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Review

Aquaponics for Circular Local Food Systems: A Review of Interconnections, Practices, and Transformation Pathways

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Abstract

As the global population continues to grow, the increasing demand for food is placing considerable pressure on vital resources such as water, land, and nutrients, emphasizing the urgent need for more efficient and resilient food production systems. In recent times, aquaponic systems have been promoted as an innovative solution for improving sustainability and circularity in local food production. Aquaponics has emerged as a promising green technology for addressing challenges related to food security and climate change. By integrating aquaculture and hydroponics within a recirculating system, it enables efficient resource use while reducing waste through circular nutrient and water flows. This study investigates the potential of aquaponics as a circular production system and its role in promoting sustainable and resilient local food systems. We examine aquaponic systems and its relevance across four different contexts—Finland, Iceland, Nigeria, and Namibia, representing diverse environmental and socio-economic conditions. The economic considerations and environmental sustainability of aquaponic systems are also considered. The findings highlight that the availability of foods in urban centres will improve with good management of aquaponic systems. Our analysis confirmed that aquaponics can contribute to resource efficiency, local food production, and sustainability, while also addressing region-specific challenges and opportunities. However, several challenges, barriers, and research gaps including policies must still be addressed for aquaponic systems to effectively contribute to alleviating food insecurity within local food systems.

Keywords: fish; food security; plants; socio-economic; sustainability

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1. Introduction

Food production systems are facing increasing pressure due to population growth, environmental degradation, and the depletion of natural resources. The imperative to secure food for over 8 billion people amid shrinking resources and climate change underscores the urgency for discovering new, efficient, and sustainable methods of food production [1]. Depending on the production practices and management of waste, global agricultural and aquaculture processes can contribute to nutrient losses and water pollution [2]. These

challenges highlight the urgent need for production approaches that will improve efficiency while reducing environmental impact [3,4].

In response, circular economy principles have gained attention as a framework for transforming food systems. Rather than following a linear model of resource use and waste generation, circular systems aim to reuse materials, minimize losses, and maintain resources within production cycles [5]. These principles when applied to food production can contribute to more sustainable and resilient systems [6]. Aquaponic systems integrate aquaculture and plant cultivation within a recirculating system [7,8]. In this system, nutrients generated from fish production are utilized for plant growth, while plants help maintain water quality for fish. This interaction creates a closed-loop process that reduces waste and improves the use of water and nutrients. As a result, aquaponics offers a practical example of how circular principles can be applied in food production [9].

Beyond its environmental advantages, aquaponics also has potential economic and social implications. Aquaponic systems can support local food production, diversify income opportunities, and contribute to improved food availability [10,11]. However, its performance and feasibility depend on several factors, including climate conditions, technological requirements, energy use, and market development. These factors vary significantly across regions, influencing the overall success of aquaponic systems [12,13].

In this review, we examine aquaponics as a circular production system based on existing literature, compare its relevance across different environmental and socio-economic conditions, analyzed factors influencing its adoption and performance, and discuss the overall contribution of aquaponics to sustainable and local food systems. By combining these processes, the aquaponic system simultaneously responds to multiple sustainability challenges, particularly in water-scarce environments, urban settings, and resource constrained communities.

The review synthesizes literature on aquaponics, circularity, and local food systems; highlights the available evidence from four selected countries—Finland, Iceland, Nigeria and Namibia. Because country-level evidence is limited and not comparable in all areas, the four countries would only serve as a purposive contrastive-case approach rather than as representative national outcomes. This approach enables the review to examine how climate, water and energy availability, infrastructure, market development, and food-security needs can shape aquaponics implementation in different contexts.

The next section (Section 2) describes our methodology, next we gather contexts and scenarios on sustainability from two Nordic and two African countries (Finland, Iceland, Nigeria and Namibia) in Section 3. Section 4 integrates aquaponics into circularity, Section 5 addresses pathways on practices and transformations, Section 6 is on the obstacles to aquaponics' implementation as a viable approach to addressing food security while Section 7 highlights the need for further research and finally Section 8 concludes.

2. Methodological Approach

The publications examined were from 2000–2026. Keywords were: aquaponic systems, circular economy, local food systems, sustainability with special emphasis on Nigeria, Namibia, Finland and Iceland. Databases searched: Scopus; Web of Science; PubMed/MEDLINE; Google Scholar; CAB Abstracts; African Journals Online (AJOL).

Inclusion criteria: Peer-reviewed articles, book chapters, and institutional or government reports addressing aquaponics, postharvest handling; value addition or processing; socio-economic roles; policy, extension, or food security.

Exclusion criteria: Sources lacking empirical or analytical evidence relevant to the review objectives; pre-2000 publications; non-English sources without translation or abstract.

Limitations: Restricting searches to English may have excluded relevant studies published in other languages.

As a structured review rather than a systematic review, the study does not claim exhaustive coverage.

3. Environmental and Economic Sustainability Dimensions in Aquaponics

Aquaponic systems are designed to use water more efficiently than conventional agriculture by continuously recirculating it within the system. This significantly reduces water losses and makes aquaponics particularly suitable for regions facing water scarcity [14].

Aquaponic systems use water efficiently by continuously recirculating it between fish and plant production, thereby minimizing losses through runoff and evaporation [15]. Compared with conventional soil-based agriculture, aquaponics can reduce water consumption by 80–95%, depending on system design and environmental conditions [16]. Although hydroponics is also water-efficient, aquaponics offers greater resource efficiency by simultaneously producing fish and crops within the same recirculating water system, reducing freshwater demand and nutrient-rich wastewater discharge [17]. These characteristics make aquaponics a practical circular production system for enhancing water conservation and sustainable food production, particularly in water-scarce regions.

Aquaponics provide the opportunity to reuse nutrients and valorize waste. The waste produced by fish is converted into important nutrients that act as natural fertilizer for plants, thus reducing the need for external inputs. Uneaten feed and fish excreta provide nitrogen and phosphorus, while nitrifying bacteria convert ammonia/ammonium into plant-available nitrate. This recycling reduces the need for synthetic nitrogen and phosphorus fertilizers and replaces part of the mineral nutrient solution normally required in hydroponics. However, it should be noted that fish-derived water is frequently deficient in potassium, calcium, and iron; targeted supplementation may therefore still be needed. Aquaponics reduce, rather than eliminate the entire external nutrient inputs [18,19].

Despite the advantages offered by aquaponics, energy use remains a major challenge in aquaponic systems. To minimize operational costs and environmental impacts, energy mitigation strategies, particularly the integration of renewable energy sources, should be considered during system design [20]. Aquaponic systems require the continuous operation of pumps, aeration systems, and environmental controls, while controlled environments require additional energy for heating and lighting. As a result, energy consumption can increase both operational costs and carbon emissions, especially when non-renewable energy sources are used [21,22]. In regions such as Nigeria and Namibia with high solar irradiance, solar photovoltaic systems can provide sustainable electricity for pumping, aeration, sensors, and water treatment [23]. Similarly, in cold climates, such as Finland and Iceland, geothermal energy, heat pumps, recovered industrial heat, improved greenhouse insulation, and energy-efficient LED lighting can substantially reduce heating and lighting demands of aquaponics, with geothermal integration being particularly suitable for Icelandic conditions [24].

While aquaponics offers environmental and social advantages, achieving financial sustainability can be challenging. High initial investment costs, ongoing operational expenses, and energy requirements can limit profitability, particularly for small-scale systems [21]. The economic performance of aquaponic systems is influenced by multiple factors, including system size, technology level, location, and access to markets. As a result, profitability varies widely across different contexts [25].

In comparison, conventional aquaculture may provide higher short-term financial returns. However, its impact on the environment can be great, which highlights the fact

that environmentally sustainable systems do not always deliver immediate economic benefits. Therefore, improving economic viability requires optimized system design, better market integration, and supportive policy frameworks. Relative to stand-alone fish farming, adding plant production introduces crop infrastructure and management requirements; comparisons with separate fish and crop production must account for both shared equipment and outputs [26]. These additional capital and operating costs can reduce short-term returns unless income from vegetables and other services compensate for them. The Sustainable Aquaponics for Nutritional and Food Security (SANFU) case study in West Africa illustrates this sensitivity: a small system based mainly on imported components had a discounted benefit-cost ratio of 0.08 over 20 years, whereas a simulated redesign using locally sourced components and a higher fish stocking density increased the ratio to 1.12 [27]. Environmental benefits do not always guarantee financial viability. Published models have estimated payback periods of approximately 7.5 years under premium-price assumptions, while one demonstration project required about 12 years, and only 31% of commercial operators surveyed reported profitability in the preceding year [28]. These findings show that aquaponics is not automatically more profitable than conventional aquaculture. Its competitiveness depends on local sourcing, energy efficiency, sufficient scale, reliable vegetable yields, premium or differentiated markets, and supportive policy frameworks [28]. European case studies also show wide variation.

Considering scale dependencies and business models for Finland and Iceland, countries that represent cold-climate environments where aquaponic systems face both opportunities and constraints. These countries benefit from advanced agricultural technologies, strong environmental policies, and high consumer awareness of sustainable food production [29]. Business models are also crucial in determining the success of aquaponics. A strong value proposition, clear market positioning, and multiple revenue streams can improve viability. Successful aquaponic businesses often combine different sources of income, such as selling fish and vegetables, offering training or consultancy services, and providing environmental or educational services like urban greening. This diversified approach helps to reduce financial risks, increase resilience, and enhances both economic and social benefits [30].

Scale and location determine which business model is feasible. In cold-climate markets such as Finland and Iceland, year-round production can benefit from advanced greenhouse technology and consumer demand for local sustainable food, but heating and lighting costs make energy integration, production scale, and premium pricing especially important [24]. Evidence from operating projects in other European countries supports the use of diversified and context-specific models. For example, Peckas Tomater in Sweden developed a commercial model based on year-round production of trout fish and tomatoes, with short distribution channels, premium positioning, and renewable electricity; the case also identified energy costs and regulatory uncertainty as major constraints [31]. Similarly, Bioaqua Farm in the United Kingdom improved their margins by combining trout fish and crop sales with value-added products such as smoked trout and basil pesto [32].

On the other hand, in a resource-constrained context, the Sustainable Aquaponics for Nutritional and Food Security (SANFU) project demonstrated that combining locally sourced components with a higher fish stocking density can shift a system from economically unviable to potentially feasible [27].

These cases indicate that successful aquaponic enterprises rarely depend on the sale of unprocessed fish and vegetables only. Other activities such as training, consultancy, workshops, agritourism, educational services, direct marketing, and value-addition to food products can diversify income and reduce exposure to fluctuations in individual product markets [31,32].

Even though aquaponics has been reported to be an efficient and sustainable food production technique that provides maximum nutrient and wastewater reuse, there are several technological and scientific challenges such as disparity in pH, nutrient requirements and temperature between interdependent subsystems [33,34]. When economic sustainability is considered, the management of nutrients in aquaponics is a widely adopted strategy to optimize the nutrient ratios for improved plant growth [6,14]. The rapid commercialization of aquaponics as a farming practice in recent years witnessed an evolution in research publications focused on optimization of design and operation (component ratio, hydraulic loading rate, etc.) to technical improvement in design to increase production efficiency and output [35,36].

Aquaponics is designed to contribute to resource efficiency, leading to circularity and sustainability as shown in Figure 1 below.

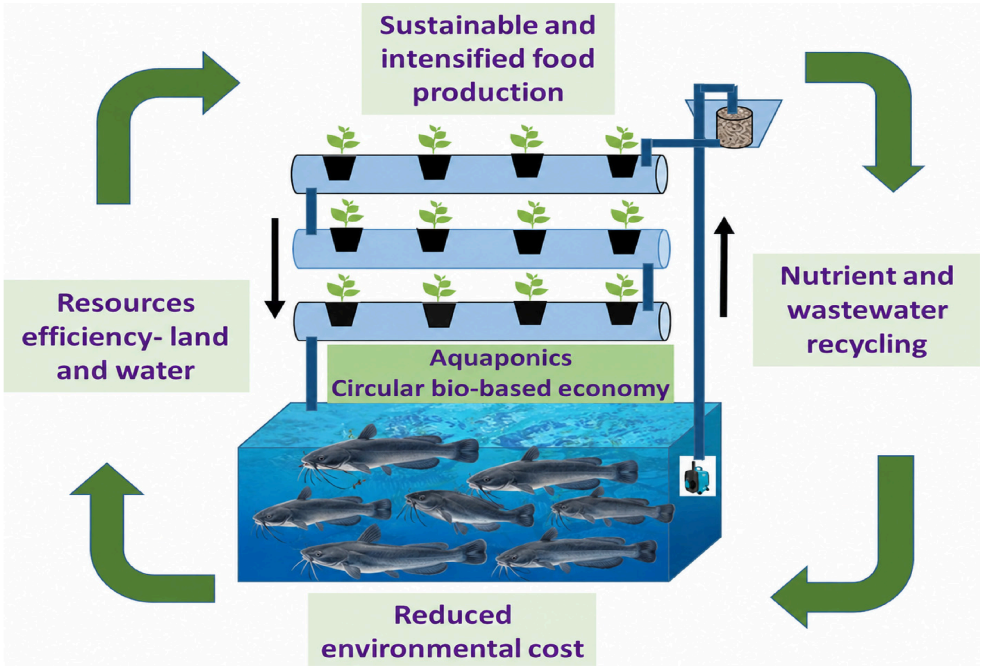

Figure 1. Aquaponics and its contribution to circularity and sustainability (Adapted from [37] Verma et al. 2023).

3.1. Sustainable Aquaponics in Finland and Iceland

Finland and Iceland provide contrasting cold-climate settings for aquaponics, but the available sources do not establish that both countries offer a supportive commercial environment. In Finland, Lipsewers discusses aquaponics development and possible links between existing recirculating fish farms and greenhouse production; these are development opportunities rather than evidence of established commercial feasibility [38].

In Iceland, the Aquaponics NOMA project established an experimental production unit and investigated fish–crop combinations, temperature, nutrient balances, and waste treatment [24]. The project also developed commercial-scale models, which should be distinguished from being evidence of a profitable commercial operation. These country-specific examples demonstrate research and development activity, while the technical guidance highlights the need to assess operating conditions, markets, and regulatory requirements [39].

One of the main challenges in Nordic countries is the cold climate, which requires significant energy for heating and limits the growing season. Goddek & Körner showed that this increased seasonal variation makes an aquaponics system more difficult to manage and less efficient as a result of the main water transfer in an on-demand coupled aquaponics

system being driven by transpiration, which in turn is mainly related to global radiation [40]. This increases operational costs and can affect the economic viability of aquaponic systems. Despite these challenges, there are several advantages when backed with the right policies to ensure high levels of technical expertise, strict environmental regulations, and strong consumer interest in sustainable and locally produced food [41].

In Finland, aquaponics benefits from advanced agricultural infrastructure and increasing interest in local food production. However, long winters and low sunlight levels make year-round production difficult. Integrating aquaponics with greenhouse systems and renewable energy sources could help overcome these challenges. There is no specific legislation for foodstuffs produced using aquaponics and a subsidy structure for Finnish fish farmers does not exist. The fish products on Finnish markets are nowadays dominated by relatively cheap Atlantic salmon (*Salmo salar*) originating from Norway and this species is regarded as everyday food for Finns [37]. There is a strategy on aquaculture aimed at sustainable growth, competitiveness and environmental balance, this is fostered by improving regulations that will encourage innovation, expand production and reduce ecological inputs [42].

Iceland plan to strengthen the regulatory framework, reduce negative environmental impacts and establish a more robust foundation for sustainable value creation through a bill, moving a step closer to new aquaculture law [43]. Iceland offers a unique advantage through the availability of geothermal energy, which can provide a more sustainable and cost-effective source of heat, while in Finland, integration with greenhouse systems and renewable energy technologies may improve system performance [8].

In the Nordic countries, to qualify as "organic food" they must be grown in the soil, most aquaponics production systems are based on a soilless hydroponic technology, the plants produced under such a system cannot be certified as organic [44].

Overall, the Nordic context highlights the importance of considering environmental, economic, and social factors together. Such a balanced approach is necessary to ensure that aquaponic systems are both sustainable and viable in these regions.

3.2. Sustainable Aquaponics in Nigeria and Namibia

In many African countries, aquaculture plays a critical role in food supply and livelihoods. However, conventional systems often face challenges related to environmental management and food safety [21].

Aquaponics and recirculating aquaculture systems (RAS) offer more sustainable alternatives by combining fish and plant production in a closed system. These systems improve water efficiency, reduce waste discharge, and support safer food production. They also provide additional social benefits, such as job creation and improved nutrition.

Despite these advantages, economic constraints remain a major barrier. High energy costs and limited production scale can reduce profitability, particularly in resource-constrained settings [45]. In Nigeria, the Lagos SANFU study evaluated a small-scale system and simulated improvements using locally sourced components and higher fish stocking density [27]. Aquaponics systems may be economically feasible if fabricated with local materials in Nigeria. The expansion of aquaponics in Nigeria requires several enabling conditions, such as affordable energy, financial assistance, clear regulatory frameworks, and adequate technical capacity [46]. Effective policy support is essential to overcome economic constraints and facilitate broader implementation [46]. Recent research on energy–water–profit trade-offs and scale economies in urban aquaponics with comparative evidence from Lagos and Abuja in Nigeria provides strong empirical evidence that urban aquaponics systems exhibit pronounced scale economies under electricity-constrained conditions. Across both Lagos and Abuja, semi-commercial systems achieved higher profit margins,

shorter payback periods, and substantially greater resource productivity compared with household-scale systems [47]. Available studies provide different types of evidence on aquaponics in South Africa and Nigeria. A South African online survey conducted in 2016 collected 44 responses and characterized aquaponics as an emerging practice dominated by small systems [48]. In Nigeria, the Lagos SANFU study evaluated a small-scale system and simulated improvements using locally sourced components and higher fish stocking density [26].

Namibia's arid climate and water scarcity make conventional agriculture difficult. Aquaponics is a suitable alternative due to its efficient water use and controlled conditions. Renewable energy, particularly solar power, can further support its use in remote areas [49].

A review on aquaponics conducted to assess the viability of setting up aquaponics systems to enhance food security, sustainability, income generation, and as an educational resource in Namibia and other African countries, showed that 430,000 Namibians are reported to be food insecure as almost 70% of food is imported from South Africa [12,50]. In Namibia, aquaponics will be a sustainable agricultural system during droughts and government policy should improve efforts to reverse this trend with support to the aquaponic sector.

Overall, successful implementation in Africa requires not only technical solutions but also supportive policies, community engagement, and adaptation to local conditions. For instance, in Nigeria, policy that highlights access to capital financing, renewable or hybrid energy integration and the inclusion of scale-sensitive support mechanisms for urban agriculture will be relevant [47]. The authors also emphasized that greater resilience and economic stability will be achieved by supporting clustered or semi-commercial aquaponic systems that will be better equipped to absorb energy volatility. Ultimately, aquaponic farms will need to adhere to both the regulations pertaining to aquaculture and horticulture.

4. Integrating Aquaponics into Circular Local Food Systems

The integration of aquaponics into circular local food systems builds on multi-loop and multi-trophic systems to deliver best practices, such as coupling aquaponics with anaerobic digestion [51]. Small-scale integrated circular aquaponic systems, which optimize circularity by repurposing component outputs as system inputs, offer substantial potential to enhance resource efficiency and drive rural economic development [7]. Aquaponic systems are known to have developed from simple designs into more advanced configurations that improve sustainability and efficiency [14]. These modern systems include multi-loop and multi-trophic approaches, which allow better use of resources, greater system stability, and increased diversity in production [10,52]. In order to achieve true circularity, ensure that the organisms are in optimal health, guarantee performance and offset the nutrient loss from harvest within an aquaponic system, internally available nutrient streams must be combined with complementary nutrients from system-external sources [41]. Changes in practices have implications for investment needs, operating costs and environmental improvement potential, and one area experiencing renewed interest is the practice of integrated multi-trophic aquaculture (IMTA) [53]. IMTA is a specialised form of polyculture, that is, co-production of species, in which fed aquaculture species are combined with species at lower trophic levels with extractive functions, with the intention of improving the utilisation of nutrients and waste [54].

Ultimately, regardless of the technological maturity of the system being assessed, it is pivotal for a prudent cost–benefit analysis to obtain reliable and realistic price and cost estimates pertaining to, for example, infrastructure and labour requirements [55].

In multi-loop systems, fish and plant production are separated into different but connected units [40]. Each unit operates under its own optimal conditions, while nutrients from fish production are transferred to plants. This separation allows better control of water

quality and improves overall system performance. This approach offers several advantages, it allows independent management of key factors such as temperature, pH, and nutrient levels, which are often different for fish and plants. It also enables the addition of nutrients for plants without affecting fish health. In addition, production can be scaled more flexibly, depending on market demand. However, these systems are more complex and require higher levels of technical knowledge, monitoring, and management [40].

Food production, water and energy consumption are closely connected within an aquaponic system, they constantly interact—a change in one of these elements will have a cascading effect on others [54]. For example, increasing water recirculation improves water efficiency but may require more energy for pumping and treatment [26]. As a result of these interactions, aquaponic systems need to be designed and managed in an integrated way [56]. A balanced approach is necessary to optimize overall performance rather than focusing on a single resource. In addition, aquaponics systems offer opportunities to create synergies, they can make efficient use of available resources, thereby improving overall sustainability [48,52]. For instance, combining aquaponics with renewable energy sources such as solar power can reduce energy costs and environmental impacts.

The side streams from RAS (effluent water and exhaust air) could be used as valuable resources for cultivating microalgae as demonstrated in a recent work from the University of Jyväskylä, Finland [57].

Aquaponics has emerged as a circular agricultural mode with the potential to transform cities into self-sufficient "edible cities" with reduced environmental footprints featuring multiple food–water–energy nexus [48,58]. When food, water, and energy are carefully considered in situ, aquaponic can become more efficient, resilient, and suitable for long-term sustainable food production [59].

Even though prior research suggests that emphasis on aquaponic fish's environmental benefits may improve consumer perceptions, marketing strategies for aquaponic produce remain underexplored [54]. Moreover, it is important that the consumption of products from aquaponic systems is well integrated in the diet of consumers.

Aquaponics are well-suited to small-scale production and is expected to serve local markets initially, aligning with consumer preferences for small family farms that support rural economies and the environment [60,61]. When fish and vegetables are efficiently produced from aquaponics commercially, it has great potential to improve production and consumption habits, even though dietary habits and sustainability still have vital roles to play [40,62]. Consumers generally prefer to pay for locally sourced foods over non-local options as evident from a study [63].

5. Practices and Transformation Pathways

Aquaponics provides eco-friendly, clean, and safe benefits that consumers may not fully recognize. This is mainly because it can increase the production of fish without further depleting wild stocks, deliver locally sourced food of high quality in water-scarce regions, and support food production in urban areas [6]. When compared to hydroponics, aquaponics results in a lower environmental impact and offer advantages such as reduced land and water use, improved operational efficiency, and year-round production in controlled environments [15,64]. Essentially, aquaponics systems in local food systems embody the principles of the circular economy by transforming the output (waste) of one process into the input (nutrient) of another. Recent research confirms that integrated aquaponic systems significantly outperform conventional agriculture in resource conservation across three primary dimensions—water, nutrients, and land [65].

5.1. Water Conservation and Nutrient Recovery

Water is the primary medium of circularity in an aquaponics system. Unlike the popular traditional soil-based farming, where water is lost to evaporation and deep percolation, aquaponics utilizes a closed-loop Recirculating Aquaculture System (RAS). The aquaponics system can achieve this through continuous recirculation and the reuse of treated fish wastewater for crop hydration. In arid regions, AI-integrated models have shown the ability to maintain optimal yields while using significantly less water than standard hydroponic controls [66].

Finland and Iceland benefit from advanced recirculation technologies, although heating requirements may increase operational costs [67]. In Nigeria, aquaponics can reduce pressure on unreliable water supplies [68], while in Namibia its high-water efficiency is especially important because of severe water scarcity [69].

Closed-loop recirculation limits replacement water mainly to evapotranspiration, cleaning, harvesting, and minor system losses. In a one-year pilot-scale study conducted by Alnuaimi and co-workers on a seawater-cooled controlled-environment facility in arid Saudi Arabia, crop production used an average of 4.6 L m^{-2} day^{-1}, or 19 L kg^{-1} of harvested crop, during the peak winter–spring season and saved approximately 90% of freshwater compared with traditional agriculture in the region [66]. This result is context-specific, as actual water savings vary with climate, crop type, system configuration, season, and the method used to calculate water use.

In Finland and Iceland, nutrient recovery in aquaponics can support circular bioeconomy and waste-reduction policies [70]. In Nigeria, it can help to reduce dependence on costly synthetic fertilizers while in Namibia, nutrient recycling can improve food production where soils are poor and agricultural inputs are limited [71,72].

Conventional agriculture relies heavily on synthetic fertilizers, which are energy-intensive to produce and often lead to environmental runoff. Aquaponics close this loop by harvesting nutrients from fish excreta (majorly ammonium), which is aerated to produce nitrate. Some optimized systems have demonstrated nitrogen recovery efficiencies exceeding 95%, particularly when integrated with microalgal polishing or specialized mineralization units [4]. A recent model of eco-industrial food parks suggests that through internal waste mineralization (e.g., converting fish sludge into plant-available nutrients), systems can achieve near-total nitrogen and phosphorus self-sufficiency, reducing external fertilizer dependency even in the most basic setups [73,74].

Closed loop systems like RAS eliminate the risk of disease transmission from farmed populations to wild populations, ensuring the long-term health of aquatic ecosystems. RAS achieved higher food conversion efficiencies and growth rates compared to traditional systems, making them more productive and cost-effective [75]. While RAS can be profitable, the overall economic viability of these systems will depend on various factors such as the type of fish being farmed, local market conditions, and the efficiency of the system.

In Nigeria, RAS is a new technological innovation that can improve water quality, minimize disease risk, and enable higher stocking densities through closed-loop water recycling [76]. However, this technology is currently being adopted by an estimated 10–15% of farms, mainly due to the high initial investment and the technical expertise that is required for proper operation [77]. This makes its adoption a context-dependent option rather than a universal solution in the Nigerian situation [78,79]. Where RAS has been implemented successfully, significant improvements have been achieved in fish growth, production efficiency, and environmental impact, which confirms its suitability for scaling high-value aquaculture operations [80].

5.2. Land Use and Spatial Optimization

As urban populations grow, the ability to produce food on limited land becomes critical. The aquaponics system can address this through verticality and co-location. The vertical integration of the aquaponic systems (aquaculture and hydroponics) has shown a 7% increase in productive land-use efficiency for leafy greens when compared to horizontal hydroponics systems [81]. In urban environments, aquaponics facilitates "zero net new land take" by utilizing rooftops and existing building footprints. A case study in Berlin estimated that city-scale aquaponic integration could save millions of cubic meters of water while drastically reducing the land footprint associated with the urban food supply chain [27].

The aquaponics system serves as a transformative technology within circular local food systems by simultaneously addressing three pillars of food security: availability, access, and stability. By integrating fish and vegetable production into a single resource-efficient loop, it offers a resilient alternative to conventional linear agriculture. In Finland and Iceland, aquaponics can support all year-round local production and reduce dependence on imported fresh food. In Nigeria, it can increase access to fish and vegetables in densely populated urban areas. In Namibia, controlled production can improve food availability where drought and water scarcity constrain conventional agriculture.

Aquaponics enhance the physical availability of food by maximizing output per unit area, particularly in space-constrained urban and peri-urban environments. Recent city-scale modeling indicates that rooftop and urban aquaponic systems can supply significant portions of local demand for fresh protein and vegetables while saving millions of cubic meters of water [81]. Its adoption in regions like Egypt and South Africa has shown that the aquaponics system can stabilize and increase the year-round supply of fresh produce in areas where traditional soil-based agriculture faces climatic constraints [82]. The small-scale community projects have demonstrated the ability to produce harvests of leafy greens and fish within as little as one month, providing a continuous stream of fresh food to local populations [8].

The decentralized nature of aquaponics system improves both the physical proximity of food production to consumers and its economic accessibility. By relocating production to urban centers or building-integrated systems, aquaponics reduces transport distances and logistical barriers, making fresh produce more physically accessible to urban residents [27]. Although the initial capital costs can be high, systems built using locally sourced materials and low-tech designs significantly improve the cost-benefit ratio, making them more accessible for low-income households and community-led initiatives [78].

Concurrently, advancements in aquaculture nutrition are accelerating through the development of specialized on-farm pellets and the integration of agro-industrial by-products into feed formulations [83]. A prominent innovation in this domain is the deployment of microbiome-enhanced feeds. These formulations incorporate beneficial microflora that optimizes nutrient assimilation and digestive efficiency, thereby augmenting fish health and somatotropic performance [84]. Empirical data indicate that these microbial additives enhance survival and growth rates by 35–54% while simultaneously mitigating reliance on antibiotics. Consequently, this dietary intervention represents a critical strategy in combating antimicrobial resistance (AMR), which remains a persistent threat to the sustainability of global aquaculture [85,86].

A simple household-scale unit will allow families, especially in rural settings, to produce high-quality protein and vitamins for direct consumption, bypassing market fluctuations and ensuring consistent access to nutrition [87].

Aquaponics enhance stability through their inherent circularity, by recycling nutrients and water. The aquaponics system minimizes reliance on external fertilizers and large-scale irrigation, making the food system less vulnerable to supply chain disruptions or resource

scarcity [7]. Stability as one of the pillars of food security, in this context refers to the reliable presence of food over time, even during environmental or economic shocks [88]. A controlled environment aquaponics prevent production from extreme weather events (e.g., droughts or floods), ensuring a stable harvest regardless of external environmental stressors [89].

To fully maximise the impacts of aquaponics as a solution towards food security in these countries, we briefly highlight some challenges, barriers, and research gaps. Following this, we emphasize the need for further research.

6. Obstacles to Aquaponics as a Viable Approach to Addressing Food Security

Although aquaponics has significant potential, several barriers limit its widespread adoption. One major challenge is the technical complexity of these systems, which require knowledge in multiple areas such as aquaculture, plant production, and system management. In addition, maintaining optimal water quality, nutrient balance, fish health, and plant productivity requires continuous monitoring and technical expertise, increasing operational complexity compared with conventional farming systems [7,9].

Henceforth, capacity assessment to ensure the viability of aquaponics should include practical training, access to water testing and technical advice, including operator experience, availability of local repair and spare-parts services.

Economic challenges also play a key role in the adoption of aquaponics. High investment costs and uncertain market conditions make it difficult for many systems to achieve stable profitability. Smaller systems often struggle to reach efficient production levels since they are unable to benefit from economies of scale, resulting in higher production costs, longer payback periods, and lower financial returns than larger commercial operations. Limited access to finance, inadequate market infrastructure, and uncertain consumer demand further constrain commercial expansion, particularly in developing countries [13,90].

Another key challenge is its economic viability. While the economic evaluation remains contradictory—some studies show marginal profitability with vegetable gains but fish losses, while others demonstrate comparable performance to hydroponics [89]. However, success will depend heavily on location-specific factors including species combination, market prices, and climatic conditions. High initial investment costs, operational expenses, and uncertainty in market demand can limit adoption. Small-scale systems often struggle to achieve cost efficiency. To address this, supportive policies, innovative business models, and improved market access are needed [3,19].

Energy demand represents another important limitation; the continuous operation of system components often results in increased costs and environmental impacts. It is important that the energy efficiency of the system is improved and the integration of renewable energy sources will be essential steps toward sustainability [3,19].

Regulatory and policy barriers further constrain its development as a viable option. In many regions, there are no clear regulations specific to aquaponics. This can create uncertainty for producers and discourage investment. By developing clear policies, standards, and certification systems will help to support growth in the aquaponics sector.

Market development and consumer acceptance are also critical issues. In many areas, awareness of aquaponic products is still limited. Consumers may be unfamiliar with how these systems work or may be hesitant to pay higher prices. Increasing public awareness, improving marketing strategies, and establishing quality standards can help build trust and demand. Consumer acceptance is also shaped by cultural perceptions, dietary preferences, trust in food production systems, and awareness of the environmental and nutritional

benefits of aquaponics. These socio-cultural factors vary across regions and should be considered when designing market development and public engagement strategies [41,90].

There are also important research gaps that need to be addressed. More studies are needed across different geographical regions, especially in under-researched areas such as Finland and Namibia. Long-term data on system performance, sustainability, and economic outcomes are still limited. In addition, more attention is needed on social aspects, including community participation, gender roles, and cultural acceptance.

Community participation is essential for improving local ownership, technology adoption, and long-term sustainability, particularly in low-resource settings. Likewise, understanding gender roles is important because women and youth often contribute significantly to aquaponic production, processing, marketing, and household nutrition, yet they frequently face barriers to accessing land, finance, training, and technology [12].

Social inclusion should also be treated as a design criterion rather than solely as a research gap. In Nigeria and Namibia, women and youth can play important roles in system management, processing, marketing, and household nutrition, but their participation may be constrained by limited access to finance, land, technology, and training. Therefore, several authors recommend participatory co-design and gender-disaggregated evaluation for future pilot and commercial projects [28,33,90]. Furthermore, the authors suggest that future aquaponics development should move beyond technical optimization and adopt a context-specific implementation model. Priority should be given to low-cost modular systems, renewable energy integration, producer training, clear standards, and market development to unlock the full potential of aquaponics.

7. Need for Further Research

Consumer acceptance of aquaponics was highlighted as an issue. By exploring how perceptions affect the role of aquaponics in local food systems will give a better understanding of consumer acceptance, these can influence the scalability of aquaponics and their overall impact on the local food system [89]. Enthusiasts of aquaponics are often driven by the idea of aquaponics being sustainable food production, minimizing waste, and making the most of water, energy, and nutrient resources [59]. However, it has been observed that there is limited information about general consumers' acceptance of aquaponics products, this warrants further investigation.

Further research is also required to improve system design and efficiency. This includes optimizing nutrient cycling, developing low-cost technologies, selecting suitable species combinations, and understanding social and institutional factors. In advanced systems, identified additional challenges were noted to include the management of water quality, preventing disease, and balancing production between fish and plants [7,89].

Robust aeration systems are essential for maintaining the high dissolved oxygen (DO) levels required to support both fish health and microbial activity. The DO level is an important criterion that should be well monitored. A well-balanced microbial community drives rapid nitrification and efficient nutrient cycling, which are vital for regulating nutrient and organic matter conversion to maintain water quality [91].

Aeration capabilities have advanced significantly with technologies like micro-nanobubble (MNB) systems, which substantially increase DO concentration. Additionally, the integration of automation and data-driven technologies including the Internet of Things (IoT), Artificial Intelligence (AI), and robotics will allow for the precise monitoring, control, and optimization of water quality and other critical environmental parameters [65].

The welfare of fish is worth considering, there is compelling evidence indicating that fish may experience pain at a cognitive level is that exposure to noxious stimuli has been shown to induce cognitive impairments, such as attention deficits, suggesting a conscious

processing of pain [92,93]. While water quality parameters and stocking densities remain primary determinants of welfare within recirculating aquaculture systems (RAS), other environmental stressors inherent to intensive facilities substantially impact fish well-being. Specifically, chronic anthropogenic noise and mechanical vibrations that are generated by pumping mechanisms, aeration units, blowers, and filtration systems alongside artificial lighting regimes varying in intensity, spectrum, and photoperiod. They can alter behavioral phenotypes, stress physiology, circadian regulation, somatotropic growth, and overall fish health [94,95].

Overall, addressing these challenges requires coordinated efforts in research, policy development, technological innovation, and capacity building. Such efforts are essential to unlock the full potential of aquaponics in improving food security and sustainability.

8. Concluding Remarks

Aquaponics links fish and plant production through water recirculation and nutrient reuse. Its contribution to circular local food systems depends on system design, energy and material inputs, operating costs, market conditions, and technical capacity.

By recirculating water, valorizing waste as nutrients, and maximizing vertical space, it provides a viable path for sustainable, local food systems that are resilient to resource scarcity. However, these conditions must be evaluated against locally relevant alternatives before ascertaining that aquaponics offers environmental or economic advantages.

Aquaponics can significantly improve food security by providing a stable, accessible, and continuously available source of high-quality foods that are produced locally. Its ability to thrive in non-traditional agricultural settings makes it a cornerstone for resilient and circular local food systems.

In this review of four-country comparison, we identified contrasting implementation pathways and gaps. We inform context-specific assessment, but do not establish comparable national adoption or commercial viability. Further operating and market evidence beyond the scope of this review will be needed to assess the overall effects of aquaponics on food availability, affordability, and stability.

A harmonized policy in Europe and Africa on regulatory and certification systems will help to support the benefits of aquaponics.

The importance of aquaponics' eco-friendly attributes should be highlighted, particularly for highly environmentally conscious consumers.

Ultimately, as public awareness and demand for sustainable food continue to grow, additional longitudinal studies could provide valuable insights into how consumer perceptions of aquaponic products will evolve over time.

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