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Exploring the Potential of Aquaponics Systems in Advancing Food Security in Kenya: A Scoping Review

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Abstract The pressing issue of global food insecurity demands immediate attention, particularly in developing nations like Kenya. Traditional agricultural methods in these regions often involve high resource consumption, limited nutrient recycling, and substantial negative environmental impacts. In light of the escalating demand for food production and the imperative for sustainable food systems, it is crucial to explore innovative and efficient technologies capable of concurrently addressing nutrient management, water utilization, and food production challenges. The prevalent reliance on chemical fertilizers within Kenya's food production sector adversely affects both soil and environmental health, leading to a gradual decline in agricultural productivity. Additionally, many regions in Kenya grapple with water scarcity, posing a significant obstacle to food production. The heavy dependence on rain-fed agriculture further exposes food production to fluctuations in climatic conditions. Monoculture-based food systems demonstrate inefficiencies in land, water, and nutrient usage. Despite its current limited adaptability, aquaponics emerges as a promising solution to confront these challenges by optimizing water, nutrient, and land utilization in food production. Case studies in Kenya have demonstrated the potential of aquaponics in enhancing food production. This scoping review provide information on the status of aquaponics adoption in Kenya, challenges and barriers to adoption and the possible solutions to enhance adoption of aquaponics in the Kenyan food production sector.

Keywords: *Food security, aquaponics, nutrient-efficiency, water-efficiency, aquaculture*

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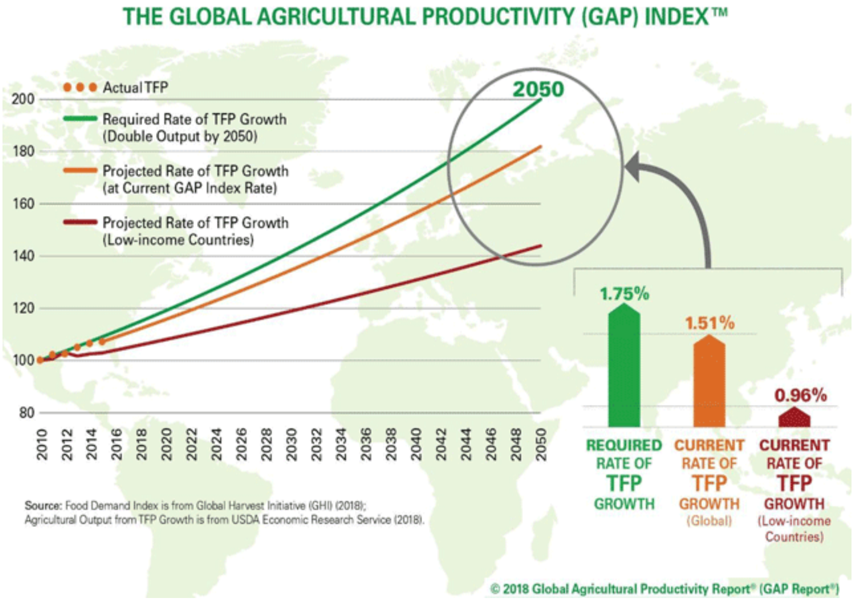
1. Introduction

Many countries in Africa, including Kenya, are facing widespread and severe localized food insecurity due to a combination of extreme weather events and inadequate economic recovery, particularly after the COVID-19 pandemic [1]. FAO emphasizes the need for prompt climate-smart actions to mitigate the effects of food and nutrition insecurity, especially in Africa. In the face of contemporary challenges such as climate change, population growth, urbanization, and pollution, the most significant impact exerted by humans on natural resources is evident in food production [2]. Consequently, there is a need to find solutions for sustainable and efficient food production to mitigate these problems. The prevalence of severe food insecurity at the global level declined from 11.7% in 2021 to 11.3% in 2022. However, the number of severely food-insecure people was still about 900 million in 2022, which is 180 million more than in 2019 [3]. The 2018 Global Agricultural Productivity (GAP) ndex, by the Global Harvest Initiative, highlights that food production is not growing fast enough to sustainably feed the world in 2050 (Figure 1). Low-income countries are experiencing a conspicuous productivity gap in food production, as they fall significantly short of expanding their agricultural output to meet the projected future demand within their borders [3]. The growth of Total Food Productivity (TFP) is way too low to cope with the growth of populations in these countries. The problems are compounded by natural factors like climate change, conflicts, and overreliance on rain-fed food systems. It is estimated that between 691 and 783 million people worldwide faced hunger in 2022 [4].

Aquaculture is recognized for its capacity to improve food security, particularly within rural and peri-urban communities in various African countries. Approximately 45% of the global consumption of fish and shellfish is sourced from aquaculture [5]. Moreover, aquaculture stands out as a more sustainable and efficient method of food production than traditional agricultural practices. This is primarily attributed to its significantly reduced demand for land and water resources compared to other conventional food systems [6]. This renders it a feasible choice for nations grappling with food insecurity, as it can offer a crucial nutrition source and bolster food security. Nevertheless, a requirement exists for the advancement, acceptance, and expansion of resource-efficient and environmentally sustainable aquaculture technologies, such as aquaponics, to amplify aquaculture production [7].

To increase diversity and enhance food and nutrition security, especially among rural communities, aquaculture has been integrated with crops and other animals under various culture systems [8]. One technology is the aquaponic system that integrates fish production and various crops under closed-loop systems. The system enhances the concept of 'more crop per drop' while also reducing the negative environmental consequences of food production [9]. Different aquaponic designs are used under different production conditions. Some designs include the Media Bed, Floating Raft, and Nutrient Film Technique (NFT) aquaponic systems. The problems associated with Media Bed and Floating Raft systems is the difficulty in controlling water flow and fluctuations resulting in management and operational difficulties [10], [11]. The Media Bed Aquaponics systems, in particular, have been shown to experience clogging, which often compromises their efficiency and production [9]. Nutrient Film Technique (NFT) on the other hand allows for ease of management since it is easier to control water flow within these systems [12]. This is because in this system, the plants are grown in aquaponic cups on grow pipes connected to the fish tank via biological and physical filters. The plants, therefore, get nutrients from the water flowing through the pipes from the fish tank. The water is then collected in a sump and pumped back to the fish tank, and the cycle continues [12]. For this reason, the NFT system is easier to design and control, making it ideal for both experimental and production purposes. The media bed method can support the growth of 4-8 kg of vegetables per year for every 1 kg of fish, producing 20-40 kg per square meter of grow bed per year [13]. Floating raft systems can sustain the growth of 4-8 kg of vegetables per 1 kg of fish per year, producing 25-45 kg of leafy vegetables and herbs per square meter of raft area per year [14]. The NFT, on the other hand, has the potential to support the cultivation of 4-8 kg of vegetables per 1 kg of fish annually with yields of 20-35 kg of vegetables per square meter of channel area [15]. The three aquaponics systems can accommodate stocking densities ranging from 20 to 40 fish per cubic meter, with yields ranging from 10 to 15 kilograms of fish per square meter [9].



Source: Food Demand Index is from Global Harvest Initiative (GHI) (2018); Agricultural Output from TFP Growth is from USDA Economic Research Service (2018).

© 2018 Global Agricultural Productivity Report® (GAP Report®)

Figure 1. Global Agricultural Productivity (GAP) Index

https://www.dtnpf.com/agriculture/web/ag/news/article/2018/10/17/group-warns-food-supply-meet-future

Aquaponics systems, have been beyond the reach of many rural poor households due to their complex designs and the high initial cost of installation [14]. Further, including them in rural and urban food production systems has also been curtailed by the relatively high energy and technical requirements [16]. Under these systems, the water and nutrient cycles are optimized to increase efficiency and reduce waste, thus increasing yields and conserving resources [15]. Nonetheless, there exists a gap in knowledge regarding the capability of aquaponics to improve food production. This scoping review investigates the potential of aquaponics in enhancing food security in Kenya, offering insights into diverse facets of aquaponics, such as water and nutrient use efficiency, adoption, scalability challenges, and recommendations.

2. Review Methodology

We conducted an extensive search of scientific databases to retrieve relevant literature. The databases included Web of Science, Scopus, Google Scholar, Lens.org, and the Food and Agriculture Organization (FAO) database. To ensure a comprehensive search, we used search strings encompassing titles, keywords, and abstracts. A combination of controlled vocabulary (MeSH terms) and free-text terms. The terms included: *"Aquaponics" AND "Aquaculture" OR "Integrated Aquaculture" OR "Food security" OR "Sustainable aquaculture" OR "Food Production" OR "Food Security"*. Through this initial search, a total of 200 articles were identified. Subsequently, 56 duplicate articles were excluded, leaving 144 unique articles for further screening. Studies had to focus on sustainable practices that promote integrated food production while enhancing resource use efficiency in aquaculture. We excluded articles that did not meet these criteria. A potential limitation of our study is that it was conducted as a narrative review, thus, it may not encompass the full breadth of aquaponics and other climate-smart food production systems in Kenya. A broader scope could yield additional insights into the diversity of approaches and their impacts on climate-resilient food production. Another potential limitation is the exclusion of non-English language literature. We may have overlooked valuable research conducted in languages other than English, particularly in regions where English is not the primary language of academic publication. Aquaponics and aquaculture are implemented globally, and it's important to recognize that non-English publications may offer unique perspectives and outcomes. Nevertheless, this review advances our understanding of the potential aquaponics in enhancing food security in the Kenyan context.

3. Results and Discussion

Status of food production in Kenya

According to the Kenya National Bureau of Statistics (KNBS), Economic Survey 2023, agriculture contributes to about 22.4% of the country's Gross Domestic Product (GDP) and employs over 40% of the population [https://www.knbs.or.ke/economic-survey-2023/]. A KNBS, Crop Production Survey 2022 reported that the country produced about 6 million tons of food crops, 4.2 million tons of horticultural crops, and 500,000 tons of industrial crops in 2022. Despite this, food production in Kenya is mainly based on small-scale, subsistence farming undertaken by smallholder farmers in rural areas [17]. One of the main challenges facing food production in Kenya is low productivity due to various factors. According to a report by the Kenyan Ministry of Agriculture, productivity in the country's agricultural sector is low due to a lack of access to modern technologies, inputs, and extension services. Smallholder farmers in Kenya often have limited access to markets and financial services, which limits their capacity to invest in their farms and improve productivity and sustainability [18]. Another challenge facing food production in Kenya is the impact of climate change. A large percentage of the Kenyan population lives in regions that are highly susceptible to droughts and floods [19]. These extreme weather events can have a negative impact on agriculture, leading to crop failures and reducing productivity and yields. International Food Policy Research Institute (IFPRI) reports that climate change is likely to increase the frequency and severity of droughts and floods in Kenya, worsening food insecurity, especially for rural communities [20]. The Kenyan government has therefore encouraged agricultural research to improve quality, productivity and better use of resources by empowering various agricultural research institutes within the country. One of the most prominent institutes is the Kenya Agricultural and Livestock Research Organization (KALRO) which focuses on various aspects of agriculture and livestock research including climate-smart food systems. This was the focus of the World Bank- funded Kenya Climate Smart Agriculture Project that was coordinated by the Kenya Agriculture and Livestock Research Organization (KALRO). Such initiatives have encouraged the use of resource-efficient and climate-smart food systems. One such technology that has gained attention in the recent past is aquaponics. This is a sustainable food production system that integrates aquaculture and hydroponics in a symbiotic relationship [21]. There are still some gaps in knowledge, especially regarding the feasibility and applicability of this technology in the Kenyan context, necessitating the need for Kenya-specific studies as detailed in this review.

The status of aquaculture in Kenya

Kenya has a high potential for the development of aquaculture because it is endowed with natural resources favoring the culture of many fish species. According to [22], fish farming started in Kenya during the 1900s by introducing trout in streams for sport fishing. The practice became more prominent during the 1960s, but it had slow growth until 2006, when aquaculture production rose from 4,218 metric tons (MT) to 24,096 MT in 2014 [23].

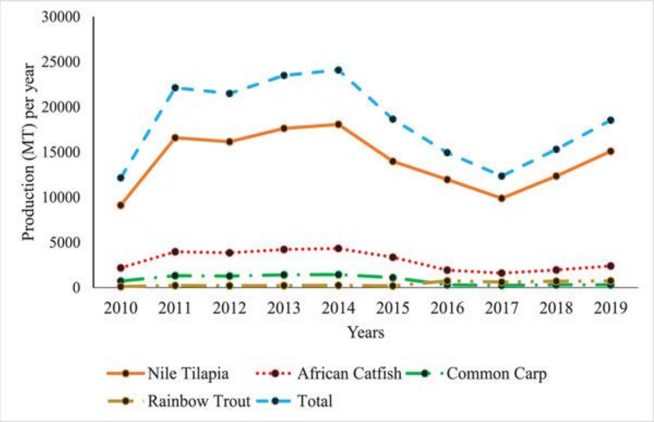


Figure 2. Cultured fish species production (in million tonnes) in Kenya from 2010 to 2019 (FAO, 2021)

This positioned Kenya as the fourth-highest aquaculture producer in Africa after Nigeria, Uganda and Ghana [24]. Some of the fish species under culture in the country include Nile tilapia (*Oreochromis niloticus*), African catfish (*Clarias gariepinus*), and Trout (*Oncorhynchus mykiss*). Some other species such as *Labeo victorianus* and *Tilapia esculentus* are still under study for possible inclusion into aquaculture [25]. Kenya's aquaculture production has grown steadily, from 20,000 metric tons in 2010 to 60,000 metric tons in 2021 [26]. The Kenyan government has recognized the importance of aquaculture for food security and economic development and has launched a number of initiatives, including the National Aquaculture Sector Strategic Plan 2022-2032.

A variety of aquaculture technologies and systems are used in Kenya, including ponds, cages, and recirculating aquaculture systems (RAS), and they have varied levels of success and challenges. Currently, more than 90 % of fish in Kenya is produced under semi-intensive culture systems, especially in earthen fishponds [27]. These semi-intensive systems are water- and resource-intensive but have low productivity. The cage culture of Nile tilapia is gaining prominence, especially in Lake Victoria, and investors are being attracted to the lake. The choice of a culture system to adopt is dictated by the available technology, finances, and cultural system to adopt is dictated by the available technology, finances, land, and other resources [16]. One of the most important factors to be considered under any system is the ability of the particular system to ensure faster and more efficient fish growth and performance. There is generally a low adoption rate of climate-smart culture systems like aquaponics in Kenya. The low adoption has been attributed to the relatively high initial cost needed to install and run these systems coupled with the high technical requirements [23]. However, there are a few farms that have already adopted these systems in Kenya but there is still a need to study and understand the systems better.

Despite the progress, aquaculture in Kenya faces several challenges and constraints. Some of the challenges facing the sector include the lack of access to quality seed and feed and the high cost of production [16]. The quality of seed and feed is essential for successful aquaculture production. However, many farmers in Kenya lack access to quality inputs, which affects their production. Many farmers in Kenya also lack the technical expertise necessary to manage aquaculture systems effectively, particularly modern intensive culture systems like aquaponics [19]. Because of this, there is a need for investment in climate-smart, resource-efficient aquaculture systems like aquaponics. The potential of aquaculture in enhancing food security in Kenya is undeniable. As the demand for fish protein increases due to population growth and shifting dietary preferences, aquaculture can provide a reliable and sustainable source of protein [28]. By boosting domestic fish production, the country can reduce its reliance on fish imports, as witnessed with almost 20,000 MT of tilapia imported from China annually [29]. The importation can be reduced through the adoption and upscaling of resource-efficient aquaculture systems like aquaponics.

Aquaponics systems

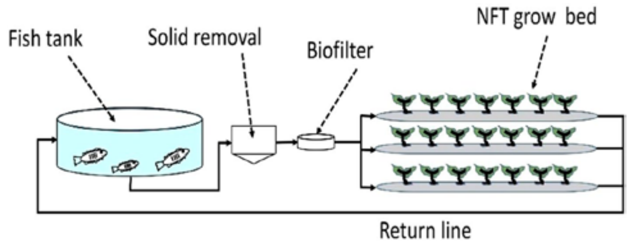


Figure 3. Schematic of generic design of NFT aquaponic system [31].Bottom of Form

Aquaponics is a sustainable agriculture system that combines the production of fish and plants in a closed-loop system, with the potential to reduce greenhouse gas emissions and provide socio-economic and environmental co-benefits [30]. The closed-loop nature of aquaponic systems allows for the recycling and reuse of water and nutrients, reducing the need for inputs such as fertilizers and pesticides and further decreasing the carbon footprint of the system [26]. There are different aquaponic designs used under different production conditions. Some of the designs include the Media Bed, Floating Raft, and Nutrient Film Technique (NFT) aquaponic systems. Nutrient Film Technique (NFT) allows for ease of management since it is easier to control water flow within these systems [30]. This is so because in this system, the plants are grown in aquaponic cups on grow pipes connected to the fish tank via biological and physical filters. The plants get nutrients from the water flowing through the pipes from the fish tank. The water is then collected in a sump and pumped back to the fish tank, and the cycle continues (Figure 1).

The principle behind aquaponics

Aquaponics is a sustainable food production system that integrates aquaculture and hydroponics in a symbiotic relationship [32]. In aquaponic systems, fish waste is converted by bacteria into nutrients that are used by plants to grow. On the other hand, the plants filter and purify the water for the fish, creating a closed-loop system that requires minimal inputs and produces both fish and crops [11]. The principles behind the operations of aquaponic systems are based on the natural nutrient cycle and the principles of recirculating aquaculture systems [9]. One of the major principles of aquaponic systems is the use of bacteria to convert fish waste into nutrients that can be used by plants (Figure 2). This process is called nitrification, and it involves two types of bacteria. Ammonia-oxidizing bacteria (Nitrosomonas and Nitrosospira) convert ammonia (NH4+), which is toxic to fish, into nitrite (NO_2-). Nitrite-Oxidizing Bacteria: e.g., Nitrobacter and Nitrospira convert NO2 nitrite into nitrate, NO_3-which is a nutrient that plants can absorb and utilize for growth [31]. The bacteria are naturally present in the water and in the biofilter component of the aquaponic system, which provides a substrate for the bacteria to attach to [9]. Another principle of aquaponic systems is the need for balanced nutrient levels. Too much or too little of any nutrient can cause problems for both the fish and the plants [31]. The most important nutrients for plant growth are nitrogen, phosphorus, and potassium, supplied by the fish waste and uneaten fish feeds from the fish tank. However, plants also require micronutrients, like as iron, calcium, and magnesium, which may need to be supplemented in the system [33].

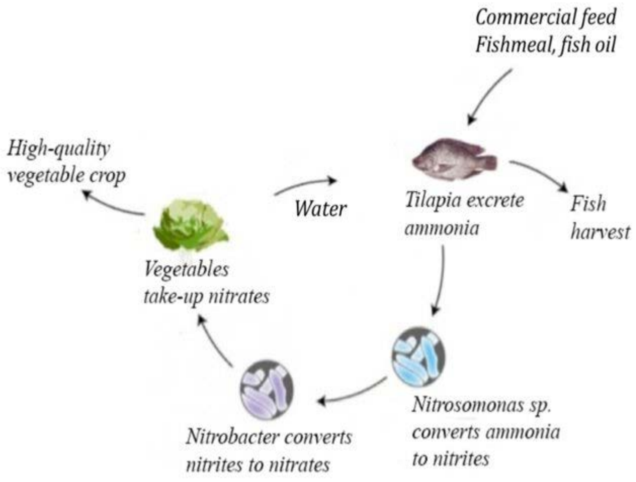


Figure 4. General principle of aquaponics function (Wilkes et al., 2017)

Resource use efficiency in Aquaponic systems

In recent years, the resource utilization efficiency of aquaponic systems has gained attention as a system for growing high-quality crops with minimum resource inputs. Aquaponics is a closed-loop system in which fish provide nutrients for plants and plants filter the water for the fish

[34]. Compared to conventional farming approaches, this technology has the potential to significantly reduce the quantity of nutrients and water needed for food production [32]. According to [35], the nutrient use efficiency of an aquaponics system can vary based on several factors. Some factors include the type of plants and fish grown, water quality parameters, and the design and operation of the system. Aquaponics systems have been shown to have high nutrient use efficiency, with some studies reporting up to 95% [35].

The fish species and type of fish feed used as a nutrient source are important components that may affect the nutrient-use efficiency of an aquaponics system. This is because different fish species have varying nutrient requirements and excretion rates, which may affect the balance and dynamics of nutrients in the system [36]. Tilapia has been reported to have lower nutrient excretion rates than other species like trout and catfish [35]. This may influence the availability of nutrients to the plants as well as the performance of the system. The kind of plants grown might also affect the nutrient-use efficiency of an aquaponics system. Some plants require more nutrients than others and may require additional fertilizers for optimal growth. Furthermore, the stage of plant growth might also influence nutrient-use efficiency since various growth phases may have varied nutritional requirements [30], [37]. Proper system design and management are also important for enhancing an aquaponics system's nutrient-use efficiency. This involves regulating water flow and nutrient delivery, as well as water temperature and pH levels. High pH values, for example, have been reported to encourage precipitation of Phosphorus, making it unavailable for plants [38].The nutrient efficiency in an aquaponics system might vary greatly based on the system and factors described above. However, research has shown that nutrient use efficiencies range between 75 and 80% [39]. This is much greater than the fertilizer utilization efficiency recorded in conventional agricultural production systems, which may range between 20 and 30%.

The water-use efficiency of an aquaponics system is determined by a variety of factors. Some of these factors include the system's design and size, the quantity and species of fish and plants, the feeding regimens, and prevailing environmental conditions [39]. According to some research findings, aquaponics systems can achieve water-use efficiencies of as high as 90%. This is significantly higher than conventional agricultural systems, which can achieve water use efficiencies as low as 50% [40] or less. Depending on specific conditions and management practices, the water-use efficiency of aquaponics systems might vary greatly. Rakocy et al. (2006) reported that an aquaponics system with tilapia and lettuce had a water use efficiency of about 85%, while a system with tilapia and tomatoes recorded a water use efficiency of 60%. These variations might be attributable to the varying nutritional and water requirements of the various fish and plant species under production. In addition to an aquaponics system's water-use efficiency, several management practices may be used to further optimize water consumption and reduce losses. The use of closed-loop systems that recycle water and nutrients, and the installation of water conservation measures such as greywater reuse are examples of these practices.

Table 1. Comparison of productivity, resource efficiency, profitability and GHG emissions between aquaponics, and conventional agriculture and agriculture

Parameter	Aquaponics	Fishpond Aquaculture	Conventional agriculture
Production per Hectare (kg/ha)	15,000	12,000	8,000
Water Usage (compared to others)	1:10 (less)	1:4 (moderate)	1:1 (higher)
Land Usage (compared to others)	1:5 (less land)	1:3 (moderate land)	1:1 (higher land)
Profitability (considering costs)	$20,000/ha	$18,000/ha	$15,000/ha
GHG Production (CO_2 equivalent)	50 kg/ha	80 kg/ha	150 kg/ha

Source: Asadu et al., 2020; Chakraborty et al., 2022; Otieno et al., 2023)

As depicted in Table 1, aquaponics is better than conventional food production systems in resource (water and land) utilization. This is due to the closed nature of the aquaponics unit, which reduces the demand for water and space. Additionally, the profitability and productivity of aquaponics systems are higher since they allow for the production of more than one product (fish and crops) in the same unit.

Compared to traditional agriculture, aquaponics boasts impressive land-use efficiency. Vertical farming techniques allow for stacked grow beds, maximizing production within a minimal footprint. This is particularly advantageous in Kenya, where arable land is scarce due to population growth and soil degradation [25]. A study by the World Bank (2013) highlights that Kenya has only 0.22 hectares of arable land per capita, significantly lower than the global average of 0.4 hectares. Aquaponics can help bridge this gap, enabling food production even in urban areas with limited land availability [41]. One of the main challenges of aquaponics in Kenya is its energy consumption. Lighting, filtration, and aeration systems require significant electricity, which can be a barrier for small-scale farmers, especially in areas with unreliable power supply. Studies estimate that aquaponics systems can consume up to 7 times more energy than traditional soil-based agriculture [42]. Despite the challenge, Kenyan researchers and entrepreneurs actively explore solutions to reduce energy consumption in aquaponics systems. Some promising approaches include strategically designed greenhouses can maximize natural light penetration, reducing reliance on artificial lighting. Implementing efficient water flow systems and minimizing aeration requirements can further reduce energy demands. Although land, nutrient, and water-use efficiency make aquaponics a viable food production system for Kenya, addressing the energy consumption challenge is crucial for its long-term sustainability and broader adoption.

Fish and crop growth and yield in aquaponics systems

Fish growth performance and survival in aquaponics systems are influenced by several factors. Some factors include the choice of fish species, feeding regimes, water quality parameters, and temperature [43]. Fish growth and productivity are generally higher in aquaponics than in conventional aquaculture systems [44]. This can be attributed to the synergistic influence of hydroponic integration, good water quality and nutrient availability in these systems [45]. However, depending on the prevailing conditions and management practices, fish growth and survival in aquaponic systems may vary. The gently flowing water of the Nutrient Film Technique (NFT) aquaponic system provides a conducive condition for the fish to grow by allowing them to graze on microscopic particles and organisms in the water. Studies have revealed that tilapia grow better in an NFT system than under conventional aquaculture. Due to the utilization of closed-loop recirculating systems and other management measures, a commercial-scale aquaponics system in Hawaii, for example, recorded fish production of up to 3.5 kg/m^2/year, with survival rates of 95% [46].

Lee, 2021 compared the growth and survival of Red Tilapia grown in aquaponics system to fish reared in a conventional aquaculture system. The research findings showed that tilapia in the NFT system grew at a significantly higher rate, with a mean weight of 340.3g, compared to 230.2g in the conventional aquaculture system. The tilapia in the NFT system also had a better survival rate, of 97.3%, compared to 77.4% in the conventional system.

The NFT aquaponic system is a popular choice for commercial food production because of its high efficiency and consistent yields [47]. Similarly, the yields of lettuce, spinach, and basil under the NFT aquaponic system have also been studied mainly in Europe and Asia with very little information available on Kenya. A study by Wang et al. (2017) reported yields of lettuce, spinach, and basil of 40.3 kg/m^2/year, 6.3 kg/m^2/year, and 2.9 kg/m^2/year, respectively. Several factors, including water quality, can affect the yields of fish and vegetables in an NFT aquaponic system. Poorly aerated and filtered water can lead to low yields of both fish and vegetables [48]. Additionally, the pH of the water needs to be maintained in the optimal range for fish and plants (between 6.5 and 8.0). The type and quantity of fish feed used can also impact the yields of fish and plants by determining the quantity and quality of nutrients available in the system for the plants. Different types of plants require different growing media and nutrients for optimal growth and development. Moreover, using soil-based growing media can result in the accumulation of solids and other debris in the water, which can be toxic to the fish and lead to lower yields [49].

Aquaponics and food security

The exploration of aquaponics as an innovative method for increasing food security is an intriguing area of research in the field of sustainable agriculture. As the world struggles with the complexities of food production and the difficulties posed by climate change, recognizing the possibilities of aquaponics becomes increasingly important. Conservation of resources goes beyond water efficiency. Aquaponics lowers the need of chemical fertilizers by fertilizing plants with nutrient-rich fish effluent, making it an environmentally friendly food production technology [50]. Aquaponics has the potential to significantly improve food security, particularly in areas where traditional agricultural practices are vulnerable to climate change. Aquaponics' regulated environment reduces the impact of climate change by providing a stable platform for food production. Furthermore, aquaponics' year-round production capabilities overcome the seasonal limits associated with traditional farming. This regular output contributes to food security by ensuring a steady supply of fresh produce throughout the year [51]. In addition to these benefits, aquaponics' economic feasibility increases its potential impact on food security. As technology progresses and aquaponics systems become more accessible and affordable, small-scale farmers and communities will be able to produce food and create revenue on a sustainable basis.

Agriculture in Kenya is primarily rain-fed, with over 80% of agricultural production being dependent on rainfall [19]. This makes the agricultural sector vulnerable to droughts and floods, which are becoming more frequent and severe due to climate change [52]. Population growth, urbanization and climate change are also putting pressure on land, leading to land degradation and loss of productivity. Additionally, agriculture in most parts of Kenya is largely dependent on the use of inorganic fertilizers, which can have negative environmental impacts [53]. Aquaponic systems have the potential to enhance significantly food production in Kenya by addressing many of the challenges facing conventional food production systems in the country. They are not dependent on rainfall, making them less vulnerable to droughts, and they utilize significantly less water and land than traditional agriculture [28]. Aquaponic systems also allow for cultivating different types of fish and plants, enhancing crop diversity and food and nutrition security. The waste products produced by the fish in these systems can be used to fertilize the plants, reducing the need for chemical fertilizers in food production.

Previous research on NFT aquaponic systems has shown that these systems can be highly efficient, producing high yields of both fish and plants. For example, in a study by Torzillo et al. (2019), a multi-loop system produced an average of 22.5 kg/m^2/year of tilapia and 37.5 kg/m^2/year of lettuce. This is significantly higher than yields under traditional agriculture systems.

Case studies of successful aquaponics in Kenya

Several Kenyan ventures demonstrate the potential for high production within the aquaponics systems. Aqua4All, a project implemented in peri-urban Nairobi, showcased a multi-loop aquaponics system yielding impressive results. The 1,000m^2 farm produced over 2 tons of tilapia and 4 tons of vegetables annually, demonstrating the viability of large-scale operations (http:// www. huismanfoundation.nl /index.php?id=30). The Green Fingers Farm project utilizes aquaponics to grow a diverse range of vegetables, including kale, spinach, and lettuce, providing fresh produce and income for the local community. These examples highlight the potential for aquaponics to contribute significantly to Kenyan food production. The impact of aquaponics extends beyond mere production figures. In Kajiado County, the Kilimo Bora project empowers women's groups to establish home-based aquaponics systems. This initiative not only improves household food security but also generates income, fosters women's empowerment, and provides valuable nutrition education. Additionally, organizations like Ecofish Farm and Jomo Kenyatta University of Agriculture and Technology (JKUAT) use aquaponics for educational purposes, training farmers and promoting the adoption of this sustainable practice. These cases showcase the positive social and educational impacts of aquaponics in Kenya. Despite its potential, aquaponics in Kenya faces several challenges. Initial setup costs remain high, hindering wider adoption, particularly among small-scale farmers [52]. Access to reliable electricity and quality fingerlings can also be problematic as with other fish intensive fish production systems [25]. Moreover, limited technical knowledge and market access pose additional hurdles. These challenges require innovative solutions and collaborative efforts to ensure the long-term sustainability and scalability of aquaponics in Kenya.

Challenges, barriers, and solutions for the adoption of aquaponics in Kenya

While aquaponics has the potential to provide sustainable food production in resource-constrained countries like Kenya, its adoption by smallholder farmers is still low [52]. Design complexity and high power consumption are major hurdles to the adoption of aquaponics in Kenya [41]. However, addressing these technological difficulties alone will not significantly increase aquaponics adoption in Kenya. To effectively promote widespread aquaponics adoption and upscaling among Kenyan smallholder farmers, a multidimensional approach is required, focusing on affordability, accessibility, information dissemination, and the development of a supportive environment especially by stakeholders within the agricultural sector. Promoting simpler, gravity-fed systems made from locally available materials can greatly lower capital expenditures. Open-source designs and guides can enable communities to create cost-effective alternatives [54]. In terms of finances, targeted microloans, financial incentives, and public-private partnerships can help farmers with limited resources develop novel financing models that reduce the initial investment burden. Encouraging local manufacture of critical aquaponics components such as biofilters and grow beds can boost employment and minimize reliance on costly imports. Hands-on training programs that target local contexts and issues are critical for increasing farmers' confidence and skill sets [41]. Mobile training units and farmer-to-farmer knowledge exchange platforms can also serve geographically diverse groups. Farmers with limited literacy or internet access can benefit from knowledge dissemination through easily accessible channels such as vernacular language manuals, visual guides, and community radio broadcasts. Using mobile apps and internet platforms can provide real-time monitoring, technical support, and access to market information, allowing farmers to run their systems more efficiently. Establishing strong market links for aquaponic produce through farmer cooperatives, direct-to-consumer methods, and collaborations with agribusinesses can ensure profitable outcomes for farmers. To address the problems of power consumption, continuous research into context-specific optimization of aquaponics systems, together with innovation in renewable energy integration, is necessary [55].

Kenyans are actively addressing these challenges. The Aquaculture Association of Kenya (AAK) provides training and technical support to aquaponic farmers, fostering knowledge sharing and capacity building. Additionally, research efforts at JKUAT are exploring low-cost aquaponics systems and alternative protein sources for fish feed, aiming to make the technology more accessible and sustainable. Moreover, initiatives like Kilimo Bora connect farmers with markets, ensuring fair prices and market access for their produce. These efforts demonstrate the Kenyan spirit of innovation and collaboration, paving the way for a brighter future for aquaponics in the country.

Conclusions and recommendations

Aquaponics presents a compelling vision for sustainable food production. While challenges exist, the case studies presented illustrate its potential for high yields, community impact, and environmental benefits. Embracing innovative solutions and fostering collaborative efforts will be key to overcoming hurdles and ensuring the long-term success of this promising agricultural practice. Aquaponics is not just a technology; it represents a paradigm shift in addressing food insecurity in Kenya. Its potential to overcome resource scarcity, empower communities, and promote environmental sustainability is a powerful tool for building a thriving, resilient future. By adopting and upscaling this sustainable food production system, Kenya can chart a new course towards food security and sustainable food production and development. However, addressing aquaponics adoption in Kenya requires a holistic approach beyond technical solutions. Building an ecosystem of affordability, knowledge sharing, supportive policies, and vibrant market linkages can empower smallholder farmers to embrace this sustainable food production technology and unlock its potential for improved livelihoods and food security in Kenya.

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