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AQUAPONICS: A SUSTAINABLE INTEGRATION OF AQUACULTURE AND DEEP-WATER CULTURE HYDROPONICS FOR FUTURE FOOD SECURITY

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ABSTRACT

Aquaponics is an innovative and sustainable food production system that integrates aquaculture (fish farming) with hydroponics (soilless plant cultivation) in a symbiotic environment. The system operates by utilizing fish waste as a nutrient source for plants, while plants help filter and purify the water, creating a closed-loop ecosystem with minimal waste and resource consumption. Aquaponics offers numerous advantages, including efficient water use, reduced reliance on chemical fertilizers, and the ability to produce fish and vegetables simultaneously in a controlled environment. Additionally, it presents an eco-friendly alternative to conventional agriculture by reducing soil degradation and limiting environmental pollution. However, the adoption of aquaponics faces challenges such as high initial investment costs, technical complexity, and the need for continuous monitoring of water quality parameters like pH, ammonia, and nutrient levels. This review highlights the potential of aquaponics in addressing food security challenges, particularly in urban and arid regions where traditional agriculture is less viable. While aquaponics presents a promising solution for sustainable food production; further research is needed to optimize system design, nutrient management, and economic feasibility. By overcoming existing challenges, aquaponics can contribute significantly to global efforts toward environmentally sustainable and resilient agricultural practices.
Keywords: Aquaponics, Sustainability, Fish-plant integration, Nutrient cycling, Water conservation

Introduction

Aquaponics is a production practice in which aquaculture (the cultivation of aquatic animals) and hydroponics (the soil-less growing of plants) function together to deliver a symbiotic environment where the waste generated by farmed fish is utilized to enhance the plants (Gosh & Chowdhary, 2019). Combining these elements reduces friction around resource spending while enabling work to be done. It is the interaction between aquatic organisms and hydroponic and plants, where the waste byproducts of one serve as nutrients for the other, the hydroponic plants clean the water for the aquatic life. It goes to show how many layers of interdependence there are in any ecosystem, and also how they can create a closed-loop, where the waste product of one component serves as a resource for another, drastically minimizing dependence on external inputs and creating a self-contained, self-regulating ecosystem (Yep & Zheng, 2019).

Aquaponics is a combination of aquaculture and hydroponics and a system can be created whereby both can thrive. The hydroponic system uses filtered aquaculture effluent, which supplies the nutrients to the roots of plants. This water can then be recirculated back into the fish farming tanks after removing the accumulated nutrients (Rajalakshmi *et al.*, 2022). In this system, fish breed in tanks, and their waste is produced in the form of Total Ammonia Nitrogen (TAN) and this TAN comes off as NH_3 and NH_4^+ in water. Beneficial bacteria, like Nitrosomonas sp. are key in transforming ammonia to nitrites (NO_2^-) (Bhanja *et al.*, 2024)

In an aquaponics system, good water quality is very important for keeping fish healthy. It's not just about having many fish; it's about making a safe place for them. We need to think about how many fish we have, how much food they get, how fast they grow, and their surroundings. If we put too many fish together, we might get more production, but it can hurt water quality. More fish need more oxygen, and if the oxygen runs low, the fish could get sick and grow slowly. On the other hand, having too few fish can waste resources. We might not use food well, leading to less growth and lower productivity. The goal is to find the right number of fish to keep the system productive and the water clean. Balancing these things is key for healthy fish and happy growers (Li *et al.*, 2019). The nitrogen-rich byproducts of fish metabolism, uneaten feed, and dissolved organic detritus are transferred to the plants that use them as nutrients by the recirculating water between the two sub-systems. The use of bio-nutrients rather than chemical supplements and the reduction of water requirements, which may be as low as 10% of what is required for traditional soil cultivation, make it a very sustainable approach. Additionally, because fish waste is converted into resources, aquaponics is essentially a circular economy concept (Mourantian *et al.*, 2023). The fish rearing tank, the settler, the biofilter, and the hydroponic unit are the key parts of an aquaponic system. The hydroponic element has a direct impact on water quality, which is crucial for raising fish. Additionally, it is the primary cause of plant evapotranspiration water loss. Special attention should be given to the hydroponic system's design and operation since it affects the process's overall sustainability, either directly through water consumption or indirectly through system management expenses (Maucieri *et al.*, 2018).

Principles of Aquaponics

Deep Water Culture (DWC) hydroponics is a widely used technique in aquaponic systems due to its efficiency and ease of implementation. In a DWC system, plants are placed on floating rafts, allowing their roots to remain submerged in nutrient-enriched water sourced from the aquaculture component. This continuous immersion supports optimal nutrient absorption and ensures proper oxygenation, which is essential for root development and overall plant health. The DWC approach is particularly advantageous for growing leafy greens and herbs, such as lettuce, basil, and spinach, which flourish in such conditions. Studies indicate that DWC hydroponic systems exhibit higher productivity compared to traditional soil-based farming, primarily due to the direct availability of nutrients and favorable growth conditions.

The key principles guiding aquaponics are: (a) biological waste generated by one system serves as a nutrient source for another; (b) integrating fish and plant cultivation allows for simultaneous production of multiple agricultural outputs; (c) biological filtration and water recirculation facilitate efficient water reuse; and (d) localized food production promotes access to fresh, nutritious food while supporting the local economy (Gosh & Chowdhary, 2019).

Incorporating DWC hydroponics within aquaponic systems presents numerous benefits. Firstly, it significantly improves water efficiency by enabling the continuous reuse of water between fish tanks and plant beds, thus drastically reducing water consumption compared to conventional farming techniques. Secondly, the system eliminates the necessity for chemical fertilizers, as the nutrients required for plant growth are naturally supplied by fish waste. This not only lowers production costs but also mitigates environmental hazards associated with chemical runoff, which can contribute to water pollution and ecosystem imbalance. Furthermore, the symbiotic relationship between fish and plants enhances waste management, as fish byproducts, which would typically require disposal in traditional aquaculture, are repurposed as valuable nutrients for plant growth. This contributes to a more sustainable and environmentally friendly agricultural model.

The adaptability and scalability of aquaponic systems make them a practical solution for diverse applications, ranging from small-scale urban farming to large commercial enterprises. Their capacity to yield food in regions with scarce arable land and limited water resources establishes aquaponics as a promising alternative for strengthening global food security (Blidariu & Grozea, 2011). Additionally, aquaponic systems function within controlled environments, allowing for uninterrupted year-round production regardless of external climatic conditions, ensuring a stable food supply. Economic evaluations suggest that although the initial investment required for setting up aquaponic systems can be considerable, the long-term benefits such as lower water and fertilizer expenses and the ability to generate income from both fish and plant sales can outweigh these initial costs, making it a viable and sustainable agricultural practice.

Key elements of the system

1. **Deep Water Culture (DWC) Hydroponic Bed**: In this system, Net pots are placed in large, trough like containers that float on water. The roots of plants within net pot are supported with clay balls which are directly suspended into the nutrient rich water. This technique eliminates the requirement for soil and allows plants to uptake nutrients

directly while receiving sufficient water (RC & Rawal, 2024). It is best suited for leafy green crops like lettuce, basil, and spinach because of their quick uptake of nutrients. This system also uses less water, eliminates soil-based pathogens, and helps improve sustainability. The aeration maintains optimal levels of dissolved oxygen and enables the roots to grow healthily and capture nutrients to give higher yields in controlled environments.

2. **Plant Species:** The selection of plant species depends upon the stocking density of the fish tanks and the associated nutrient level in the aquaculture effluent. They can provide a wide range of crops but the most frequent crops produced are herbs, medicinal plants, and fast-growing leafy vegetables, as they require minimal fertilization (Hao *et al*., 2020). Lettuce and leafy greens, herbs, and certain specialty vegetables (spinach, chives, basil, and watercress) thrive in these systems. Fruiting plants, including tomatoes, bell peppers, and cucumbers, have much higher nutrient requirements and will be most productive in an established mature aquaponic system with high stocking densities (Bailey & Ferrarezi, 2017).

3. **pH and EC balance**: In an aquaponics unit, electrical conductivity (EC) and pH are crucial factors that influence system stability, plant growth, and fish health. EC measures the concentration of dissolved salts and nutrients in the water which typically ranges from 0.5 to 2.0 mS/cm. Maintaining optimal EC levels ensures that plants receive adequate nutrients while preventing harmful salt buildup that could stress fish. Meanwhile, pH affects the balance between fish and plants. The ideal pH range for an aquaponics system is 6.5 to 7.5, where fish thrive and plants absorb nutrients efficiently. Proper management of EC and pH is essential to maintaining a healthy, productive, and sustainable aquaponics system.

Following readings of Ec and pH were recorded from our unit

Table 1 : Weekly Variations in Electrical Conductivity (EC) and pH Levels in an Aquaponic System

Sr. No	Week	Ec	pH
1	1 (3/2/25 - 8/2/25)	1.1	8.1
2	2 (9/2/25 - 15/2/25)	1.0	8.08
3	3 (16/2/25 - 22/2/25)	1.1	7.7
4	4 (23/2/25 - 1/3/25)	0.9	7.6
5	5 (2/3/25 - 8/3/25)	0.9	7.7
6	6 (9/3/25 - 15/3/25)	0.9	7.2
7	7 (16/3/25 - 22/3/25)	0.9	7.6
8	8 (23/3/25 - 29/3/25)	1.0	7.8

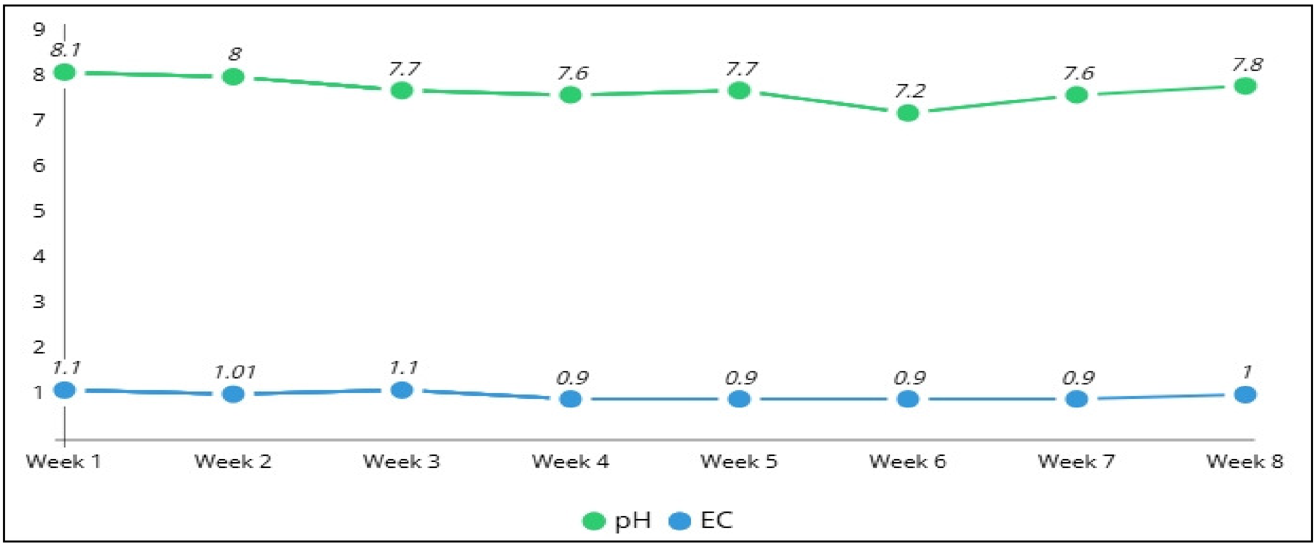

Fig. 1 : Graph shows the Variations of Electrical Conductivity (EC) and pH Levels in an Aquaponic system

4. **Fish Rearing Tank:** These tanks serve as habitats for aquatic organisms such as fish. As these organisms consume food and carry out metabolic processes they produce waste, primarily in the form of ammonia, which accumulates in the water (Mullins *et al.*, 2016). This waste serves as a valuable nutrient source for plants after undergoing biological conversion. To ensure a healthy environment for aquatic species, some parameters such as temperature, and dissolved oxygen levels must be closely monitored and regulated. For this, heater in winter and air pump was installed.
5. **Suitable fish species**: Fish is the main component of aquaponics system. It is the main source of nutrient rich water for the hydroponic plants cultivated in grow beds. Fish must withstand minor fluctuations in pH, ammonia, and temperature since aquaponics relies on a balanced ecosystem. The selection depends on climate, purpose and local regulations of the area (Krastanova *et al.*, 2022).

- **Tilapia** is one of the most popular choices due to its rapid growth, high tolerance for poor water quality, and ability to thrive in warm water. It gives approximately 10–14%ofnitrogen.
- **Catfish** are another excellent option, especially in warmer climates, as they are resilient and grow quickly. It gives approximately 12–16% of nitrogen.
- **Trout** are suitable for cooler water temperatures but require well oxygenated water, making them ideal for systems in temperate regions.
- **Goldfish**are often used in small scale systems because of their hardiness, though they grow slower and are less commonly harvested for food. It gives approximately 7–11% of nitrogen (Mchunu *et al.*, 2017).

6. **Mechanical Filtration**: Mechanical filtration is an essential element of aquaponic systems, helping to maintain water quality through the removal of solid waste prior to entering the hydroponic system. Solid waste can include uneaten fish feed and fish fecal material, which can block pipes and overall efficacy of the aquaponic system (Wei *et al.*, 2019). Mechanical separators, such as clarifiers are used for solid waste particle trapping.

Mechanical filtration not only prevents the blocking of pipes, but also improves water clarity, and subsequently improves the overall performance of the biofiltration system (Ani *et al.*, 2021). Mechanical filtration ensures that nutrient rich and relatively clean water is delivered to the plants, while also maintaining an environment suitable for fish. The management of solids in aquaponic systems is significant to achieving balance and sustainability of both the aquaculture and hydroponic system components.

7. **Water Circulation System**: A network of pumps and pipes ensures continuous water movement between the fish tanks and the hydroponic beds. It provides nutrients to plants in the growing system, and returns cleaned water to the aquaculture section, clearing the way for nutrient uptake and maintaining appropriate system balance. Pump size and maintenance is essential as clogs can and will occur, reducing water flow in both systems (Hussain *et al.*, 2024).

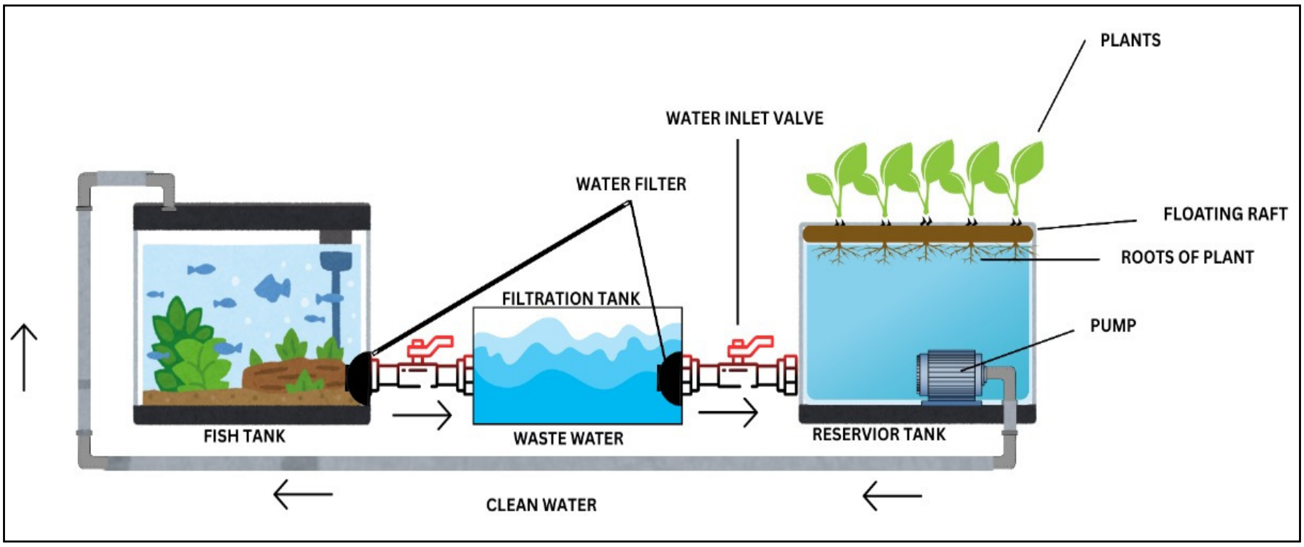

Fig. 2 : Schematic configuration of an Aquaponics with of Deep-water culture

Fig. 3 : Experimental Aquaponics setup in integration with Deep water culture

Table 2 : Growth Duration and Yield Potential of Common Crops Cultivated in Aquaponic Systems

Sr no.	Crops	Scinetific Name	Harvesting	Yield / m²
1	Lettuce	*Lactuca sativa*	30-45 days	3–7 kg
2	Spinach	*Spinacia oleracea*	35-50 days	2–6 kg
3	Kale	*Brassica oleracea*	50-60 days	3–7 kg
4	Mint	*Spinacia oleracea*	40-50 days	3–6 kg
5	Basil	*Ocimumbasilicum*	4-5 Weeks	4–8 kg
6	Coriander	*Coriandrum sativum*	30-40 days	2–4 kg
7	Pak choi	*Brassica rapa*	25-30 ays	8 kg

Source: Bailey &Ferrarezi, 2017.

Advantages of Aquaponics

1. **Conservation of Water**: For a variety of reasons from convenience of management to making the best use of scarce resources for maximum output large scale food fish production is frequently carried out in confined or small locations. The removal of ammonia from the water, which is highly harmful to the fish and is expelled, is one consequence of these living conditions. This is lessened by frequently changing the water used in commercial fish farming to prevent negative impacts on the fish raised and, consequently, the yield. In addition to the ongoing loss of limited resources in static aquaculture system management, the water renewal technique is incredibly ineffective in removing waste from the system (Okomoda *et al*., 2023). Less water is released because the hydroponics component of the system may recover dissolved nutrients from the system, which significantly reduces the waste that is present in the circulating water. Freshwater is only required in the system to compensate for losses from plant transpiration, evaporation from the water's surface, and the removal of accumulated solid wastes. This means that the technique uses around 2 percent less water than is typically required for irrigated farms to produce a comparable number of plants. As a result, aquaponics makes it possible to produce food commodities efficiently in places where resources like water and arable land are scarce or have highly competing applications (Rakocy *et al*., 2016).

2. **Improved growth rate and yield**: There is currently a higher demand that the traditional method of farming be improved to meet the exponential sapiens. As a result, the pressure also growth of the ubiquitous species, Homo increased farming inputs, including chemical fertilizers, translates into herbicides, pesticides, fungicides. Conventional farming productivity and inputs due to reduced profitability are reduced without these high-cost farm soil fertility. Compared to the traditional farming system, aquaponics production system incorporates ecologically sustainable practices of nitrogen and constant watering of plants with nutrient-laden wastewater (Love et

cycling *et al.*, 2014). The implications are clear it will not be long before the adoption and commercialization of a sustainable food production system like aquaponics to improve food production better than a conventional system is will help achieving to date. Therefore, both tgrow and develop he plant and also the fish extra quickly with much less input or exterior intervention.

3. **Food security and space efficiency**: of food production Aquaponics could be a consistent source as a consistent basis of food production is almost always guaranteed, aside from system failure. This success may be due to the fact that the conditions of rates) can be controlled in which growing (light, water parameters, and flow the fish and plants are never exposed to extreme frost, heat, rain, or other bad weather conditions (Rakocy *et al.*, 2016). One other benefit of aquaponic area usage viewpoint. systems to grow crops is the fact they work well from an used for This means that instead of needing the horizontal open spaces that are growing in the conventional system, farmers can work with smaller, vertical-oriented grow beds. This means that food commodities can be produced scales. in much smaller spaces at commercial
4. **Labor requirement is low**: When it comes to labor, weeding is to require lower no longer needed for your crops so aquaponics can be said maintenance. So, after a few early days of lock in super labor-intensive cost setting up it runs by itself and requires about half hour of watching or of relates human intervention to keep the system going. Most of this intervention to the feeding of fish and monitoring the parameters of the water quality. Another function is checking the plants for insect invasion and diseases, which time to time (Liang ideally only requires attention from & Chien, 2013).
5. **Adaptability to urban areas**: Because of migration leads individuals from town to urban without reasons, such as job school, and convenience, presented a contradiction for today's hunting, resulted in a fake scarcity of rural farmers, therefore society. This has even in urban areas; maybe restricting agricultural yield. Food can be produced urban aquaponics will be one of the ways to get back on track. Many cities around the world such as Islamabad, Milwaukee, and Melbourne, Kuala Lumpur, and practicing this (Nandy, 2020) In developing countries Singapore are lead to clashes (particularly in Africa), traditional agricultural farming can between crop farmers and cattle or nomadic herdsmen. The conflicts over grazing routes and water availability that this leads to are the basis of the deadly Africa resulting in hundreds of deaths over age-long violent in many parts of time.

Challenges of Aquaponics

1. **Maintenance of pH of water**: Aquaponics is a difficult system since it combines three unique concepts: fish, plants, and microorganisms. Water quality management, including pH, is prioritized throughout this type of cultivation procedure. Otherwise, pH changes could kill fish, plants, and helpful bacteria all at once. In general, the pH requirement for most of the plant species is varies from 6 to 6.5 to enhance the nutrient uptake. In contrast, fish require a pH range of 7-9 for optimal growth. Nitrifying bacteria demand high pH levels (Goddek *et al.*, 2015).In general, three species of bacteria play an important part in the nitrification process, with ideal pH levels ranging from 7.5 to 8.0-8.3 for Nitrobacter, Nitrosomonas, and Nitrospira, respectively. As a result, the optimal pH range for the entire aquaponics system is 6.0-8.0. Maintaining this pH range is crucial for regulating water quality metrics in this aquaponics system.
2. **Maintenance of nutrient content of water**:Another essential factor is nutrient balance, which is primarily determined by the fish feed following the nitrification process. This feed is separated into three categories: assimilated feed, uneaten feed, and soluble fish excreta. Soluble excreta are primarily ammonia and are the most accessible minerals until they are converted into nitrite and nitrate by nitrifying bacteria (Mishra *et al.*, 2020). Unused feed and solids must be converted to ionic mineral forms that plants can easily absorb. Mineral solubilization rates typically vary and do not accumulate in equal amounts. This impacts their concentration in the water. Mechanical filtration on a regular basis can partially solubilize solid wastes. Turbid and unfavorable nutrient loaded water can make fish more susceptible to diseases like fin rot and white spots. To address this issue, it's important to minimize overstocking of fish, which leads to lower harvest yields.
3. **Dependence on Electricity & Equipment Failures:** The continuous functioning of electrical components, such as water pumps and aerators, is essential for maintaining water circulation and oxygenation in aquaponic systems. Both fish and

plants require these processes to maintain their health and growth. However, this dependency on electricity creates considerable issues, especially during power outages or device malfunctions. To overcome this type of issue, farmers/producers require a power backup setup in which they can compete any kind of failure.

4. **Economic viability:** Aquaponics enterprises face economic challenges, including high production costs, inadequate scale, a lack of established business models, and low profitability, according to study respondents. Aquaponics is a high-risk industry with undefined markets and prices, therefore, newcomers should be cautious. During company planning, the costs of fish and plant production, as well as actual selling prices, must be examined and considered (Pattillo *et al.*, 2022). System scale has a direct impact on production costs. Inadequate planning or funding can lead to aquaponic systems being too small for profitability. Incorporating alternative income sources such as agritourism, educational activities, and the sale of non-food goods (for example, compost, decorative plants/fish, etc.)

Conclusion

Aquaponics represents a groundbreaking approach to sustainable agriculture, merging aquaculture and hydroponics into a highly efficient, resource-conscious food production system. As global populations rise and arable land diminishes, this innovative method offers a viable solution for producing fresh, nutritious food while mitigating environmental challenges. By integrating fish farming with plant cultivation, aquaponics creates a symbiotic ecosystem where fish waste supplies essential nutrients for plants, and plants, in turn, purify the water for fish. This closed loop system not only reduces water consumption but also minimizes the need for synthetic fertilizers and pesticides, making it a promising avenue for eco-friendly food production.

One of the most significant advantages of aquaponics is its ability to maximize resource efficiency. Traditional agriculture relies heavily on vast land areas, extensive irrigation, and chemical inputs, often leading to soil degradation, water scarcity, and pollution. Aquaponics, by contrast, uses up to 90% less water than conventional farming methods while enabling year round cultivation in controlled environments. The ability to grow crops without soil eliminates the risks of erosion and nutrient depletion, ensuring long term agricultural sustainability. Moreover, aquaponics promotes local food production, reducing dependency on global supply chains and lowering carbon footprints associated with food transportation. Urban areas can benefit immensely from aquaponic farms, as they require minimal space and can be established in warehouses, greenhouses, or even rooftops. This decentralized food system enhances food security by providing communities with access to fresh produce and protein sources, reducing vulnerabilities linked to climate change and geopolitical disruptions.

Despite its numerous benefits, aquaponics faces several challenges that must be addressed to facilitate its widespread adoption Due to high initial setup costs, technical complexities, and specialized knowledge requirements, aquaponic systems are often out of reach for small scale farmers and entrepreneurs. Policy support and public awareness are also crucial in driving the adoption of aquaponics. Governments and institutions should implement incentives, grants, and training programs to encourage farmers and businesses to integrate aquaponics into their agricultural practices. Furthermore, continued scientific research into optimizing fish plant symbiosis, improving system scalability, and enhancing nutrient cycling efficiency will contribute to refining aquaponic technology for broader application.

Looking ahead, aquaponics holds immense potential as a sustainable agricultural solution in the face of global food security challenges. With advancements in technology, increased investment, and community-driven initiatives, aquaponics can play a vital role in shaping the future of food production. By harnessing nature's synergy, aquaponics not only aligns with the principles of environmental stewardship but also fosters economic opportunities for farmers and entrepreneurs worldwide. As the world seeks resilient and sustainable food systems, aquaponics stands as a beacon of innovation, offering a harmonious balance between productivity and ecological responsibility.

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