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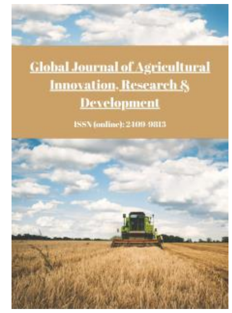

Brief History, Design Innovations, Sustainability, and the Future Prospects of Aquaponics: A Review

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ABSTRACT

The rising demand for food due to the increasing population is one of the world's major issues. It is aggravated by the decreasing area for food production due to land conversion and the effects of climate change that threaten food security. Thus, alternative methods for producing more food efficiently and sustainably have been the focus recently. Aquaponics is a promising food production technology that combines fish and plants within a single system. Among the existing techniques, the recirculating aquaponics system, or RAS, is one of the most sophisticated land-based aquaculture production systems, integrating hydroponics to promote the reuse and recycling of nutrient-rich water while maintaining high-quality fish and plants. Aquaponics originated from traditional practices that utilized abundant natural resources. Modern developments have evolved from small, modular systems to medium- and large-scale, commercial designs, incorporating automation and the Internet of Things (IoT) to enhance efficiency and precision. This paper reviews the evolution of aquaponics, highlighting existing designs, innovations, and performance. Additionally, it explores future work in aquaponics aimed at improving profitability and sustainability.

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1. Introduction

The concept of aquaponics was first designed and implemented by the Aztec people of Mexico around 1000 A.D. They occupied most of the lands surrounding Lake Tenochtitlan and no longer had land to grow their crops, so they utilized the lake by creating rafts covered with soil to grow vegetables [1]. Approximately 1,500 years ago in China, farmers combined the production of duck, finfish, and rice to maximize space while creating a natural ecosystem. The ducks and finfish contributed to the control of weeds and insects in the rice field, while their waste served as fertilizer for the rice [2]. These historical practices laid the foundation for modern aquaponics systems by demonstrating the benefits of integrating plant and animal production in a symbiotic relationship. The Aztec chinampas demonstrated the use of floating rafts for intensive cultivation, which inspired the development of floating raft systems, such as DWC, in modern aquaponics [1]. Similarly, the ancient Chinese rice–fish–duck systems showcased nutrient recycling and biological pest control, concepts that have been incorporated into contemporary multi-trophic and polyculture designs [2]. These ancient innovations proved that closed-loop systems could sustainably produce food, and modern technology has enhanced these principles with automation, biofiltration, and improved water quality management.

The first known modern aquaponics was cultivating various plants in hydroponics systems that directly utilize effluents from catfish grown in holding tanks [3]. However, wastewater drains freely without biofilters, requiring frequent replenishment of lost water. As a result, plants were undernourished in this open-flow system, as most nutrients were lost before they could be absorbed. To address this issue, a recirculating aquaponics system was developed, integrating hydroponically grown lettuce and tomato with Mozambique tilapia (*Oreochromis mossambicus*) and Common carp (*Cyprinus carpio*) [4]. This closed-loop system incorporated a biofilter, settling tank, and sludge denitrification, enhancing nutrient utilization efficiency and sustaining plant growth. Similarly, another recirculating system successfully cultivated catfish and tomatoes, efficiently converting fish waste into nitrate (NO_3^-) to nourish plants while maintaining water quality [5]. In 1985, a more complex recirculating aquaculture system was developed [6], which included sedimentation tanks, biofilters, and hydroponic beds, enabling efficient nutrient recycling. However, its complexity required continuous pumping and aeration, resulting in high energy costs. It was later refined by simplifying the system using a single-loop design with improved solids removal and low-head water flow to reduce energy use and enhance overall system stability [7]. Biofiltration is a key component of recirculating aquaponics, wherein nitrifying bacteria colonize filter media to convert toxic ammonia (NH_3) and nitrite (NO_2^-) from fish waste into nitrate (NO_3^-), a plant-available form of nitrogen, under aerobic conditions [8]. In contrast, denitrification occurs under anaerobic conditions, where microbes reduce excess nitrate to nitrogen gas (N_2), thereby helping maintain water quality by preventing nitrogen accumulation [9].

Aquaponics continues to evolve with various designs, scales, applications, and sophistication in an attempt to optimize its potential. This review paper aims to summarize the transformation of aquaponics and identify the critical parameters involved in the sustainability of the systems. This paper highlights the global players in aquaponics, designs and innovations, nutrient and water management, and the future of aquaponics. A general concept diagram of a recirculating aquaponics systems is depicted in Fig. (**1**).

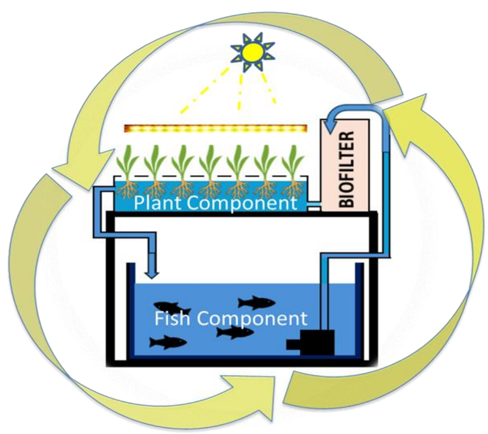

Figure 1: General concept diagram of aquaponics system.

2. Global Interest in Aquaponics

In recent years, considerable attention has been given to aquaponics technology, as seen by the number of scientific publications. A 10-year comparison from the Web of Science data summary showed that 2015-2024 recorded more than a thousand scientific publications as compared to 57 in 2005-2014, as shown in Fig. (**2**). These publications were traced from various places worldwide, which tell of the global interest in this technology.

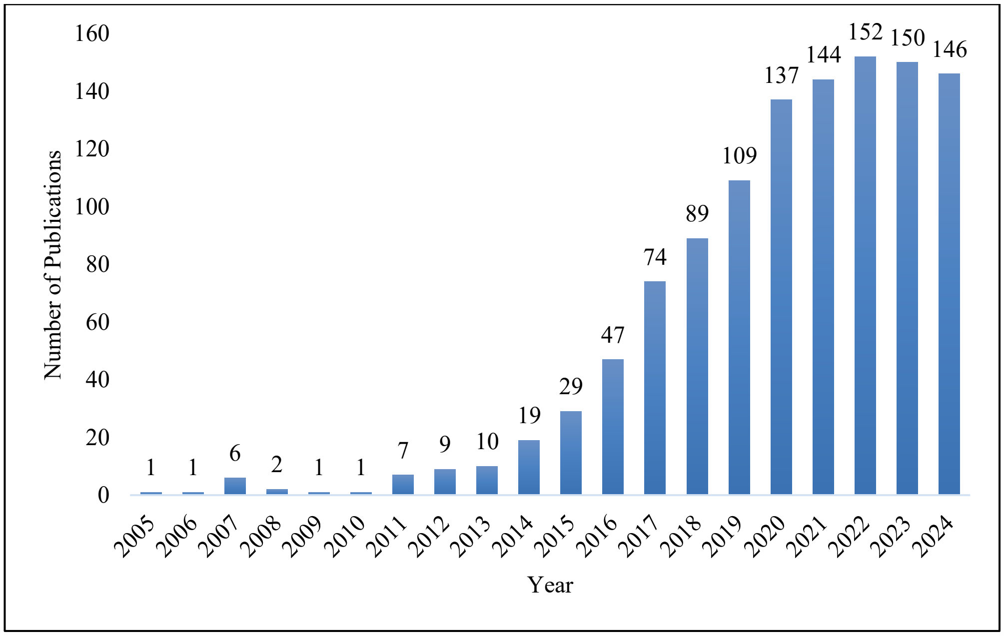

Figure 2: The number of publications on aquaponics worldwide from 2005 to 2024 (*webofscience.com*).

Many Asian countries consider aquaponics the next big thing when it comes to urban and intensive food production. For example, Singapore, China, and Taiwan focused on the automation and Internet of Things (IoT) applications to achieve the optimal state and maximize yield [10-13]. China, currently the world's second most populous country, must feed its people and aggressively seek to improve its food production systems. From traditional to sophisticated setups, aquaponics is a technology that they continuously use for food production [12, 14, 15]. Other countries in Asia, like Thailand, Indonesia, Malaysia, and Vietnam, are also active in the research, development, and commercialization of aquaponics [16-18]. Moreover, with more advanced applications, Japan focused on the controlled environment setup of growing leafy vegetables and catfish [19]. Pioneering work in Singapore, China, and Taiwan demonstrated how smart systems, IoT, and automation could enhance yields and reduce labor [10, 12]. Similarly, in Saudi Arabia, where freshwater is limited, they successfully operated an aquaponics system that recycled 98% of water and produced impressive yields [20]. Beyond Asia, Europe has also seen a surge of interest in aquaponics. Urban aquaponics in the European Union (EU) is still in its early stages, but it is recognized as a promising solution for sustainable food production in cities. It aligns with the EU Green Deal and the Farm to Fork Strategy, promoting food systems that use less water, recycle nutrients, and minimize environmental impacts [21]. Most European aquaponics farms are small-scale initiatives integrated with community programs, schools, and research centers rather than purely commercial ventures. These systems are commonly located on rooftops, in underutilized buildings, or on marginal urban land. Both coupled and decoupled system designs are in use, with decoupled systems being favored due to their ability to optimize conditions separately for fish and plants [22]. Recent projects such as CITYFOOD and BLUE-CYCLING illustrate how aquaponics is being integrated into broader circular city frameworks. An example is the BIGH aquaponics farm in Brussels, built on the rooftop of a 2,000 m² food market. This facility reuses waste heat from refrigeration units to maintain optimal temperatures for fish and plants, significantly improving energy efficiency [23-25]. The EU Aquaponics Hub (2014–2018) also supported research and knowledge-sharing activities across European countries, fostering innovation in urban farming models. However, high energy requirements, initial capital costs, and fragmented regulations remain challenges for the wider adoption of commercial aquaponics in Europe [26].

In the Netherlands and Germany, research institutions such as Wageningen University have been at the forefront of aquaponics innovation, working on decoupled systems that combine high-value crops like tomatoes and lettuce with aquaculture species such as tilapia. These studies emphasize resource circularity, the use of waste heat, and advanced environmental control technologies [21]. In North America, aquaponics systems have been widely implemented at both community and educational levels. The Sustainable Technology Optimization Research Center (STORC) in Sacramento operates a closed-loop aquaponics system that uses campus food waste as inputs to produce plants and fish [27]. Urban programs such as Growing Power in Milwaukee [28] and initiatives in Denver demonstrate how aquaponics can contribute to food access and local resilience [29, 30]. In Latin America, countries such as Brazil and Nicaragua are implementing low-cost aquaponics systems in urban and peri-urban areas. In Brazil, sustainability assessments have shown that urban aquaponics significantly reduces water use while enhancing food self-reliance. Nicaraguan systems typically use tilapia and leafy vegetables, often linked to universities and non-profit organizations to enhance local food security and education [31, 32].

3. Designs and Innovations

Aquaponics evolved from the concept of the Aztec people of Mexico in 100 A.D. to the nurturing of the Chinese people 1,500 years ago, up to the present enthusiasm of many researchers, hobbyists, and entrepreneurs worldwide [33]. In the last century, the application of aquaponics was more of a traditional setup that utilized natural ecosystems. However, the exponential growth of the human population and the proliferation of agricultural and farming activities have led to the exploitation and depletion of natural resources. Today, interest in aquaponics has sprouted as a response to the dwindling land area and scarce resources [34].

The basic component of RAS was illustrated as shown in Fig. (**3**) [35]. The water runs continuously to move out all unwanted materials inside the fish tanks to the solids removal tank and to the biofilter unit for denitrifying bacteria to convert ammonia (NH_3) into nitrite (NO_2^-), and NO_2^- into NO_3^-. The processed nutrients then flow through the hydroponic trays and nourish the plants. The water comes out of the hydroponics setup cleaned and filtered as it returns to the fish tank through the water pump. An optional component between the hydroponics setup and the fish tank is a dissolved gas control, which can infuse dissolved oxygen (DO) and remove carbon dioxide (CO_2).

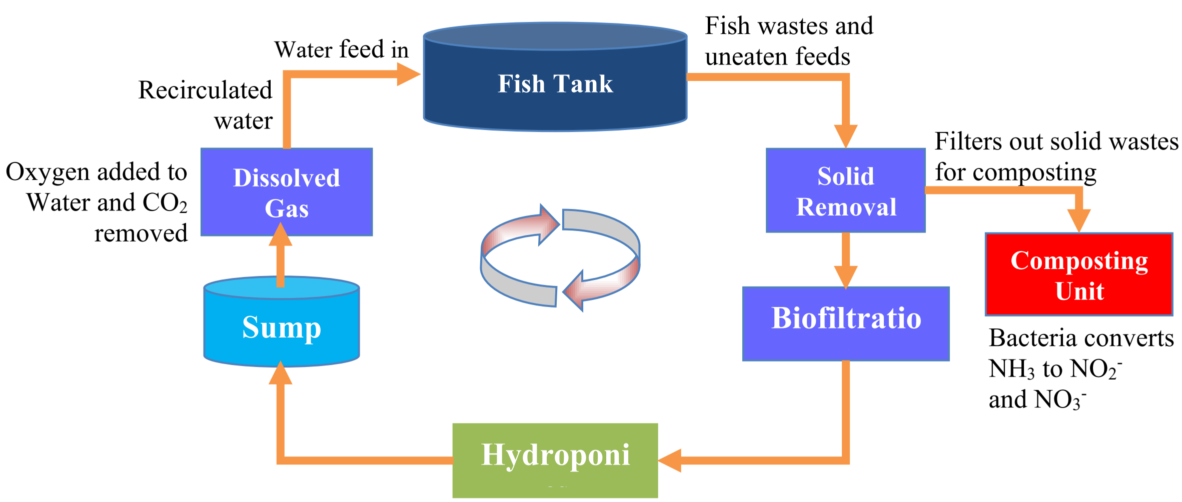

Figure 3: The basic components of aquaponics [35].

Three common designs of aquaponics were shown in Fig. (**4**-**6**), such as deep-water culture (DWC), nutrient-film-technique (NFT), and media-based (MB) [36]. DWC generally involves 20-40 cm of water in a tank or other culture unit, with floating rafts often made of expanded polystyrene or other floating foam material. Holes are cut or drilled in the foam where plants in the net pot were inserted, allowing roots access to the nutrients in the water. This system requires a substantial volume of water and generally can only support leafy crops. NFT system, on the other hand, uses a thin film of water containing nutrients and minerals from the fish wastes that is constantly circulated over the roots of the plants. The plants are grown in a channel or tubes, making it a highly efficient method of growing plants in aquaponics, as it requires minimal water and has a small footprint. However, this system usually can only support leafy crops. The MB is a type of aquaponics system where plants are cultivated in a grow bed filled with a solid medium, such as gravel or clay pebbles, instead of floating on top of the water. The roots of the plants are anchored in the grow bed and absorb nutrients from the water that is constantly circulated from the fish tank. The solid media provides a better root anchorage and can support many types of crops, such as leafy and fruiting vegetables. These aquaponics designs and advantages and disadvantages became the basis of most aquaponics systems today. A practical comparison of DWC, NFT, and MB systems highlights their unique applications. For instance, DWC is widely used in commercial lettuce production because its large water volume provides stable root environments and buffers temperature fluctuations, making it ideal for leafy greens [36]. NFT is commonly adopted in urban rooftop farms for leafy greens and herbs like basil and mint due to its low water requirement and small footprint, though it is sensitive to temperature fluctuations [37]. On the other hand, MB systems are often favored in community gardens for their versatility in supporting both leafy and fruiting vegetables, with the solid media anchoring the plants and enhancing filtration [38].

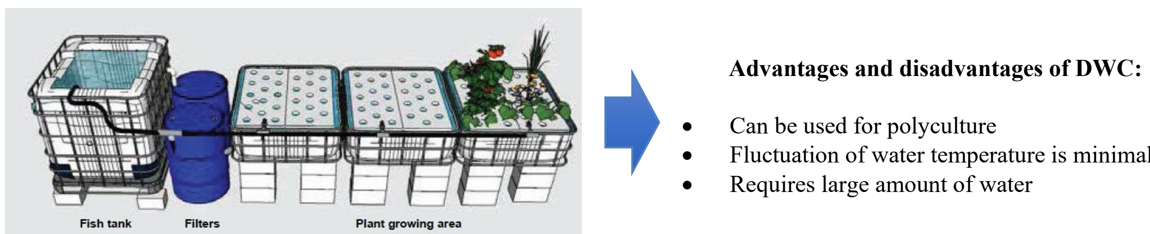

Figure 4: Deep-water-culture (DWC).

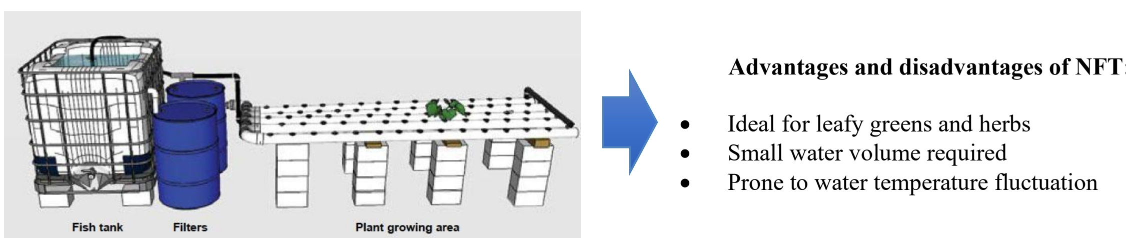

Figure 5: Nutrient-film-technique (NFT).

Figure 6: Media-based (MB).

Several studies have been conducted to test the workability and efficiency of these aquaponics designs. In Australia, a laboratory-based study compared the growth and yield of hydroponically and aquaponically-grown lettuce [39]. Part of the experiment was using NFT in combination with aquaculture, which may not be the best technical method for plant components due to the uneven distribution of nutrients into the plants, but overall, it equaled the lettuce production in a standard hydroponics system. In 2022, the photosynthesis re-oxygenation aquaponics (PRO-AP) was introduced Fig. (**7**), which added a culture tank for Spirogyra that helped in the biofiltration process and improved the number of nitrifying bacteria [40]. The addition of Spirogyra did not affect the yield and roots of the plants, but rather improved the water quality by reducing the NO_2^- and NH_3. In 2021, a laboratory experiment was conducted using oxygen and ozone nanobubble (NB) technology in the control of Vibrio parahaemolyticus (AHPND Strain) and improvement of water quality [41]. Acute hepatopancreatic necrosis disease (AHPND) is an infection of shrimp caused by gram-negative bacteria, Vibrio parahaemolyticus. The outbreak of V. parahaemolyticus in ponds is a major factor affecting the shrimp farms in Vietnam. After 96 hours of 4-6 minutes of ozone NB treatment, the V. parahaemolyticus bacteria infused into the water could no longer be detected and after 168 hours, the water indicated an improvement in DO and oxidation-reduction potential (ORP) level from 5.70-5.79 mg/L to 20.92-26.86 mg/L and 194-225 mV to 378-463 mV, respectively.

Nanobubble technology generates highly stable, ultra-fine bubbles (<200 nanometers) that remain suspended in water longer than regular bubbles, providing increased surface area for gas exchange and enhancing dissolved oxygen levels [42, 43]. These bubbles also produce reactive oxygen species (ROS) such as hydroxyl radicals and hydrogen peroxide at the bubble–water interface or during collapse [44]. ROS contribute to water disinfection by oxidizing organic matter and destroying pathogens. These properties improve water quality, suppress harmful microorganisms, and enhance nitrification processes, making nanobubbles a promising innovation in aquaponics and aquaculture systems [45-47]. Oxidation-reduction potential (ORP) indicates the electron activity in water and is an important indicator of its sanitizing and oxidative potential. High ORP values are associated with improved water disinfection and control of harmful bacteria [48-50]. Maintaining optimal ORP levels can help balance microbial activity and ensure a healthy aquatic environment [51].

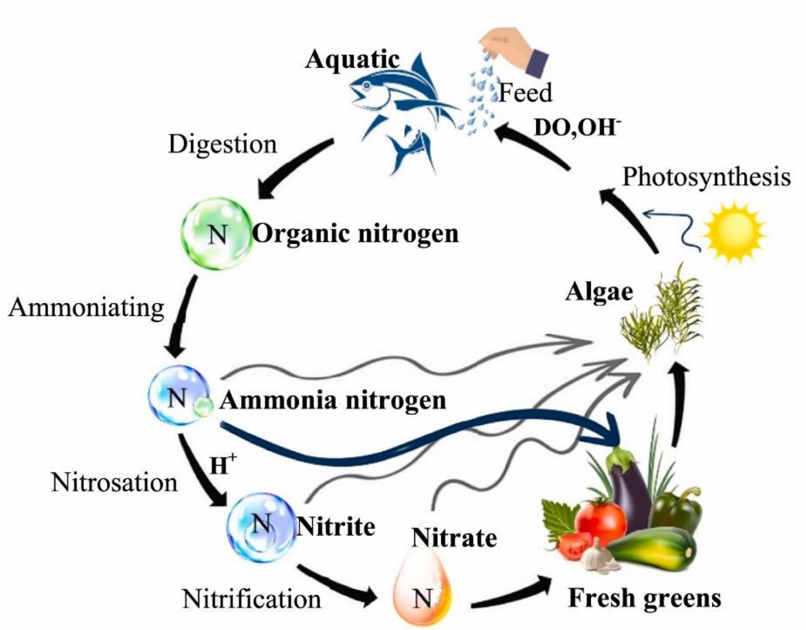

Figure 7: Conceptual diagram of the photosynthesis re-oxygenation aquaponics (PRO-AP) [40].

An older aquaponics design was introduced in 2016 with added components to the common aquaponics system called the double recirculating aquaponics system (DRAPS), as shown in Fig. (**8**) [52]. The DRAPS has two separate recirculating units, one each for the aquaculture unit and hydroponics. The advantage of this design was that nutrients generated from the aquaculture unit were recirculated to the plants without affecting the water quality in the aquaculture unit. While DRAPS consumes more energy due to operating two recirculation loops, this energy cost is justified by its significantly improved nutrient uptake, which enhances plant productivity and water quality management [38, 52]. The separation of water loops allows for optimal conditions for both fish and plants, increasing overall system efficiency and economic returns despite higher energy demands [38]. A case study conducted in Germany reported that the DRAPS system produced an average of 4.6 kg/m² of tomatoes per production cycle, which was about 20% higher than comparable hydroponics systems while maintaining stable fish growth rates and water quality [53]. This concrete evidence demonstrates the DRAPS system's ability to enhance yield and nutrient utilization despite higher energy demands.

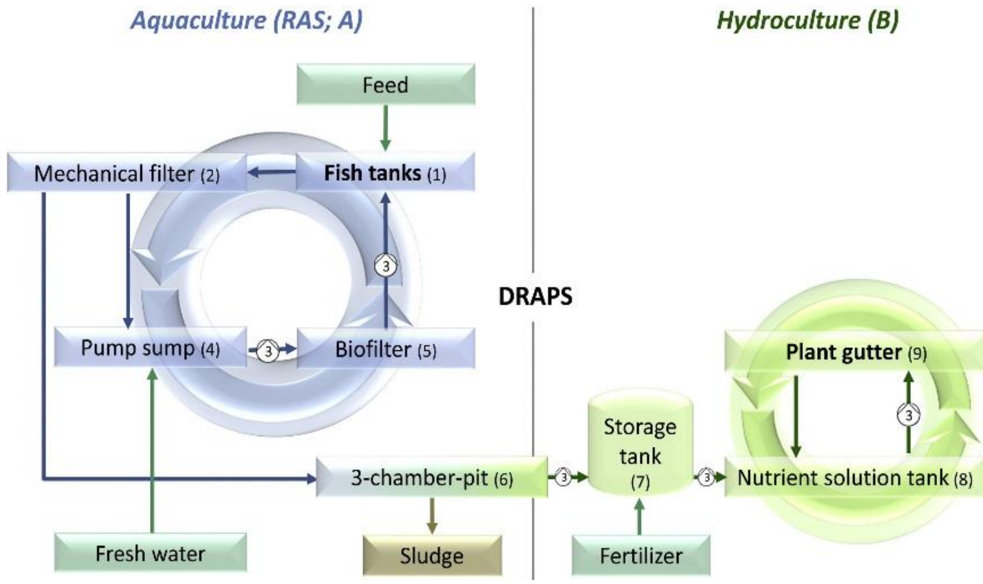

Figure 8: Schematic diagram of a double recirculation aquaponics system (DRAPS) [53].

4. Sustainability and Limitations of Aquaponics

The challenges of sustainable aquaponics were analyzed in 2015, and considered aquaponics as an important factor in the expansion of integrated food production systems [12]. Some of the critical issues in the environmental and economic sustainability of the aquaponics systems were the infrastructure, energy, and water consumption [54]. Specifically, electricity and feed were identified as the main contributing factors to the environmental impact of a commercial-scale aquaponics system [31]. Realizing these issues, aquaponics was integrated into a greenhouse operation and established a local market for the products [28].

To further assess the sustainability of aquaponics, specific metrics such as water use efficiency (L/kg of produce), energy consumption (kWh/kg), nutrient recovery rate (%), and carbon footprint (CO_2e/kg) are increasingly being applied in research and practice [31, 55]. These metrics allow for a quantitative comparison of aquaponics to conventional agriculture, highlighting its potential for reduced resource use and environmental impact while maintaining productivity.

However, despite its potential, aquaponics also faces significant limitations that need to be acknowledged to guide realistic expectations and future improvements. Scalability remains challenging due to the high initial investment costs, spatial constraints for large-scale operations, and the dependency on controlled environments [56]. Moreover, aquaponics requires considerable technical expertise to manage the complex biological and engineering interactions between fish, plants, and microbial communities, which can limit its adoption among inexperienced growers [57]. Finally, the long-term economic viability of aquaponics remains uncertain, as profitability is highly dependent on local market conditions, energy prices, and efficient resource utilization [37, 55]. These limitations underline the importance of developing training programs, supportive policies, and technological innovations to make aquaponics more accessible, resilient, and economically viable.

To address this concern, a genetic algorithm (GA) neural network model for the prediction of DO in aquaponics was designed [12]. GA neural networks combine evolutionary optimization techniques with neural network learning to effectively model complex, nonlinear relationships between variables, making them suitable for predicting water quality indicators in aquaponics [12, 58, 59]. Additionally, a smart aquaponics system was developed in Singapore using sensors, actuators, and microcontrollers to monitor and control water quality, light intensity, and fish feed delivery [10, 13]. These smart systems leverage the Internet of Things (IoT) and automation to optimize operations, reduce labor, and improve system stability by providing real-time feedback and control through email, SMS, or push notifications [11].

5. Water Quality Management

Water is considered the "blood" of the aquaponics system. The water quality directly impacts the growth and yield of reared plants and aquatic animals. The critical water quality parameters in aquaponics that need continuous monitoring and management are temperature, electrical conductivity (EC), DO, and pH [60]. Monitoring and maintaining the water quality in an aquaponics system is complex, yet the most important task. This becomes tricky due to the different ideal pH requirements of fish and plants. In aquaponics, balancing pH is critical because fish, plants, and nitrifying bacteria each have different requirements. Most fish thrive in a slightly alkaline range of pH 7.0–8.5 [8], while plants grow best in a slightly acidic range of pH 5.5–6.5 [61, 62], where nutrient availability is maximized. Meanwhile, nitrifying bacteria, which are essential for converting toxic ammonia into nitrate, perform optimally at pH 7.0–8.0. To accommodate all three, aquaponics systems are generally maintained at a compromise range of pH 6.8–7.2, which supports fish health, plant nutrient uptake, and efficient microbial activity simultaneously.

In 2020, a new sensor network was developed to automatically monitor, control, and optimize water quality and other environmental conditions [63]. A depth camera module was used to quantify growth with environmental and water quality parameters. The system could perform correlations and maintain water quality, including bacterial activity suitable for different types of plants and fish.

The recirculation of water in an aquaponics system is also critical in maintaining water quality and increasing water use efficiency. Realizing this issue, three identical integrated RAS with varying recirculating rates (RRs): 50, 200, and 400% or equivalent flow rates of 0.35, 1.4, and 2.8 L/min were evaluated [64]. Water spinach (*Ipomoea aquatica Forssk*.), lettuce (*Lactuca sativa L*.), and canna (*Canna glauca* L.) were planted in the hydroponics component. Tests were run in two different stocking densities: 220 and 122 fish/m^3 for 18 and 14 days, respectively. After 18 days, the fish under 200 and 400% RRs gained 30 and 85 g FW/m^3/d weight, while the 50% RR did not gain weight. For the other test, after 14 days, the fish gained weight of 9, 109, and 144 g FW/m^3/d for the 50, 200, and 400% RRs, respectively. Higher RRs have provided a suitable environment for the fish to grow faster. The DO concentrations in the fish tanks were 2.7-4.5 mg/L, with the lowest values in the systems with low RR. The water pH was between 7.0 and 7.4, with the 400% RR maintaining a pH of 7.0 throughout the experiment. The NH_3 in the systems was 4.6-9.2 mg/L, with the highest values running in low RR. The mortality was high at 50% RR with a 73% survival rate, while the 200 and 400% RRs had 90% and 98% survival rates, respectively.

6. Nutrient Management and Recovery

Nutrient enrichment in NH_3^+, NO_2^-, NO_3^-, and PO_4^{3-} is beneficial and detrimental in aquaponics operations. Depending on its management, It can improve or impair fish and plant production. The accumulation of nutrients resulting from protein-based meals is a significant consideration in designing an aquaponics system. Fish urine and gill excretion can allow nitrogen byproducts to build up to a toxic level that contaminates the water when left unchecked [65]. Biofiltration plays a vital role in converting the accumulated wastes in the aquaponics system into a usable form for the plants. This component contains biofilter media where nitrifying bacteria are nurtured, transforming the NH_3 produced from fish wastes and uneaten feeds, first into NO_2^-, then into a usable form (NO_3^-) by plants. The size, shape, structures, and surface area were the primary considerations in the performance of biofilter media.

In 2021, biochar and zeolite were compared with the conventional plastic biofilter media as a sustainable alternative for denitrification aquaculture effluents [66]. Under the pseudo-steady state conditions, zeolite exhibited the highest nitrate removal efficiency, followed by biochar and plastic (maximum 95.02 ± 0.01%, 92.91 ± 0.01%, and 92.57 ± 0.02%, respectively). The rough texture of the zeolite and biochar provided better adhesion and enhanced the development of bacteria. Previous studies have examined three biofilter media, such as PVC pipe (2.5 cm diameter cut into 5 cm pieces), plastic hair rolls (3.5 cm diameter x 7.5 cm length), and scrub pads (9 cm diameter x 3 cm width) in RAS [20]. The plastic roll biofilter had a superior removal rate and removal efficiency of TAN and NO_2^- with 3.46 g TAN/m^3 and 0.77 g NO_2^-/m^3/day, and 29.37% and 27.3%, respectively. This could be attributed to the configurations of the plastic roll, where more spaces were available for nitrifying bacteria to develop. Another study evaluated sand (SF), polystyrene microbeads (PF), and Kaldnes beads (KF) as biofilter media in a red seabream culture [67]. The TAN removal rates of SF and PF were significantly higher than those of KF, with 193.8, 183.9, and 142.6 g/m^3/day, respectively, as well as the NO_3^- removal rates with 113.4, 105.9, and 85.8 g/m^3/day, respectively.

The plants' roots in the aquaponics system's hydroponics component also served as biofilters. Plant species selection significantly affects system productivity and marketability because different plants have varying capacities for nutrient uptake, growth rates, and consumer demand [14, 22]. For example, leafy greens such as lettuce and basil are commonly chosen due to their fast growth, high nitrogen uptake efficiency, and strong market appeal, whereas fruiting crops like tomatoes may have higher economic value but require longer production cycles and more precise nutrient management due to their more stable root system [37, 38]. Selecting the right plant species thus balances system efficiency, sustainability, and profitability.

In 2018, a comparative study on aquaponics setup (red tilapia with pakchoy) had a lower NO_2^- against the aquaculture setup (red tilapia only) with 0.011-0.078 mg/L and 0.065-0.183 mg/L, respectively [65]. The NO_2^- for the aquaculture setup was slightly higher than the optimal range for tilapia of 0.02-0.12 mg/L, which implied that pakchoy effectively absorbed the nutrients produced in the system. Rice, the primary staple in Asia, is a good biofilter in an aquaponics system. In 2018, the nutrient removal capacity of floating-raft rice in a carp aquaponics setup was assessed [15]. The effluent water was cleared of TAN, total nitrogen (TN), and total phosphorus (TP) of about 34.31%, 64.53%, and 73.75%, respectively. This is consistent with the reports from previous studies that aquaponics can reduce total nitrogen from 25% up to 78.3% of N input [68-70]. However, most of the plants used in aquaponics such as lettuce, kale, basil, and tomatoes, could only extract a maximum of 46% TN [13]. This indicated that the rice plant was superior in TN recovery in aquaponics for its extended root mass.

Applying biofloc technology (BFT) is another technique for managing and using the nutrient accumulation in fish tanks. BFT is a method of aquaculture that involves manipulating the microbial community in a tank or pond to create a balanced and stable environment for the aquatic animals [71]. In BFT, waste produced by the aquatic animals is converted into food for other microorganisms, which are then consumed by the animals, thus closing the nutrient cycle. This process is facilitated by adjusting the pH and other water parameters, adding appropriate bacterial and fungal cultures, and controlling the amount of organic matter and dissolved oxygen in the system. An experiment, combining Nile tilapia, shrimp, lettuce, and watercress in a polyculture setup, maintained a better water quality [72]. In this experiment, integrating BFT in aquaponics enhanced the quality of Nile tilapia fillet with increased fat content.

Another factor that influences the nutrient recovery is the aquaponics design itself. The advantages and disadvantages of various growing components in aquaponics systems related to different practices and productivity were summarized in Table **1**. The MB aquaponics setup, DRAPS, and DWC demonstrated a high nutrient uptake, while the NFT system, SRAPS, and PRO-AP had a low nutrient uptake. The additional surface area provided by the growing media and higher volume of water in MB and DWC boosted the growth of nitrifying bacteria, and for DRAPS, the recirculation of wastewater to the hydroponics system improved the nutrient utilization but increased the power use.

7. Balance Ecosystem in Aquaponics

The stocking density of fish and the number of plants are critical factors in maintaining the ecological balance and productivity of aquaponics systems. Achieving optimal ratios between fish biomass and plant uptake capacity ensures that plants effectively utilize nutrients generated from fish waste, preventing the accumulation of toxic compounds and sustaining overall water quality. High or low stocking densities can directly influence system stability, fish health, plant nutrient availability, and microbial community dynamics. To evaluate the impacts of stocking density on fish growth and water quality in aquaponics, a comparative study was conducted using rainbow trout (*Oncorhynchus mykiss*) in a low-tech aquaponics setup [77]. This experiment established two treatments: aquaponics with low stocking density (ALD) and aquaponics with high stocking density (AHD). The initial stocking densities were 3.81 kg/m³ for ALD and 7.26 kg/m³ for AHD. Water quality parameters were carefully maintained within the optimal range for rainbow trout culture, with temperature ranging from 7.0–16.0 °C, pH from 6.7–8.1, dissolved oxygen (DO) from 8.69–11.31 mg/L, and electrical conductivity (EC) between 1.63–2.81 dS/m. While NH_3 and NO_2^- concentrations were kept below the toxic threshold (0.06–1.10 mg/L), the NO_3^- levels rose above the recommended limit of 400 mg/L, reaching 600 mg/L in both stocking treatments—likely due to active nitrification by bacteria converting nitrogenous waste.

Table 1: Summary of the advantages, disadvantages, and nutrient uptake of plants for different growing systems in aquaponics.

Growing System	Advantages	Disadvantages	Nutrient Uptake	Source
MB	- Develops more nitrifying bacteria in biofilter media - Enhance mineralization in the grow bed - Can support different plant varieties	- Needs a large-sized pump for flood and drain - Heavy structure - Difficult to clean and maintain - Frequent clogging - Poor root aeration	- High nutrient uptake due to more roots exposed to the water	[36, 55, 73]
DWC	- Continuous flow of water - Good aeration of roots - Only needs a small sump tank and a small pump - Easy to maintain and clean - Can grow different species of fish	- Needs a separate biofilter - Large volume of water required - Heavy structure for hydroponic - An additional aerator for roots is mandatory	- High nutrient uptake due to more roots exposed to the water	[36, 54, 73, 74]
NFT	- Constant flow of water - Easy to maintain and clean - Needs a small sump tank and a small pump - Small volume of water needed - Light structure for hydroponics	- Needs a separate biofilter - Limited to leafy vegetables - Frequent maintenance is needed - Materials are expensive - The hydroponics system is less stable with less water	- Low nutrient uptake due to a small portion of roots submerged	[36, 55, 73]
SRAPS	- Continuous flow of water - Good aeration of water and roots - Only needs a small sump tank and a small pump	- low production of plants - Suboptimal conditions for fish, plants, and bacteria - High rate of contamination due to nutrient accumulation and bacteria	- Low nutrient uptake due to continuous recirculation of water	[55, 75, 76]
DRAPS	- Separation of fish and plants creates optimal production conditions - Allow intensive crop production - Only needs a small sump tank and a small pump	- Not optimized plant-to-fish ratio	- High nutrient uptake	[53]
PRO-AP	- Increased number of nitrifying bacteria - Improved water quality due to the presence of spirogyra that absorbed nutrients	- Increased power requirement due to the use of two water pumps - Competition of nutrients between plants and spirogyra	- Low nutrient uptake by plants due to the absorption by spirogyra	[40]

High stocking densities can lead to reduced water quality, increased competition for oxygen and nutrients, and elevated levels of stress and disease among fish [78, 79]. These risks emphasize the need for effective management strategies, such as maintaining appropriate biomass-to-water ratios, regular monitoring of water quality parameters, and using biofilters or oxygenation technologies to sustain optimal conditions [77, 79]. Implementing periodic restocking and adjusting feeding rates are also practical approaches to mitigate the negative effects of overcrowding while maintaining productivity and fish welfare [80].

8. Conclusions and Future Work

Aquaponics has grown dramatically recently, with numerous system designs, components, control mechanisms, and cultured species being developed. These systems greatly promise to enhance overall sustainability by reducing nutrient losses and efficiently producing protein and plants. However, further development is needed to improve system robustness, ease of maintenance, operational stability, efficiency, profitability, and long-term sustainability. As climate change intensifies pressure on agricultural food production systems, yields of many crops are significantly declining while demand continues to rise. Open-field production systems are the most vulnerable to these challenges, increasing the adoption of controlled environment production systems. Food availability and security remain critical factors for human survival.

Due to its potential as an integrated food production system, aquaponics technology is seen as "unpolished diamonds" in agriculture. The development of modular aquaponics systems, whether it be a hobby or for personal consumption, is slowly increasing. In highly urbanized cities, modular aquaponics can be a potential idea. Although the basic components of aquaponics have already been established, the variety of designs and the nature of operation, which depend on many parameters, have become difficult to standardize. Sizes and measurements are not well established, leading to complex and sometimes too sophisticated designs and applications. Multi-disciplinary knowledge of the environment, plant and fish physiology, biology, biochemistry, and biotechnology is necessary for aquaponics' design, fabrication, installation, operations, and maintenance. The energy supply and consumption of aquaponic farms can also be a source of problems, especially when it is not adequately planned. The power consumption can become tremendously high when power equipment is not optimized.

This paper partially consolidated the advances in aquaponics from the time it was conceptualized out of nature's abundance to this period of relative resource scarcity. More research is needed to provide further improvements. More research on the optimization and economic feasibility must correspond to the designated scale, utilization, and operation to present consistent optimization techniques from biophysical and financial approaches. Another potential research is the combination of fruiting and leafy vegetables in one system to sustain nutrient uptake and avoid mineral buildup and high fluctuations in water parameters caused by frequent changes of plants during harvest. Also, marine aquaponics is another research possibility. While many salt-tolerant plants may not be suitable for human consumption, some can be potentially used for fuel, feed, fodder, and fiber with considerable economic value. The stakeholders' interests in aquaponics continue to expand and rise. Currently, most applications are research-based. Thus, there is a need for public-private partnerships to develop cost-effective and sustainable aquaponics for intensive and sustainable food production. Future research should also explore the integration of emerging technologies such as artificial intelligence (AI), robotics, and machine learning (ML) in aquaponics. AI and ML can optimize system parameters in real-time, predict nutrient imbalances, and reduce energy use through advanced analytics, while robotics can automate maintenance tasks and harvesting, improving efficiency and reducing labor demands [11, 13]. These technologies could play a critical role in developing smart, scalable, and sustainable aquaponics systems. Furthermore, integrating aquaponics into urban planning could address the challenge of food security in growing urban centers by reducing the reliance on external food supply chains and utilizing underused urban spaces. Aquaponics systems can be incorporated into rooftops, basements, and vertical farms, making fresh produce more accessible to urban populations while minimizing transportation costs and emissions [28, 37]. Policies promoting urban agriculture could include incentives for aquaponics adoption, zoning adjustments to support installations, and educational programs to increase public awareness of its benefits. Such integration not only contributes to local food resilience but also aligns with sustainable urban development goals.

Conflict of Interest

The authors declare no competing interests.

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Author contributions

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