multiple layers. However, some researchers propose that adjusting lighting and reflective materials on supporting structures could improve light transmission and enhance yield from the lower layers (Choubchilangroudi & Zarei, 2022; Maucieri et al., 2017.

Mohapatra et al. (2023) recommended an increased flow rate in aquaponics systems to achieve optimal mechanical stimulation and improved root growth, as the best water quality and highest flower production were observed when the fish tank operated at a flow rate of 200 liters per hour (LPH) in their experiment. One of the limitations identified here is that there is a lack of sufficient data on flow rate and nutrient consumption in aquaponics systems (Choubchilangroudi & Zarei, 2022; Maucieri et al., 2017). Further research is needed to establish comprehensive benchmarks for water usage efficiency and identify best practices for balanced nutrient distribution and sustainable water management in aquaponics.

The studies of Bracino (2023) and Ariffin et al. (2022) also aimed to develop new or improve existing designs for aquaponic systems, focusing on increasing efficiency or adapting to specific environments. This was done with two independent systems, one with a biofilter unit and one without a biofilter, and the presence of a biofilter in the former system increased the amount of nitrifying bacteria, which is beneficial for the plants as it converts nitrogen ($N_2$) into $NO_3$. These findings highlight the potential benefits of biofiltration as it increased the productivity of both the plants and fishes in the experiments. This study supports the exploration of biofiltration in more complex systems, such as vertical or stacked aquaponic designs.

The experiment of Gaspar et al. (2023) designed a low-cost design for aquaponics systems that uses solar energy that also integrates automated monitoring capabilities. This can act as a remedy to the demanding workload mentioned in (Raulier et al., 2023). These advancements and innovations in aquaponics further the implementation and credibility of aquaponics as a form of sustainable agriculture, which can be used as a main source of produce in the future.

### *B. Value*

Innovations in the aquaponics systems have improved system designs, increased scalability, and optimized energy use, in both conventional and advanced, which has also increased the cost of the set-up (Touliatos et al., 2016).

For instance, the experiment of Fernández-Cabanás et al. (2020) identified that the lower tiers of the vertical aquaponic system receive insufficient lighting compared to those on top, negatively impacting plant growth. To address this issue, researchers installed additional LED lighting, thereby increasing overall costs to, exclusive of electricity expenses.

In another study, the experiment of Shafahi & Woolston (2015) found that housing an aquaponics system within a greenhouse significantly influenced the financial cost of the system. This accounted for 42% of the total cost, which amounted to around $68,646 to $69,593. Additionally, it was mentioned that labor costs accounted for 52% of the operating cost of the system, estimated to be between $33,088 and $33,294.

Moreover, the implementation of biofiltration in Bracino's (2023) aquaponics system which aimed to enhance water quality and increase system's yield incurred an additional cost of approximately ₱2,641, bringing the overall system cost to ₱113,322.15. It was mentioned that labor was the top contributing factor to the expenses.

In the experiment of Chaudhari et al. (2024), the researchers made an aquaponics system for use on balconies with materials costing up to ₱2171.88, including a plastic tank, galvanized steel tubes, gravel holder, pump and fittings plastic tank, galvanized steel tubes, gravel holder, pump and fittings. The experiment of Babatunde et al. (2021) studied the viability of aquaponics in South Africa by creating a test gravel bed aquaponics design with an initial cost of approximately P150,290.19 with 55% of costs coming from the hydroponic components, 28% from aquaculture and 18% from testing and miscellaneous items.

Aquaponics systems are becoming increasingly popular among hobbyists and small-scale farmers operating within economically constrained areas, as shown by their adaptability to diverse environments, from small-scale urban settings to larger agricultural applications. But based on the findings from this comprehensive review, while aquaponics systems show promise in specific environments, economic feasibility is mainly contingent on carefully managing energy costs, fish-to-plant ratios, and system design

### *C. Feasibility*

The feasibility of aquaponics systems, especially in small-scale operations or areas with elevated energy costs, poses significant challenges. Studies indicate that the high expenses associated with electricity for supplemental lighting in vertical systems greatly impact their economic viability for small-scale applications. The additional energy requirements for LED lighting in vertical arrangements, especially in the lower tiers where plants receive less natural light, make such systems less feasible for operations with limited budgets or in regions where electricity is expensive (Fernández-Cabanás et al., 2020).

The production costs associated with fish, particularly tilapia, typically account for a substantial portion of operational expenditures in aquaponics, often approaching 90% of total variable costs. This high cost structure renders small-scale aquaponic systems less competitive against lower-priced imports, such as tilapia sourced from China. These costs make profitability difficult, particularly in markets with access to lower-cost alternatives (Babatunde et al., 2021).

However, studies exploring modular, energy-efficient designs, such as those powered by solar energy, show potential for improving the feasibility of aquaponics in specific environments. These systems offer a more sustainable approach to aquaponics, reducing the dependence on grid electricity and lowering operational costs. Despite this, the integration of solar power systems is still limited by high initial investment costs, which may restrict their adoption by small-scale or peri-urban farmers (Gaspar et al., 2023).

Designs for small-scale, low-cost setups demonstrated practical applications in peri-urban areas, showing profitability potential despite challenges with fish-to-plant ratios as long as it is appropriately managed (Mohapatra et al., 2023; Babatunde et al., 2021). Modular systems for urban farming are noted for their adaptability to limited spaces, like balconies and residential complexes (Chaudhari et al., 2024).

This versatility allows aquaponics systems to be paired with all kinds of technologies and applications, such as modular designs integrated with automated monitoring and biofiltration systems, enhancing productivity by improving water quality and nutrient distribution.

## 4. CONCLUSIONS

Research of various aquaponics system designs reveal critical information regarding the configurations that would work effectively across horizontal and vertical systems. Horizontal aquaponic systems provide an easier management of nutrient flow and uniform light distribution because of its consistency in all the plants' growth. Vertical systems stand out in being space efficient, especially useful in urban or limited-space environments, but faced with challenges related to uneven light distribution and nutrient availability, decreasing up to 43% plant productivity in the lowest tier in Fernández-Cabanás et al.'s (2020) experiment without the use of artificial lights to compensate. Consequently, further studies on using reflective materials to optimize light distribution and adjusting flow rates are critical to ensure balanced plant growth and fish health. Moreover, the low-cost solar-powered automated monitoring technology of Gaspar et al.'s (2023) experiment may be a feature to considering the unpredictable weather in the Philippines. The findings suggest that while high-tech and scalable systems work well in well-supported environments, simpler designs are often more practical and sustainable for hobbyists or small-scale farmers in economically constrained areas. While various aquaponics systems show promise in specific environments, their feasibility mainly depends on the initial cost of the system's design. Further research, innovation, and experimentation will solidify aquaponics as a credible, sustainable alternative for food production, transforming it into a primary produce source in the Philippines.

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## Appendix A:
## Cross-Diagram of Common Designs of Aquaponics System

| Objective | Design | Criteria | | | References |
|---|---|---|---|---|---|
| | | Performance | Value | Feasibility | |
| Basil (*Ocimum basilicum*) production in vertical – horizontal aquaponics system comparison | Two distinct (horizontal and vertical) systems designed to evaluate the effects of lighting placement and system orientation on plant growth. | Top-most tier of vertical aquaponics is more productive than horizontal systems but decreased in lower tiers. | Additional cost of electricity from LED lighting affected system's profitability to increase basil production. | Limited for small-scale operations or locations with high energy cost. | (Fernández-Cabanás et al., 2020) |
| Evaluation of technical, business aspects of professional aquaponics in Europe | Quantitative questionnaire was distributed to companies that use aquaponic farming systems. | 63 percent reported a production of more than 100 kg of fish annually. | Ranges from:<br>44 to 93 €/m$^2$ for non-heated greenhouses,<br>150 to 313 €/m$^2$ for heated greenhouses,<br>More than 700 €/m$^2$ for indoor systems. | 63% of respondents showed profitability in the past year. However, the system often depends on volunteers, highlighting demanding workload. | (Raulier et al., 2023) |
| To design and develop a vertical aquaponics that conserves both space and energy | Vertical aquaponics system containing 20 Guppy fish *(Poecilia reticulat)*<br>6 hybrid Petunia and Zinnia *(Zinnia angustifolia)* | Flow rate at 52.83 gallons per hour (200 liters per hour) showed highest flower production. | Total cost of one unit is around 7,000 Indian Rupee (approx. ₱4,796.63). | Design of system is suited for peri-urban areas and hobby farming. | (Mohapatra et al., 2023) |
| To determine the economic viability of a small-scale and low-cost aquaponics system in South Africa | Cost-benefit analysis was done with the cost of the system and the biomass and yield from the vegetables. | Total fish yield was 319 kg of tilapia, generating a revenue of 15,939 South African Rand (ZAR) (approx. ₱55,396 then) which accounted for 50.5 percent of total revenue | The total capital cost for the construction of the gravel bed aquaponic system amounted to 46,200 ZAR (approx. ₱150,290)<br>55% from the hydroponic component. 28% from the aquaculture component. 18% from miscellaneous items. | Fish production accounts for at least 90% of the total variable costs in small-scale aquaponics systems is uncompetitive and unprofitable to that of China's imported tilapia. | (Babatunde et al., 2021) |
| To propose a new low-cost design for aquaponics systems that uses solar energy | Solar-powered aquaponics system is equipped with automated monitoring capabilities. | Monitoring accuracy rate of over 90 | Overall cost is less than ₱25,000 | Integration of solar panels and automation features makes the system more refined and feasible, supported by its practicality in real-world settings. | (Gaspar et al., 2023) |
| To design and develop an aquaponics piping system for use in urban farming | | Climbing perch *(Anabas testudineus)* housed achieved a total size of 6.70 ± 0.57 cm.<br>Pak Choi (*Brassica rapa subsp. chinensis*) grew to an average height of 5.2 ± 0.02 cm<br>Lettuce (*Lactuca sativa*) reached 4.2 ± 0.07 cm. | The first concept was priced at 704 RM (approx. ₱9,408)<br>The second concept was priced at 858 RM (approx. ₱11,466)<br>The third concept was priced at 990 RM (approx. ₱13,230) | Easy integration and adaptation into residential settings, suited for urban areas that lack arable lands. | (Ariffin et al., 2022) |
| To implement machine learning in an aquaponics farm. | Two similar but different model systems were made for the trials.<br>Both models were compared after a 30-day trial. | The yield of *Brassica rapa L.* in the PRO-AP system was measured to be 73.20% higher than the traditional system<br>The PRO-AP system also demonstrated an increase of 1.38 mg/L in dissolved oxygen concentration due to the oxygen produced by the algae. | The total cost of the system was listed at 340.30 USD compared to the total annual revenue of 1,038.7 USD, which resulted in a positive net return of about 698.4 USD | The main components in the system, such as fish, plants, bacteria, and algae, are well-integrated together.<br>Additionally, the system had the ability to reduce aeration costs, which indicates that it can operate effectively with low operational expenses in comparison to traditional aquaponic systems. | (Zhang et al., 2022) |
| To design and develop a vertical aquaponics system for use in a multi-house complex. | A trial design was created with the purpose of being used on balconies.<br>The system was composed of a hydroponic and aquaponic component with water circulation made with PVC piping. | The Koi carp housed within the system recorded a 0.58 ± 0.05 cm length gain and a 1.09 ± 0.06 g weight gain<br>Additionally, it exhibited a 100% survival rate over an experiment duration of 28 days. | The components of the system include a plastic tank, galvanized steel tubes, gravel holder, pump, and fittings, which resulted in a total cost of 3,170 INR (approx. ₱2,172) | The performed system can be easily adaptable for urban farming as it only requires beginner-friendly tools for assembly.<br>The experiment was conducted in a limited space (balcony), demonstrating its potential for urban farming. | (Chaudhari et al., 2024) |
| Techno-economic analysis of a recirculating aquaponics system | An aquaponic system was created for the trial using a design from Central State University (CSU).<br>A techno-economic analysis was done based on the cost of the system and the profit from the production. | The system is designed to produce around 189 to 190 fish annually, depending on factors like fish weight and quantity.<br>It was also stated that for every kilogram of tilapia produced, the system can generate between 3.5 and 4.9kg of lettuce | The initial investment for the system ranges from \$68,646 to \$69,593, with the annual operating cost falling between \$33,088.6 and \$33,294.4 | Projections show a positive Net Present Value (NPV), which ranges from about \$8,956 to \$12,216. This supports that the investment could produce a worthwhile return over time.<br>However, it is important to note that the success of the system highly depends on numerous factors such as the market value of lettuce, space needed for growing, labor costs, and such. | (Zappernick et al., 2022) |
| To create and design an aquaponics system with automated monitoring and a biofiltration system. | The setup was done in a pilot-scale manner, with two independent systems, one with a biofilter unit and one without a biofilter. | Among the two systems, the experimental system performed better in comparison to the controlled setup.<br>The experimental setup showed an increase in the growth rate of both the crop and fish. | The capital cost of the setup was ₱113,000, with most of the spending being from the construction of the aquaponics setup. | The presence of a biofilter in the system increased the amount of nitrifying bacteria, increasing the amount of nitrates in the system. | (Bracino, 2023) |