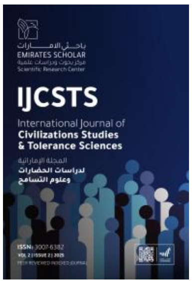

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Food Security & GHG Knowledge Gaps in Aquaponic Grow Systems

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ABSTRACT

The increasing pressures of climate change, resource scarcity, and environmental degradation necessitate a paradigm shift towards sustainable food production systems. Aquaponics, an integrated cultivation method combining aquaculture and hydroponics, emerges as a promising solution, embodying the principles of a circular economy. However, the utilisation of aquaponics, especially under changing climatic and resource-depleting conditions, as well as its contribution towards global greenhouse gas emissions, has been little discussed. Therefore, this study examines how aquaponics addresses the limitations imposed by climate change by enabling food production on non-arable lands, including urban areas, and potentially reducing greenhouse gas emissions, carbon, water, and energy footprints compared to traditional farming for equivalent yields. The study further examines technological advancements, socio-economic benefits such as localised food systems and job creation, as well as the inherent challenges and limitations of aquaponics. Likewise, innovative waste management strategies, particularly the utilisation of fish sludge as a valuable resource, are discussed and evaluated. In conclusion, if considered and utilised to its full potential, aquaponics has the potential to make a significant contribution to a more sustainable and resilient global food system in the face of growing environmental and resource constraints.

Keywords: *aquaponics, integrated systems, climate change, waste management, socioeconomics*

Introduction

The convergence of escalating global challenges, including the pervasive impacts of climate change, widening economic disparities, and accelerating environmental degradation, has brought the critical need for innovative and sustainable solutions in food production into sharp focus (Malhi *et al.*, 2021). Conventional agricultural practices, which have long served as the basis of human sustenance, are increasingly recognised for their unsustainable nature (Gomiero *et al.*, 2008; Sumberg and Giller, 2022). The sheer volume of fresh water consumed by traditional farming, accounting for up to 70% of global withdrawals, places immense pressure on this vital resource (Mishra, 2023). Furthermore, the widespread adoption of monoculture and the intensive use of synthetic fertilisers have led to a significant decline in soil health and overall land degradation worldwide (Belete and Yadete, 2023; Jiang *et al.*, 2019). The environmental consequences extend beyond land and water, with agriculture being a major contributor to greenhouse gas emissions, habitat destruction, and the eutrophication of water bodies (Li *et al.*, 2021; Scanes, 2018; Withers *et al.*, 2014). This unsustainable trajectory highlights the urgent requirement for alternative food production systems that can mitigate these detrimental effects and ensure food security for a growing global population.

In response to these pressing concerns, aquaponics has emerged as a promising integrated approach that synergistically combines aquaculture—the raising of aquatic animals—and hydroponics, the soilless cultivation of plants in water (Nair *et al.*, 2025; Verma *et al.*, 2023). This innovative system operates on a closed-loop principle, where the waste generated by one component is converted into a valuable resource for the other. The integration of these two traditionally separate practices creates a symbiotic relationship that has the potential to revolutionise food production, offering a pathway towards greater sustainability and efficiency (Atique *et al.*, 2022; Hochman *et al.*, 2018;). This article aims to provide a comprehensive and detailed analysis of aquaponics, exploring its multifaceted contributions to a circular economy, its pivotal role in addressing the limitations imposed by climate change and resource scarcity, and its overall environmental footprint in comparison to conventional agricultural methods. Furthermore, this review will delve into the technological advancements shaping the field, the socio-economic benefits it offers, the inherent challenges and limitations, and the crucial strategies for effective waste management within these integrated systems.

Aquaponics

At its core, an aquaponic system functions through a carefully composed interaction between fish, plants, and beneficial microorganisms (Stathopoulou *et al.*, 2018). The process begins with the fish, which, through their natural metabolic processes, produce waste, of which ammonia is a key component (Yavuzcan Yildiz *et al.*, 2017). If allowed to accumulate, this ammonia can become toxic to the fish, necessitating its removal from the aquatic environment (Rakocy, 2012). In a conventional aquaculture setting, this typically involves frequent water changes, resulting in the discharge of nutrient-rich wastewater (Tom *et al.*, 2021). However, in an aquaponic system, this seemingly problematic waste stream is transformed into a valuable resource for plant growth.

The key to this transformation lies in the presence of beneficial bacteria, specifically nitrifying bacteria such as *Nitrosomonas* and *Nitrobacter*, which colonise the surfaces within the system, particularly in a component known as the biofilter (Wongkiew *et al.*, 2017). These microorganisms facilitate a two-step process called nitrification. First, *Nitrosomonas* bacteria convert the ammonia into nitrites, and subsequently, *Nitrobacter* bacteria convert the nitrites into nitrates. Nitrates are a form of nitrogen that plants readily absorb as an essential nutrient for growth.

The nutrient-rich water, containing nitrates, is then circulated from the fish tank to the plant grow beds (Alnuaimi, 2024). As the plants absorb these nitrates and other dissolved nutrients from the water, they effectively act as natural filters, removing waste products that could be detrimental to the fish. This natural filtration process purifies the water, making it suitable for recirculation back to the fish tank, thus completing the closed-loop cycle (Jose *et al.*, 2025). This continuous exchange and purification create a symbiotic relationship where the fish provide the necessary nutrients for the plants, and the plants, in turn, help maintain a healthy aquatic environment for the fish (Stoyanova *et al.*, 2024). This inherent synergy within the aquaponic system minimises the need for external inputs, such as synthetic fertilisers. It significantly reduces water consumption compared to both traditional agriculture and conventional aquaculture practices.

Aquaponic systems can be implemented using various techniques, each with its own advantages and suitability depending on the scale, environment, and types of crops being cultivated. In media-based systems, plants are grown in an inert medium, such as gravel, clay pebbles, or lava rock, which provides structural support for the roots and serves as a habitat for beneficial nitrifying bacteria, effectively functioning as a biofilter (Oladimeji *et al.*, 2020; Tanveer *et al.*, 2025). The nutrient-rich water is periodically flooded through the media bed, allowing the plants to absorb the nutrients before draining back into the fish tank. The Nutrient Film Technique (NFT) involves growing plants in narrow channels where a shallow stream of nutrient-rich water continuously flows over the roots (Mohapatra *et al.*, 2020; Palmitessa *et al.*, 2024). This ensures a constant supply of nutrients and oxygen to the roots, supporting their growth and development. Deep Water Culture (DWC), also known as the raft system, involves suspending plants in holes in floating rafts, with their roots submerged directly in the nutrient-rich water in a separate tank (Gillani *et al.*, 2023; Nursyahid *et al.*, 2021). This method is particularly well-suited for leafy greens (Rajaseger *et al.*, 2023). Finally, hybrid systems combine elements of these different techniques to optimise production goals or environmental conditions (Dewi *et al.*, 2025). This versatility in system design highlights the adaptability of aquaponics as a food production method applicable across a wide range of contexts.

Aquaponics and the Circular Economy

The concept of a circular economy revolves around the principles of resource efficiency, waste minimization, and the creation of closed-loop systems where resources are kept in use for as long as possible, extracting the maximum value from them whilst in use, then recovering and regenerating products and materials at the end of each service life (Liu *et al.*, 2023; Zeng *et al.*, 2022). Unlike the traditional linear economy model of "take-make-dispose," the circular economy aims to decouple economic growth from the consumption of finite resources (Li & Xu, 2022). Aquaponics, by its very design and operation, embodies these core tenets, representing a tangible application of circular economy principles in food production (Gott *et al.*, 2019; Ibrahim *et al.*, 2023). The fundamental principle of aquaponics, where the waste from one biological system (fish) becomes the primary input for another (plants), perfectly mirrors the cyclical flow of resources that defines a circular economy (Alnuaimi, 2024). This approach not only seeks to mitigate adverse environmental impacts but also aims to generate positive outcomes by maximising resource utilisation and minimising waste generation (Rizal *et al.*, 2018).

Aquaponics significantly contributes to resource reuse and recycling, particularly in the areas of water and nutrient management. The fish waste, rich in essential nutrients such as nitrogen, phosphorus, and potassium, is not discarded as in conventional aquaculture but is instead directly utilised by the plants as a natural and readily available fertiliser. This eliminates or drastically reduces the reliance on synthetic fertilisers, which are often produced through energy-intensive processes and can have detrimental environmental consequences. Furthermore, aquaponic systems demonstrate remarkable water efficiency due to the continuous recirculation of water within the closed loop. Compared to traditional agriculture, which often requires significant amounts of water for irrigation that is lost through evaporation, runoff, or absorption, aquaponics can achieve water savings of up to 90-99% (Ibrahim *et al.*, 2023). Some innovative aquaponic designs even incorporate rainwater harvesting, further minimising the demand for external water resources (Love *et al.*, 2015). This efficient utilisation of water and nutrients underscores how aquaponics actively promotes resource efficiency by minimising the need for external inputs and maximising the value derived from internal resources.

In terms of waste minimisation, aquaponics offers significant advantages over traditional agricultural practices (Behr *et al.*, 2025). Traditional farming often relies on synthetic fertilisers, a portion of which can be lost through runoff, polluting waterways and harming aquatic ecosystems (Luna Juncal *et al.*, 2023). Aquaponics, which utilises fish waste as the primary nutrient source, essentially eliminates the issue of fertiliser runoff (Joyce *et al.*, 2019). Furthermore, the closed-loop environment of aquaponic systems significantly reduces the need for pesticides and herbicides, which are commonly used in conventional agriculture and can have adverse effects on the environment and human health (Joyce *et al.*, 2019; Nair *et al.*, 2025). Unlike traditional fish farming, which can discharge water heavily contaminated with ammonia and antibiotics (Zhou and Wang, 2023), aquaponic systems are often characterised as near-zero discharge systems, thereby minimising the release of harmful substances into the surrounding environment (Zhu *et al.*, 2022).

Beyond the primary components of water and nutrients, aquaponics also presents opportunities for upcycling byproducts, such as fish sludge (Shaw *et al.*, 2022). Fish sludge, which consists of fish faeces and uneaten feed, is typically removed from aquaponic systems to maintain water quality (Cristiano *et al.*, 2022). However, this sludge is rich in nutrients and organic matter, representing a valuable resource (Sele *et al.*, 2024). Various methods can be employed to process this sludge, including mineralisation, both aerobic and anaerobic, which breaks down the organic matter and releases the bound nutrients in a form readily available to plants (Zhang *et al.*, 2020). The resulting nutrient-rich solution can then be reintroduced into the aquaponic system, closing the nutrient loop and reducing the need for external inputs.

Additionally, the anaerobic digestion of fish sludge can produce biogas (Xia *et al.*, 2023), a renewable energy source that can be utilised to power components of the aquaponic system, thereby contributing to energy independence and reducing reliance on fossil fuels (Zhu *et al.*, 2022). Even plant waste generated from the hydroponic component can be utilised through anaerobic digestion to produce biogas. By viewing these byproducts as potential resources, aquaponics further exemplifies the principles of a circular economy, striving for a zero-waste system where all outputs are either reused within the system or repurposed for other beneficial applications.

Climate Change, Resource Limitations and Aquaponics

The escalating challenges posed by climate change, particularly the increasing frequency and intensity of droughts and extreme weather events, coupled with the growing global population, are placing unprecedented strain on traditional agricultural systems and exacerbating the issue of water scarcity (Saleem *et al.*, 2024). In this context, aquaponics emerges as a promising solution, offering a highly water-efficient method for food production. Due to the closed-loop nature of aquaponic systems, water is continuously recirculated, resulting in a significant reduction in water usage compared to conventional agriculture, with savings often ranging from 90% to 99% (Joyce *et al.*, 2019). For instance, while traditional farming requires approximately 15.9 gallons of water to grow one pound of lettuce, an aquaponic Recirculating Aquaculture System (RAS) can achieve the same with only about 7.6 gallons (Food & Water Watch, 2009). This remarkable water efficiency makes aquaponics an especially vital approach in regions facing increasing water scarcity due to droughts or other climate-related factors. The ability to produce substantial amounts of food with significantly less water positions aquaponics as a key strategy in mitigating the impacts of climate change on food security.

Furthermore, aquaponics offers a unique opportunity for food production on non-arable lands, including urban areas, degraded soils, and even rooftops (Goddek *et al.*, 2019). Unlike traditional agriculture, which is heavily reliant on fertile soil, aquaponic systems can be established in diverse locations, including areas deemed unsuitable for conventional farming, such as rooftops and abandoned factory sites (Alsanius *et al.*, 2017). The concept of urban aquaponics is gaining traction, with systems being developed on rooftops, underground spaces, and marginal lands within cities. Initiatives like GrowUp Urban Farms in London, which utilise rooftops and vacant urban spaces for aquaponic food production, serve as compelling real-world examples of this potential. Aquaponics enables localised food production with minimal land use, making it particularly well-suited for densely populated urban environments, where space is at a premium. This adaptability to various environments, from urban centres to rural landscapes, highlights the potential of aquaponics to expand food production into areas where traditional farming is not feasible, thereby enhancing food security and resilience in the face of climate change-induced land degradation and resource limitations.

Compared to conventional farming, aquaponics demonstrates a significantly reduced reliance on land (Joyce *et al.*, 2019). By eliminating the need for soil, aquaponics bypasses the limitations associated with arable land availability. It opens up opportunities for vertical farming, where crops can be grown in stacked layers, maximising production per unit area (Nair *et al.*, 2025). This land efficiency is crucial as the global population continues to grow, and the demand for food increases, placing further pressure on already limited arable land resources. The ability to achieve higher yields per unit area through controlled environments and vertical farming techniques enables aquaponics to produce more food using less land compared to traditional methods. This reduced land footprint not only makes it suitable for urban agriculture but also has broader implications for land conservation, potentially freeing up land for other vital purposes, such as conservation and reforestation. As climate change and population growth continue to strain global resources, the land-efficient nature of aquaponics positions it as an essential tool in ensuring future food security while minimising environmental impact.

Environmental Footprint Comparison

Understanding the environmental footprint of different food production systems is crucial for making informed decisions about sustainable agriculture. Several studies have compared the ecological impacts of aquaponics and conventional agriculture across various metrics, including greenhouse gas emissions, carbon footprint, water usage, and energy consumption.

In terms of greenhouse gas (GHG) emissions, aquaponics presents a complex picture. On one hand, aquaponics can significantly reduce carbon emissions by eliminating the need for synthetic fertilisers, whose production is an energy-intensive process that releases substantial GHGs (Kalvakaalva *et al.*, 2022; Zhu *et al.*, 2022). One study even reported a negative carbon footprint for an aquaponic system utilising black soldier fly larvae meal as fish feed, indicating a net removal of CO_2 equivalent from the atmosphere, in stark contrast to the positive emissions typically associated with conventional agriculture and aquaculture (Tadesse, 2023). However, the operation of aquaponic systems often requires electricity for pumps, aeration, temperature control, especially heating in colder climates, and artificial lighting in indoor setups (Zhang *et al.*, 2023), which can contribute significantly to GHG emissions depending on the source of the electricity (Le *et al.*, 2020). Studies have shown that electricity consumption can be the parameter with the most significant impact on the global warming potential of aquaponic systems (Ravani *et al.*, 2024; Zoli *et al.*, 2024). The integration of renewable energy sources, such as solar power, has demonstrated the potential to reduce the global warming potential of aquaponic systems by as much as 50% or even more (Vo *et al.*, 2021; Zainal Alam *et al.*, 2022). Therefore, while aquaponics holds promise for lower GHG emissions compared to conventional agriculture, particularly when coupled with renewable energy, a comprehensive assessment requires considering the specific energy sources and operational practices employed.

The carbon footprint of food production encompasses various factors, including the production and transportation of inputs such as fertilisers and pesticides, on-farm energy use, and the transportation and distribution of the final products (Zhu *et al.*, 2022). Aquaponics can contribute to a lower carbon footprint through several mechanisms. The localised nature of aquaponic food production, particularly in urban environments, significantly reduces the carbon emissions associated with the long-distance transportation of produce from traditional farms to consumers.[1] Furthermore, the elimination of synthetic fertilisers in aquaponics avoids the substantial carbon footprint associated with their manufacturing and transportation. In greenhouse-based aquaponic systems, the carbon dioxide emitted by the fish through respiration can be captured and utilised by the plants for photosynthesis, further contributing to carbon sequestration.

The comparison of water usage between aquaponics and conventional agriculture overwhelmingly favours aquaponics. As previously discussed, aquaponic systems can achieve water savings of up to 90-99% compared to traditional soil-based farming for the same quantity of crops grown. This efficiency is achieved through a closed-loop system, where water is continuously recirculated, thereby minimising losses due to evaporation and runoff. Notably, aquaponics is also more water-efficient than traditional hydroponic systems, which require periodic water changes. This superior water efficiency makes aquaponics a desirable solution in regions facing water scarcity and for promoting sustainable water management in agriculture.

Energy consumption in aquaponics versus conventional farming is another important aspect of environmental impact. Traditional agriculture relies on energy-intensive practices such as tilling, irrigation, and the operation of heavy machinery, as well as the energy required for the production and transportation of synthetic fertilisers and pesticides (Gamage *et al.*, 2024; Kakraliya *et al.*, 2022). Aquaponics, while eliminating the need for these energy-intensive inputs, requires energy for its own operations, primarily for water pumps, aeration systems, temperature control (especially heating in colder climates, as mentioned above), and artificial lighting in indoor or greenhouse setups. Studies comparing energy consumption have yielded varying results, with some indicating that aquaponics can have higher energy demands per unit of yield, particularly when heating and artificial lighting are required (Terrascope, 2024). However, aquaponics systems can be designed for energy efficiency, and the integration of renewable energy sources, such as solar power, can significantly reduce their reliance on fossil fuels and lower their overall energy footprint. Furthermore, the potential for higher yields in aquaponics compared to traditional farming in the same area could lead to a lower energy consumption per unit of food produced in some cases (Table 1).

Table 1: Comparison of Environmental Impact Indicators: Aquaponics vs. Conventional Agriculture

Environmental Indicator	Aquaponics (Example Values)	Conventional Agriculture (Example Values)
GHG Emissions (kg CO_2-eq/kg lettuce)	-1.5 (annual system)	0.02 - 0.11
GHG Emissions (kg CO_2-eq/kg tomato)	0.13 - 0.6	0.02 - 2.7
Water Usage (L/kg lettuce)	7.6	250
Water Usage (L/kg tomato)	Lower than conventional	Higher than aquaponics
Energy Consumption (kWh/kg lettuce)	Variable	Lower than some hydroponics
Energy Consumption (kWh/kg tilapia)	159	Not directly compared

Technological Advancements and Innovations in Aquaponics

The field of aquaponics is characterised by continuous technological advancements and innovations that aim to enhance efficiency, sustainability, and scalability. Recent advancements in system design and automation are playing a crucial role in improving the overall performance of aquaponic systems. The development and implementation of sophisticated monitoring and control systems enable the continuous tracking of critical water quality parameters, including pH, temperature, dissolved oxygen, and nutrient levels (Chavhan *et al.*, 2025). These systems often incorporate sensors and data analytics to provide real-time insights and enable automated adjustments, thereby maintaining optimal conditions for both fish and plants. Automation is also being increasingly applied to tasks such as feeding the fish and controlling water flow, reducing the need for manual labour and improving the consistency and accuracy of these processes (Alnuaimi, 2024). Furthermore, the adoption of vertical farming techniques and the design of stacked grow beds are becoming more prevalent in aquaponics to maximise space utilisation, particularly in urban environments and indoor facilities, leading to higher yields per unit area. The development of modular aquaponic systems provides greater flexibility and scalability, enabling easier expansion and adaptation to various production needs.

Innovations are continually emerging to enhance the sustainability of aquaponic systems further. Significant research is focused on optimising biofiltration processes to ensure the efficient conversion of fish waste into plant nutrients and the effective removal of harmful compounds from the water (Asadujjaman *et al.*, 2024; Ibrahim *et al.*, 2023; Thakur *et al.*, 2023). There is also a growing interest in exploring alternative and more sustainable protein sources for fish feed, such as black soldier fly larvae meal (Romano *et al.*, 2022), which has a significantly lower carbon footprint compared to traditional fish meal derived from wild-caught or farmed fish. The integration of microalgae into aquaponic systems, known as algaeponics (Kotzen *et al.*, 2019), is being investigated for its potential to help balance pH levels, increase dissolved oxygen, control ammonia levels, and enhance nutrient utilisation. For regions facing freshwater scarcity, the development of saline aquaponics, also referred to as maraponics or haloponics, is exploring the use of salt-tolerant fish and plant species in brackish or seawater environments (Chen *et al.*, 2020; Heo *et al.*, 2024; Romano *et al.*, 2023). A number of emerging technologies also hold promise for improving sustainability: these include vermi-aquaponics, which integrates earthworms into plant growth beds to further break down fish waste and enhance nutrient cycling, and flocponics, which combines biofloc technology with soilless agriculture for efficient nutrient management (Chandramenon *et al.*, 2024).

Significant advancements are also being made in scaling up aquaponics for commercial viability. The development of patented, commercial aquaponic systems designed specifically for large-scale food production is a crucial step in this direction (Alnuaimi, 2024). Research and practical experience are leading to a deeper understanding of the optimal fish-to-plant ratios for efficient nutrient utilisation in commercial settings. The implementation of automated systems for monitoring and control is becoming increasingly crucial for reducing labour costs and improving overall efficiency in larger operations (Alnuaimi, 2024; Kok *et al.*, 2024). While challenges persist in relation to initial investment and operational complexity, ongoing technological advancements and a growing body of knowledge are steadily paving the way for commercially viable large-scale aquaponics to make a significant contribution to sustainable food production.

Socioeconomics of Aquaponics

Beyond its environmental advantages, aquaponics offers a range of significant socio-economic benefits, contributing to more resilient and sustainable communities (Adeleke *et al.*, 2022). One of the key benefits is its role in promoting local food systems and reducing food miles (Obirikorang *et al.*, 2021). Aquaponics systems can be established in urban and peri-urban areas, bringing food production closer to consumers. This localisation reduces the carbon footprint associated with the long-distance transportation of food from traditional farms, which can travel an average of over 2,000 kilometres in the U.S., for instance (Wakeland *et al.*, 2011; Weber and Matthews, 2008). By providing fresher, locally sourced produce, aquaponics supports the growing farm-to-table movement, enhancing the nutritional value and quality of food available to communities (Bano, 2024).

Aquaponics also has significant potential to enhance food security and improve access to nutritious food, particularly in regions facing challenging environmental conditions or limited resources. The controlled environment of aquaponic systems enables year-round food production, regardless of external weather conditions or seasonal limitations, thereby ensuring a consistent and reliable supply of both fish and vegetables (Ghamkhar *et al.*, 2022; Johnson *et al.*, 2017). This is particularly important in areas with harsh climates or limited arable land, where traditional farming may struggle to meet the population's nutritional needs. Furthermore, aquaponic systems produce both a source of protein and a variety of vegetables, contributing to a more balanced and nutritious diet, which is crucial for overall health and well-being (Pantanella, 2012).

The adoption of aquaponics can also lead to the creation of economic opportunities and green jobs within communities (Egyir *et al.*, 2023; Peal, 2017). Both small-scale and commercial aquaponic farms can generate income through the sale of fresh produce and fish, providing livelihoods for individuals and families. The development and operation of these systems also create jobs in related sectors such as system design, installation, maintenance, and the supply of necessary inputs (Pattillo *et al.*, 2022). By promoting local food production and supporting the growth of sustainable agriculture, aquaponics can contribute to the development of more resilient and economically vibrant communities.

Finally, aquaponic farms can serve as valuable platforms for community engagement and education (En & Yii, 2023; Kluczkovski *et al.*, 2024). These systems offer unique opportunities to teach about sustainable agriculture practices, the interconnectedness of ecosystems, and the importance of environmental stewardship (Peña *et al.*, 2025). Community-based aquaponic gardens can foster social interaction, collaboration, and a sense of shared responsibility towards food production. Furthermore, engaging with aquaponic systems can raise awareness about the benefits of healthy eating and the importance of sustainable food production practices, contributing to a more informed and engaged citizenry.

Challenges and Limitations of Aquaponics

While aquaponics offers numerous advantages, it is also associated with specific challenges and limitations that need to be carefully considered for successful implementation and widespread adoption. One significant hurdle is the initial setup costs and the overall financial investment required to establish an aquaponic system (Asciuto *et al.*, 2019; Babatunde *et al.*, 2023). The cost of equipment such as fish tanks, grow beds, pumps, filters, plumbing, and monitoring systems, along with the infrastructure needed for controlled environments like greenhouses, can represent a substantial upfront investment (van Beukering, 2021). Scaling up aquaponic operations for commercial production can also be considerably expensive, requiring significant capital expenditure for larger systems and potentially more sophisticated infrastructure. This high initial investment can be a substantial barrier to entry for many potential aquaponics farmers, particularly those with limited financial resources.

The successful operation of an aquaponic system requires a certain level of technical expertise and management skills (König *et al.*, 2018). Unlike traditional farming, aquaponics requires an understanding of both aquaculture and hydroponics, which involves managing two distinct biological systems simultaneously (Ng, 2017). Careful and consistent monitoring of water quality parameters, such as pH, ammonia, nitrates, and dissolved oxygen levels, is crucial for the health and productivity of both fish and plants. Due to the interconnected nature of the system, a failure in one component can potentially impact the entire operation, leading to losses in both fish and plant production. The learning curve for effectively managing an aquaponic system can be steep, requiring time and dedication to acquire the necessary knowledge and skills.

Another limitation of aquaponics relates to the range of suitable plant and fish species. Not all types of crops are well-suited for aquaponic systems; for instance, root vegetables and tubers generally do not thrive in the soilless environment (Goddek *et al.*, 2015; Palm *et al.*, 2018). Furthermore, the fish and plant species selected for an aquaponic system must have compatible environmental requirements, particularly in terms of water temperature and pH levels (Yavuzcan Yildiz *et al.*, 2017). Balancing the nutrient needs of different types of crops within the same system can also be a challenge, as each plant has varying requirements for specific nutrients. The selection of appropriate fish and plant species is therefore crucial for the success of an aquaponic system. It can limit the diversity of produce that can be grown.

Maintaining system balance and optimal water quality is another ongoing challenge in aquaponics (Tyson *et al.*, 2011; Goddek *et al.*, 2015). Achieving a perfect match between the nutrient supply from fish waste and the nutrient demand of the plants can be difficult, potentially leading to nutrient imbalances. Maintaining stable pH levels suitable for the fish, the plants, and the nitrifying bacteria simultaneously can also be a delicate balancing act (Al Tawaha *et al.*, 2025). Aquaponic systems can also be susceptible to algae blooms and outbreaks of plant or fish pathogens, requiring proactive management strategies (Ezenarro *et al.*, 2020). Furthermore, some systems may require precise regulation of water acidity and temperature to ensure optimal growth and health of the organisms involved. Maintaining a stable and healthy environment for all components of the aquaponic system demands careful monitoring, timely interventions, and a thorough understanding of the biological and chemical processes at play.

Finally, the economic viability and profitability of commercial aquaponics operations are still subjects of ongoing research and debate (Cammies *et al.*, 2021; Greenfeld *et al.*, 2019). Retail prices and market demand for both the fish and the produce can significantly influence profitability. Generally, larger aquaponic systems tend to be more economically viable than smaller ones due to economies of scale (Babatunde *et al.*, 2023). Labour costs and energy expenses can significantly impact the overall profitability of an aquaponic operation. It is also crucial to develop effective marketing and distribution strategies to ensure the financial success of a commercial aquaponics venture. As a result, while aquaponics presents a promising avenue for sustainable food production, achieving consistent profitability in commercial settings requires careful planning, efficient management, and a thorough understanding of market dynamics.

Waste Management in Aquaponics

The accumulation of fish sludge within aquaponic systems presents a significant challenge that requires effective management strategies (Zhang *et al.*, 2020; Zhanga *et al.*, 2021). This solid waste, primarily composed of fish faeces and uneaten feed, needs to be removed from the system to prevent the formation of anaerobic zones, which can lead to the production of toxic substances, such as hydrogen sulfide, that are harmful to fish (Choudhury *et al.*, 2023). If allowed to build up, fish sludge can also contribute to nutrient imbalances within the system and cause fluctuations in pH levels, further disrupting the delicate balance of the aquaponic ecosystem. Therefore, the efficient management of fish sludge is crucial for maintaining a healthy and stable environment for both the fish and the plants in an aquaponic system.

However, instead of viewing fish sludge as merely a waste product, it can be considered a valuable resource for sustainable management and utilisation. One effective method for utilising fish sludge is through mineralisation (Zhanga *et al.*, 2021), which involves breaking down organic solid waste into biologically available nutrients for plants. This process can be carried out aerobically by adding air to a separate tank containing the sludge, promoting the growth of beneficial bacteria that decompose the organic matter and release nutrients (Abbo, 2020; Lobanov *et al.*, 2021). Anaerobic mineralisation, where the sludge is broken down in the absence of oxygen, is another option (Boone, 2022; Delaide *et al.*, 2018). The nutrient-rich water resulting from mineralisation can then be reintroduced into the aquaponic system, providing an additional source of essential elements for plant growth and reducing the need for external nutrient supplementation. Another promising approach is anaerobic digestion of fish sludge (Monsees *et al.*, 2017), which not only recovers nutrients but also produces biogas (Netshivhumbe *et al.*, 2024), a renewable energy source that can be used to power various components of the aquaponic system, such as pumps and heaters. The remaining nutrient-rich supernatant after anaerobic digestion can also be utilised as a liquid fertiliser for the plants (Delaide *et al.*, 2019). Furthermore, processed fish sludge can be used as a soil amendment or compost in traditional agriculture, providing a valuable organic fertiliser (Madady *et al.*, 2025). By implementing sustainable waste management practices that utilise fish sludge as a resource for nutrient recovery and energy production, aquaponics can further enhance its environmental benefits and move closer to a truly circular system.

Conclusion

In conclusion, aquaponics stands out as a promising integrated approach to food production that aligns remarkably well with the principles of a circular economy, offering significant potential for addressing the escalating challenges of climate change and resource scarcity. This review has highlighted how aquaponics, through its symbiotic relationship between aquaculture and hydroponics, fosters resource reuse and minimises waste generation, representing a substantial improvement over many conventional agricultural practices. The ability of aquaponic systems to recycle fish waste as essential plant nutrients and to drastically reduce water consumption through recirculation highlights their contribution to a more sustainable and resource-efficient food system.

Furthermore, aquaponics offers compelling solutions to the challenges posed by a changing climate. Its significantly lower water requirements make it a vital tool in regions facing increasing water scarcity. The adaptability of aquaponic systems to non-arable lands, including urban environments, opens up new possibilities for localised food production, reducing reliance on traditional agriculture and shortening food supply chains. While the energy footprint of aquaponics can be a concern, particularly in systems that require heating or artificial lighting, the potential for integration with renewable energy sources offers a significant pathway to reduce its environmental impact.

The socio-economic advantages of aquaponics are also noteworthy. It can foster local food systems, enhance food security by providing a year-round source of nutritious food, and create economic opportunities and green jobs within communities. Moreover, aquaponic farms can serve as valuable educational platforms, promoting awareness about sustainable agriculture and environmental stewardship.

Despite its numerous benefits, aquaponics is not without its challenges. The initial setup costs can be high, and successful operation requires a specific set of technical skills and consistent management. Limitations in the range of suitable plant and fish species, as well as the need for careful maintenance of system balance, are also important considerations. However, ongoing research and innovation are continuously addressing these challenges, leading to advancements in system design, automation, and the development of more sustainable practices, including effective methods for managing and utilising fish sludge.

Looking towards the future, aquaponics holds immense potential to play a crucial role in creating more sustainable and resilient food systems globally. Continued research and innovation are essential for further optimising energy efficiency, developing system designs tailored to diverse climates and scales, and enhancing the economic viability of commercial operations. Policy support and educational initiatives will be vital in promoting the adoption of aquaponics as a key component of sustainable agriculture in the face of growing global challenges. By embracing integrated approaches like aquaponics, we can move towards a future where food production is both environmentally responsible and capable of meeting the nutritional needs of a growing world population.

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