



## Innovations in Aquaponics Technology and Building Sustainable Infrastructure for Agriculture

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**ABSTRACT:** Aquaponics, a symbiotic integration of aquaculture and hydroponics, presents a promising approach to sustainable agriculture by maximizing resource utilization and minimizing environmental impact. This study explores recent innovations in aquaponics technology and the development of sustainable infrastructure to support its widespread adoption. A systematic literature review is conducted, showing the fundamentals of aquaponics and its key components such as fish tanks, grow beds, and biological filters. Innovations in technology are examined, including advanced monitoring and control systems, integration of renewable energy sources, automation, and novel growing techniques. Sustainable infrastructure for aquaponics is analyzed, focusing on water management strategies, energy efficiency measures, material selection, and integration with urban agriculture. Furthermore, the alignment of aquaponics technology and sustainable infrastructure development with the United Nations Sustainable Development Goals (SDGs) is studied, particularly in achieving goals related to zero hunger, clean water and sanitation, responsible consumption and production, and climate action.

**Keywords:** Organic Farming, Nutrient Cycling, Sustainable Agriculture, Aquaponics Technology, Integrated Farming Systems

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## INTRODUCTION

Aquaponics is an innovative and sustainable approach to agriculture that combines fish farming with soilless plant cultivation. It creates a closed-loop system where fish waste becomes fertilizer for plants, and the plants filter the water for the fish. The core of aquaponics lies in the mutually beneficial relationship between fish and plants. Fish produce ammonia through excretion, which can be toxic. However, beneficial bacteria convert ammonia into nitrites and nitrates, readily absorbed by plants as nutrients.

Aquaponics is a sustainable practice. It reduces waste by creating a closed-loop system and promotes biodiversity by integrating plants and fish. Furthermore, it has the potential to be located in urban areas due to its minimal land requirements. Aquaponics systems can be set up in greenhouses or controlled environments, enabling year-round production regardless of the climate. This allows for consistent yields and increased food security (Sulaiman et al., 2023).

New technologies are continuously emerging to improve aquaponics. Automation systems for monitoring water quality are becoming more prevalent. Research is also ongoing in areas like biofloc technology, which utilizes microorganisms for improved nutrient processing. Aquaponics systems can be scaled for various applications. Small, home-based systems are suitable for personal use, while larger, commercial-scale systems can produce significant quantities of fish and vegetables for market.

Aquaponics can be integrated with existing agricultural infrastructure, such as greenhouses or vertical farming systems, to further optimize resource use and production. As aquaponics adoption grows, education and training programs are becoming increasingly important. These programs equip individuals with the knowledge and skills necessary to set up, manage, and maintain successful aquaponics systems. Continued research and development are crucial for advancing aquaponics technology. This includes exploring new plant and fish varieties, optimizing system designs, and developing cost-effective solutions for wider adoption. Our current food systems face serious challenges. To ensure food security and environmental well-being, we need innovative solutions. Sustainable agriculture infrastructure is key, promoting practices that meet our needs without compromising the future (Akhtar et al., 2024).

Sustainable infrastructure can be integrated with existing agricultural systems. Retrofitting existing irrigation systems for water conservation, incorporating renewable energy sources into farm operations, and utilizing cover crops in traditional farming practices are examples of how sustainability can be achieved within existing frameworks. Sustainable agriculture practices can contribute to building resilience against natural disasters. Practices like soil conservation techniques can minimize soil erosion during floods, while diversified cropping systems can be more adaptable to changing weather patterns. By focusing on resource conservation, environmental protection, and building resilience, sustainable agriculture infrastructure is vital for ensuring long-term food security.

The future of aquaponics is even brighter with the integration of the Internet of Things (IoT) and machine learning. These technologies have the potential to collect real-time data and optimize system performance through automation.

Another innovative approach is biofloc technology. This method utilizes microorganisms to manage nutrients within the system, reducing the need for external fertilizers and fostering a more natural ecosystem.

Aquaponics and advancements in sustainable agriculture infrastructure are revolutionizing food production, directly contributing to several Sustainable Development Goals (SDGs). Aquaponics, a closed-loop system, dramatically reduces water usage compared to traditional agriculture. Automation and sensor technology further optimize water use by precisely monitoring and adjusting water flow. This directly addresses SDG 6, ensuring sustainable water and sanitation for all.

These innovations also contribute to SDG 2, zero hunger. Aquaponics enables year-round food production in controlled environments, increasing yields and overall food security, particularly beneficial in areas with limited arable land or harsh climates. By eliminating the need for chemical fertilizers and pesticides, aquaponics promotes organic food production and minimizes environmental pollution, aligning with SDG 12, responsible consumption and production. Aquaponics biofilters help purify water used for fish, reducing potential harm to aquatic ecosystems when discharged, contributing to SDG 14, life below water.

The rise of aquaponics creates new job opportunities in system design, installation, and maintenance, supporting SDG 8, decent work and economic growth. Sustainable practices like cover cropping and integrated pest management in agriculture capture carbon and reduce greenhouse gas emissions, aligning with SDG 13, climate action (Okemwa, 2015). Aquaponics' potential for energy-efficient operation further contributes to climate change mitigation. Sustainable infrastructure promotes soil health through practices like crop rotation and reduced tillage. This protects biodiversity and ecosystem services provided by healthy soil, contributing to SDG 15, life on land.

## **THEORETICAL REVIEW**

### ***Components of an Aquaponics System***

An aquaponics system is a synchronized system between three key components: a fish tank teeming with aquatic life, a plant grow bed teeming with beneficial bacteria, and a tireless pump and filtration system connecting them. The fish tank houses the fish, which are the source of the nutrient-rich water that nourishes the plants. Choosing the right fish species is crucial. They should be able to tolerate fluctuating water conditions that are inevitable in a closed-loop system. Tilapia, perch, and goldfish are commonly used due to their resilience.

The grow bed is the stage where plants in an aquaponics system flourish. Unlike traditional agriculture, plants here don't reside in soil. Instead, their roots dangle freely in a supportive medium, like gravel or clay pebbles. This medium provides anchorage and allows the nutrient-rich water from the fish tank to bathe the roots constantly. The design of the grow bed is crucial for optimal plant growth and efficient water flow. They are typically long and narrow, with a slight slope to facilitate drainage. The ideal size depends on the number and size of plants you plan to cultivate (Baig et al., 2024).

The pump continuously draws water from the fish tank. Submersible pumps are often preferred for this task as they sit directly in the tank. The plumbing then takes center stage. Pipes carry the nutrient-rich water from the fish tank to the grow beds, where it showers the plant roots. The design should allow for even distribution of water throughout the grow bed. After interacting with the plants, the water exits the grow bed through a drainpipe and is then directed back to the fish tank for filtration, completing the loop.

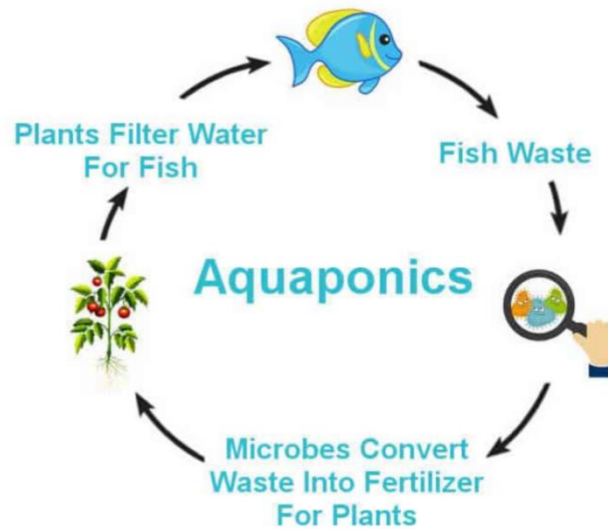
Biological filters ensure the health of both fish and plants. They remove harmful ammonia, a byproduct of fish waste, which can be toxic in high concentrations. However, biological filters don't simply eliminate ammonia. They provide a habitat for beneficial bacteria that convert ammonia into nitrites and then nitrates. These nitrates are the magic ingredient plants crave, readily absorbing them for healthy growth.

### *Nutrient Cycling in Aquaponics*

This nutrient cycling process is the core of a healthy aquaponics system. Fish produce waste, with ammonia being a key component. However, ammonia is toxic to fish in high concentrations. Beneficial bacteria, the unsung heroes of aquaponics, come to the rescue. These microscopic marvels colonize the biological filters within the system. As the nutrient-rich water from the fish tank flows through the filters, these bacteria convert harmful ammonia into nitrites through a process called nitrification.

Another set of beneficial bacteria takes over, transforming the nitrites into nitrates. These nitrates are the gold mine for plants, readily absorbed by their root systems as a primary source of nitrogen, a crucial nutrient for healthy growth. This conversion process is vital as ammonia is toxic to plants as well. Beneficial bacteria ensure the transformation into a usable form, preventing harm to both fish and plants. The cleansed water, now enriched with nitrates, exits the biological filters and journeys to the grow beds. The pump takes over here, ensuring a continuous flow of this nutrient-rich water as shown in **figure 1**.

In the grow beds, plant roots become the next stop. Dangling freely in the medium, like gravel or clay pebbles, these roots are constantly bathed in the water. The nitrates in the water are readily absorbed by the plants, fueling their growth and producing lush, healthy foliage. Over time, the water circulating through the grow bed can become depleted of oxygen and essential minerals. The design of the grow bed comes into play here. A slight slope and a drainpipe at the end of the grow bed allow this excess water to return to the fish tank.



**Figure 1:** Nutrient cycle in aquaponics (Parkes, Azevedo, Domingos, & Teixeira, 2022)

### *Innovations in Aquaponics Technology*

Aquaponics technology is constantly evolving to improve efficiency, sustainability, and user-friendliness. One exciting area of development is automation. Systems are emerging that can continuously monitor water quality parameters like pH, temperature, and nutrient levels. This allows for real-time adjustments and improved control over the entire aquaponics setup.

#### *a. Advanced Monitoring and Control Systems*

Traditionally, farmers relied on manual testing to measure water quality. This process is time-consuming, error-prone, and doesn't provide real-time insights. Advanced monitoring systems use sensors placed in the fish tank and grow beds to continuously collect data on various water parameters, providing a real-time picture of the system's health. The data is then transmitted wirelessly for easy access and analysis. Real-time monitoring allows farmers to identify potential problems early on. Advanced control systems take monitoring a step further by automating adjustments based on pre-programmed parameters. This automation saves time, labor, and ensures consistent growing conditions. The choice of system depends on the scale and complexity of the setup.

The future of aquaponics control systems is promising. Integration with the Internet of Things (IoT) could allow for remote monitoring and control. Machine learning algorithms are being explored to analyze sensor data and predict potential issues. This predictive maintenance could further enhance efficiency and sustainability. While the initial investment can be higher, the long-term benefits are undeniable. Increased yields, improved plant and fish health, reduced labor costs, and minimized water waste are just some of the advantages these systems offer. As technology continues to evolve, advanced monitoring and control systems will become even more sophisticated and affordable, making aquaponics a more accessible and sustainable method of food production.

### ***b. Integration of Renewable Energy Sources***

Solar energy is a popular choice. Solar panels can be installed on rooftops or nearby land to capture sunlight and convert it into electricity. This electricity can then be used to power various components of the aquaponics system, reducing reliance on the grid. Wind power is another option, particularly in areas with consistent wind patterns. Wind turbines can generate electricity that can be used to run the aquaponics system, further reducing its dependence on fossil fuels (Tehseen et al., 2024).

Hydropower can also be a viable option for some aquaponics setups located near moving water sources like rivers or streams. By harnessing the power of moving water, hydropower can generate electricity for the system. Integrating renewable energy sources offers several advantages for aquaponics. First and foremost, it significantly reduces the system's carbon footprint, making it more environmentally friendly. Secondly, it can lower operational costs by decreasing reliance on the grid for electricity.

### ***c. Automation and Robotics in Aquaponics***

One of the most significant applications of automation lies in water management. Traditionally, tasks like monitoring water quality parameters (pH, temperature, ammonia, etc.) and manually adjusting pumps or dosing systems were commonplace. Automation steps in with sensors strategically placed within the fish tank and grow beds. These sensors collect real-time data on these parameters, transmitting it wirelessly to a central hub or smartphone app (Ullah, Ishaq, et al., 2024).

This real-time data allows for automated adjustments. For instance, if the pH level dips below the ideal range, the system can automatically activate a dosing pump to add a pH-balancing solution. This ensures consistent and optimal growing conditions, minimizing the need for constant manual intervention. Automation extends beyond water management. Repetitive tasks like feeding fish can be automated using programmable feeders. These devices dispense precise amounts of fish food at designated intervals, ensuring proper nutrition for the fish without the need for manual feeding.

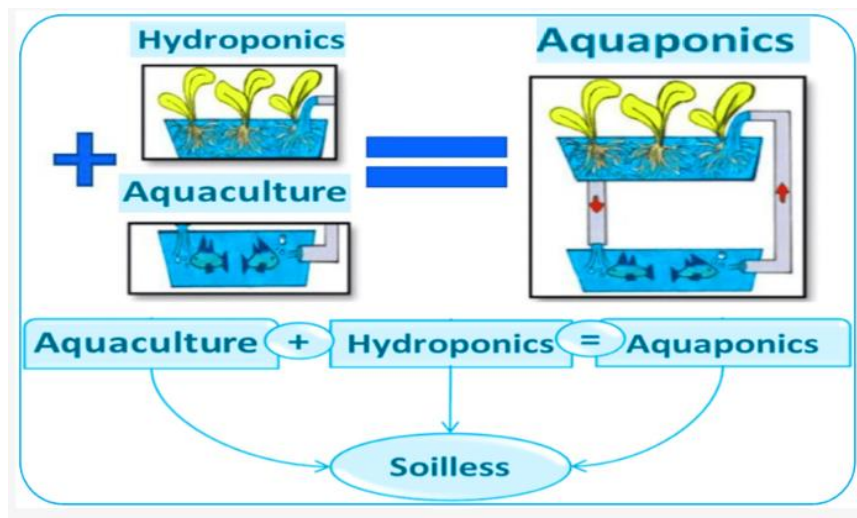
Aquaponics systems often require maintaining specific temperature and air quality ranges. Automated systems can monitor these factors and activate heaters, coolers, or ventilation systems as needed, creating a stable environment for both fish and plants. Robotics is also making its mark on aquaponics. For larger commercial setups, robotic arms are being explored to automate tasks like plant seeding, transplanting, and even harvesting (Sajid et al., 2024). These robots can navigate precisely within the grow beds, performing delicate tasks with greater speed and accuracy compared to manual labor as shown in figure.

### ***Sustainable Infrastructure for Aquaponics***

Aquaponics offers a unique opportunity to cultivate food in a closed-loop system, minimizing environmental impact. However, the infrastructure choices we make significantly influence the overall sustainability of the system. Water conservation is paramount. Capture rainwater using gutters and store it in tanks to

reduce reliance on municipal water supplies. Opt for closed-loop designs that minimize water loss and utilize techniques like multi-tiered grow beds to maximize water usage. Choose water-efficient grow media like aquaponic clay or recycled plastic media for good aeration and water retention.

Powering the pumps and other electrical components significantly impacts sustainability. Explore renewable energy sources like solar panels, wind turbines, or hydropower to generate clean electricity and reduce dependence on fossil fuels. Select energy-efficient pumps specifically designed for aquaponics and utilize natural ventilation strategies whenever possible to regulate temperature and minimize reliance on cooling systems as shown in **figure 2**.



**Figure 2:** Sustainable way for aquaponics (Raulier et al., 2023)

Aim for a closed-loop system that minimizes waste and maximizes resource utilization. Implement a system to collect and compost uneaten fish food and plant debris to create nutrient-rich compost. The nutrient-rich water from the aquaponics system can be used to irrigate gardens or potted plants, reducing the need for additional fertilizers (Ullah, Munir, et al., 2024). Opt for eco-friendly materials when constructing the aquaponics infrastructure. Use recycled or upcycled materials for building the fish tank, grow beds, and support structures. Invest in high-quality, long-lasting materials to reduce the need for frequent replacements. Minimize the environmental impact of transportation by sourcing materials and supplies locally whenever possible.

## METHODOLOGY

The data for this review were sourced from a diverse range of secondary materials, including peer-reviewed journals, governmental publications, and established databases. The criteria for selecting these sources focused on their relevance to the advancements in aquaponics technology, the reliability of the publications, and the timeliness of the information. Innovations in aquaponics technology encompass more than just the development of physical systems. The Nutrient Film Technique (NFT) offers a highly efficient method for maximizing plant growth within aquaponics systems. Unlike traditional grow beds where water sits around plant roots, NFT utilizes shallow channels with a constantly

moving film of nutrient-rich water from the fish tank. Plant roots dangle within these channels, having direct access to essential nutrients for optimal absorption (Pfeiffer, Silva, & Colquhoun, 2015).

## RESULTS AND DISCUSSION

### *Results of Integration with Urban Agriculture*

Integrating aquaponics with urban agriculture yields a multitude of benefits. Since aquaponics thrives in vertical spaces, it allows for increased food production in urban environments with limited land availability. This translates to fresh, local fish and vegetables grown within city limits, reducing reliance on long-distance transportation and bringing access to healthy food sources closer to communities.

The environmental impact of urban agriculture is also minimized through aquaponics. Closed-loop systems significantly reduce water use and eliminate the need for chemical fertilizers and pesticides, contributing to a more sustainable urban environment. Aquaponics even promotes resource recovery within cities. Fish waste is cleverly converted into nutrients for plants, minimizing overall waste generation.

Urban air quality can also see improvement with the integration of aquaponics. Plants within these systems act as natural filters, helping to remove pollutants and improve the air we breathe in cities. Economically, the growth of urban aquaponics creates new job opportunities in areas like system design, installation, maintenance, and food production, providing a boost to the urban economy.

Climate resilience is another advantage. Urban aquaponics systems can be more adaptable to extreme weather events compared to traditional agriculture, contributing to the overall climate resilience of cities (Fiaz, Noor, & Aldosri, 2018). By integrating with urban agriculture, aquaponics offers a promising approach to building more sustainable and self-sufficient food systems within our cities as shown in **table 1**.

**Table 1:** The benefits of integrating aquaponics with urban agriculture

Benefit	Integration with Urban Agriculture	References
Increased Food Production	Smaller footprints for urban environments	(El Essawy, 2017)
Fresh, Local Food	Access to healthy, local food sources	(Forchino et al., 2018)
Reduced Environmental Impact	More sustainable urban environments	(Kledal, König, & Matulić, 2019)
Waste Reduction and Resource Recovery	Resource recovery within cities	(Forchino et al., 2018)
Improved Air Quality	Improved air quality in cities	(Forchino et al., 2018)

Job Creation and Economic Opportunities	Economic boost for urban areas	(Haidri et al., 2024)
Community Engagement and Education	Community engagement in sustainable practices	(Maryam, 2023)
Enhanced Urban Aesthetics	Improved aesthetics and social interaction in urban spaces	(Maryam, 2023)
Climate Resilience	Increased climate resilience of cities	(Fatima et al., 2024)
Sustainable Urban Food Systems	Sustainable and self-sufficient urban food systems	(Aguiar Borges & Matthiesen, 2024)

### *Relation with SDGs*

Aquaponics offers a unique solution with the potential to address multiple Sustainable Development Goals (SDGs) established by the United Nations. Aquaponics enables food production in areas with limited land or poor soil quality. A 2020 study found it can produce up to 7 times more vegetables per unit area compared to traditional methods, contributing to food security and hunger reduction. Recent data suggests a growing trend in urban aquaponics projects, indicating its potential for contributing to SDG 11 (Sustainable Cities & Communities). The ability to produce food locally with minimal environmental impact makes aquaponics highly relevant in this context. However, challenges remain. Initial investment costs can be a barrier for small-scale farmers, potentially hindering progress towards SDG 1 (No Poverty). The relation of aquaponics with other SDGs is shown in **table 2.1**.

**Table 2:** Relation of SDGs with aquaponics

SDG	Description	Relation to Aquaponics	References
SDG 2: Zero Hunger	Aims to achieve food security and eradicate hunger.	High yields, nutritious food production in difficult areas.	(Ullah, Qasim, et al., 2024)
SDG 6: Clean Water and Sanitation	Ensures access to clean water and sanitation for all.	Reduces water consumption, naturally filters water.	(Brewer, 2019)
SDG 7: Affordable and Clean Energy	Promotes access to sustainable and modern energy for all.	Integrates renewables, reduces energy consumption.	(Haidri et al., 2024)

SDG 8: Decent Work and Economic Growth	Promotes sustained economic growth, and decent work for all.	Creates jobs, empowers communities.	(Demmer, 2022)
SDG 9: Industry, Innovation and Infrastructure	Build resilient infrastructure, and foster innovation.	Improves efficiency, sustainable infrastructure.	(Demmer, 2022)
SDG 11: Sustainable Cities and Communities	Make cities and human settlements inclusive, safe, resilient and sustainable.	Sustainable urban food production.	(Phungula, 2019)
SDG 12: Responsible Consumption and Production	Ensure sustainable consumption and production patterns.	Minimizes waste generation.	(Phungula, 2019)
SDG 13: Climate Action	Take urgent action to combat climate change and its impacts.	Reduces reliance on fossil fuels, resource efficient.	(CITIES, 2021)
SDG 15: Life on Land	Protect, restore and promote sustainable use of terrestrial ecosystems and halt and reverse land degradation.	Promotes biodiversity.	(CITIES, 2021)

### *Challenges and Opportunities*

Aquaponics offers a sustainable way to grow food by combining fish farming with plant cultivation in a closed system. However, there are hurdles to overcome before it becomes widely adopted. Setting up an aquaponics system requires an initial investment that can be a barrier for small-scale farmers. Operating it successfully requires knowledge of fish care, plant science, and maintaining a balanced water environment. Without proper training, systems can fail and productivity suffers. Smaller setups might rely on manual labor for tasks like monitoring water quality, feeding fish, and harvesting produce, which can be physically demanding and time-consuming. Developing modular and scalable systems that can be easily expanded as operations grow is crucial. This allows farmers to start small and gradually increase production capacity as they gain experience and market demand rises.

### **CONCLUSIONS AND RECOMMENDATIONS**

Innovations in aquaponics technology and sustainable agriculture infrastructure are revolutionizing the way we grow food. Aquaponics, which combines aquaculture and hydroponics, creates closed-loop ecosystems where fish waste fertilizes plants and plants clean the water for fish. Advancements include

efficient recirculating systems, automation for monitoring and control, and modular designs for scalability. Sustainable building materials and renewable energy sources further reduce environmental impact. Research is expanding the range of species suitable for aquaponic cultivation and improving their traits. This diversification enhances system resilience and opens opportunities for niche markets.

Collaborative efforts between researchers, engineers, farmers, and government agencies are driving innovation and adoption of sustainable agriculture practices. Open-source platforms and knowledge-sharing networks facilitate the dissemination of best practices. Partnerships with academic institutions support research and development initiatives, ensuring continuous improvement. Future research should focus on enhancing the efficiency of aquaponics systems by developing advanced sensors, automation technologies, and AI-driven management tools to optimize resource use and system performance. Scaling aquaponics systems for commercial use requires understanding their economic viability, identifying potential markets, and overcoming commercialization challenges.

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