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Review

Aquaponics: A Sustainable Path to Food Sovereignty and Enhanced Water Use Efficiency

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Abstract: This comprehensive review explores aquaponics as an environmentally friendly solution aligned with SDGs and food sovereignty, assessing various aspects from system design to automation, and weighing social, economic, and environmental benefits through literature and case studies. However, challenges persist in obtaining organic certification and legislative recognition, hindering its growth. Achieving remarkable water use efficiency, up to 90%, relies on adaptable fish species like Nile tilapia and carp. Nutrient-rich fish feeds notably benefit low-nutrient-demanding greens. Ensuring water quality and efficient nitrification are pivotal, supported by IoT systems. Despite its efficiency, integrating Industry 4.0 involves complexity and cost barriers, necessitating ongoing innovation. Economies of scale and supportive horticultural policies can bolster its viability. Aquaponics, known for its efficiency in enhancing crop yields while minimizing water use and waste, is expanding globally, especially in water-scarce regions. Aquaponics, pioneered by the University of the Virgin Islands, is expanding in Europe, notably in Spain, Denmark, Italy, and Germany. Asia and Africa also recognize its potential for sustainable food production, especially in water-limited areas. While it offers fresh produce and cost savings, challenges arise in scaling up, managing water quality, and meeting energy demands, particularly for indoor systems. Egypt's interest in desert and coastal regions highlights aquaponics' eco-friendly food production potential. Despite the associated high costs, there is a quest for practical and affordable designs for everyday integration. Research in arid regions and industry advancements are crucial for aquaponics' global food production potential. Deeper exploration of intelligent systems and automation, particularly in large-scale setups, is essential, highlighting the industry's promise. Practical application, driven by ongoing research and local adaptations, is a key to fully harnessing aquaponics for sustainable food production worldwide.

Keywords: aquaponics; automation; food sustainability; food sovereignty; water productivity

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1. Introduction

Irrigation is essential for agriculture, especially in areas with limited rainfall. Various methods like surface, drip, sprinkler, and sub-surface irrigation are used based on crop type, soil, and water availability. Amidst the challenges posed by burgeoning population growth, water scarcity, and environmental changes, efficient irrigation techniques have become increasingly important [1]. Traditional irrigation techniques frequently lead to substantial water loss through evaporation, runoff, and uneven distribution. This has prompted numerous researchers and analysts to explore alternative approaches, aiming to optimize current methods to boost agricultural output while conserving water resources and ensuring the long-term sustainability of agriculture and water usage [1–7]. In an era defined by the urgent need for sustainable solutions, the convergence of agriculture and aquaculture has given rise to a revolutionary method known as aquaponics. This innovative approach not only challenges conventional farming practices but also offers a transformative pathway towards achieving food sovereignty and optimizing water usage. This review encapsulates the core principles of this impactful agricultural technique, harmoniously merging aquaculture (the cultivation of aquatic animals) and hydroponics (plant cultivation without soil) in a mutually advantageous symbiosis (Figure 1) [8,9].

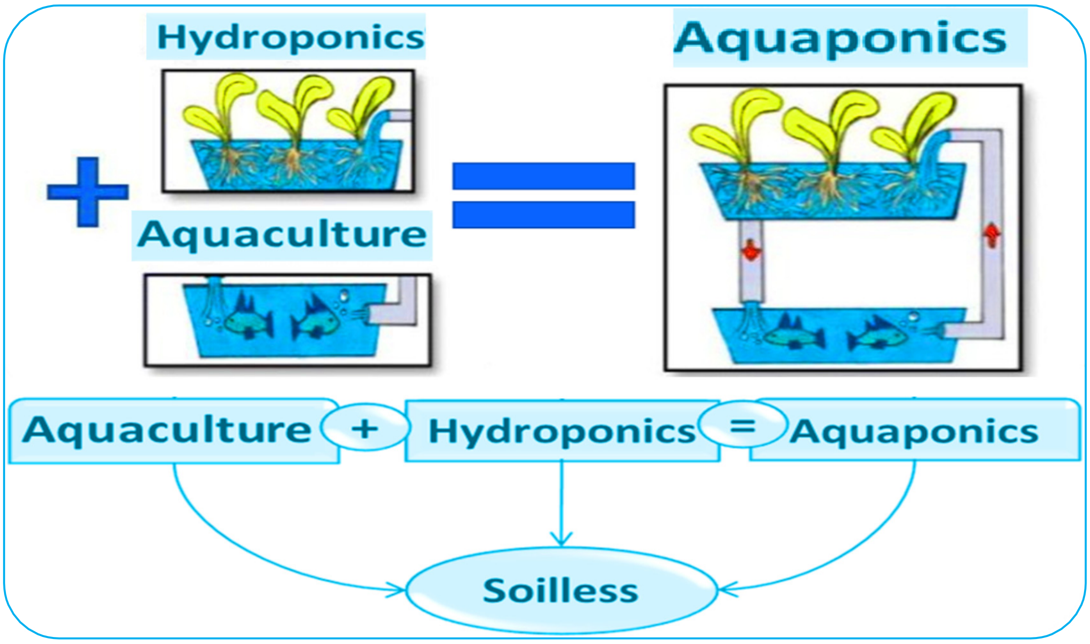

Figure 1. Aquaponics system overview, featuring the indication of water recycling direction via the red arrow.

Aquaponics emerges as a beacon of hope, showcasing how humanity can adapt, innovate, and thrive while preserving the delicate balance of our natural resources [9–14]. Within aquaponic systems, a symbiotic cycle unfolds: fish waste serves as vital nutrients for plants, while these same plants act as natural filters, purifying the water destined to circulate back to the fish tanks. This harmonious relationship between aquatic life and vegetation fosters a closed-loop ecosystem, significantly curbing water wastage and elevating the system's overall sustainability [10]. This method not only produces high-quality organic vegetables and fruits but also sustainable protein sources, addressing the challenges of both food security and water conservation [9,10]. Aquaponic systems can also be automated and monitored using sensors and IoT technologies, allowing for precise control over factors like fertilization, irrigation, and lighting [11–13]. Automation in aquaponics not only increases efficiency but also contributes to higher yields and better resource utilization. However, while this approach holds promise, gaps in existing research are apparent [11–15]. The current focus lacks attention to technological innovation in aquaponic systems, particularly in emerging technologies like AI integration and IoT applications. Additionally, scalability challenges in large-scale aquaponics and the adaptability of systems to diverse environmental conditions remain understudied, along with limited guidance on urban agriculture integration.

The chemistry within aquaponics stands as a linchpin for the effective functioning of automated commercial setups, significantly impacting system functionality [13]. Efficient control of water quality, proper management, and good system design are essential for achieving high yields and quality produce [13]. This not only contributes to food security but also ensures access to safe, culturally fitting, and healthful sustenance via sustainable means, aligning with the concept of food sovereignty [14]. However, manually managing and analyzing aquaponics systems can be challenging, particularly when scaling up to commercial levels. Additionally, research gaps persist in addressing challenges related to manual management at commercial scales, hindering the development of efficient strategies for optimal system functionality.

Moreover, the adaptability of aquaponic systems to various environmental conditions, encompassing extreme climates or unpredictable weather patterns, remains inadequately explored in current research. Limited studies address the resilience of aquaponics in diverse environmental contexts, highlighting a gap in understanding the system's robustness under varying conditions. Moreover, there is a lack of nuanced guidance in the existing literature concerning urban agriculture and the integration of aquaponic systems into urban settings. The distinct demands posed by urban environments present logistical challenges often overlooked in current studies. These gaps emphasize the need for comprehensive exploration and targeted research in addressing the resilience of aquaponics in diverse environments and providing specific guidance for urban agriculture integration. Moreover, the adaptability of aquaponic systems to diverse environmental conditions, including extreme climates or variable weather patterns, remains inadequately explored. Research addressing the resilience of aquaponics in different environmental contexts is limited. Lastly, urban agriculture, especially the integration of aquaponic systems in urban settings, lacks nuanced guidance in the existing literature. The unique demands of urban environments pose logistical challenges that current studies often overlook.

In this review, our objective is to comprehensively address the identified gaps in understanding aquaponics, providing actionable insights and innovative approaches that bridge these voids for both research and practical applications. We will explore sustainable aquaponics, emphasizing various critical aspects such as system design, resource efficiency, automation, and future potential. We will delve into diverse aspects such as the selection of fish and plant species, tank and grow bed designs, water circulation, and biofiltration techniques. Significantly, we will focus on irrigation efficiency, particularly in terms of water, nutrients, and energy recycling. The incorporation of automation technologies, including sensors and monitoring systems, will be examined for optimizing performance and reducing labor requirements. Additionally, we will probe into the future prospects of aquaponics, considering technological advancements, economic viability, and its integration into urban settings. Through this exploration, our aim is to assess aquaponics' role in enhancing factors like food sovereignty, sustainable development goals, and environmental resilience, with a specific emphasis on irrigation efficiency.

2. Methods

The bibliometric method applied in the context of the review title involves the systematic analysis of scientific literature. In this work, the bibliometric analysis followed a systematic process, shown in Figure 2. First, the researchers chose a reliable database and software. Next, they carefully selected keywords relevant to the topics, including aquaponics and sustainable aquaponics. They applied specific limitations to the search results, such as filtering by year range and document type. The data collected were then exported using the ScienceDirect and PubMed exporters and transferred to literature tools for in-depth analysis. Finally, the researchers used VOSviewer (VOS) software version 1.6.18 [1] for data visualization, and data were filtered based on relevance to the topic. The selected articles were then critically analyzed, and key themes and findings were identified and synthesized to provide a comprehensive overview of the subject matter. Additionally, the article explores the gaps and limitations of existing research and proposes potential areas for future study.

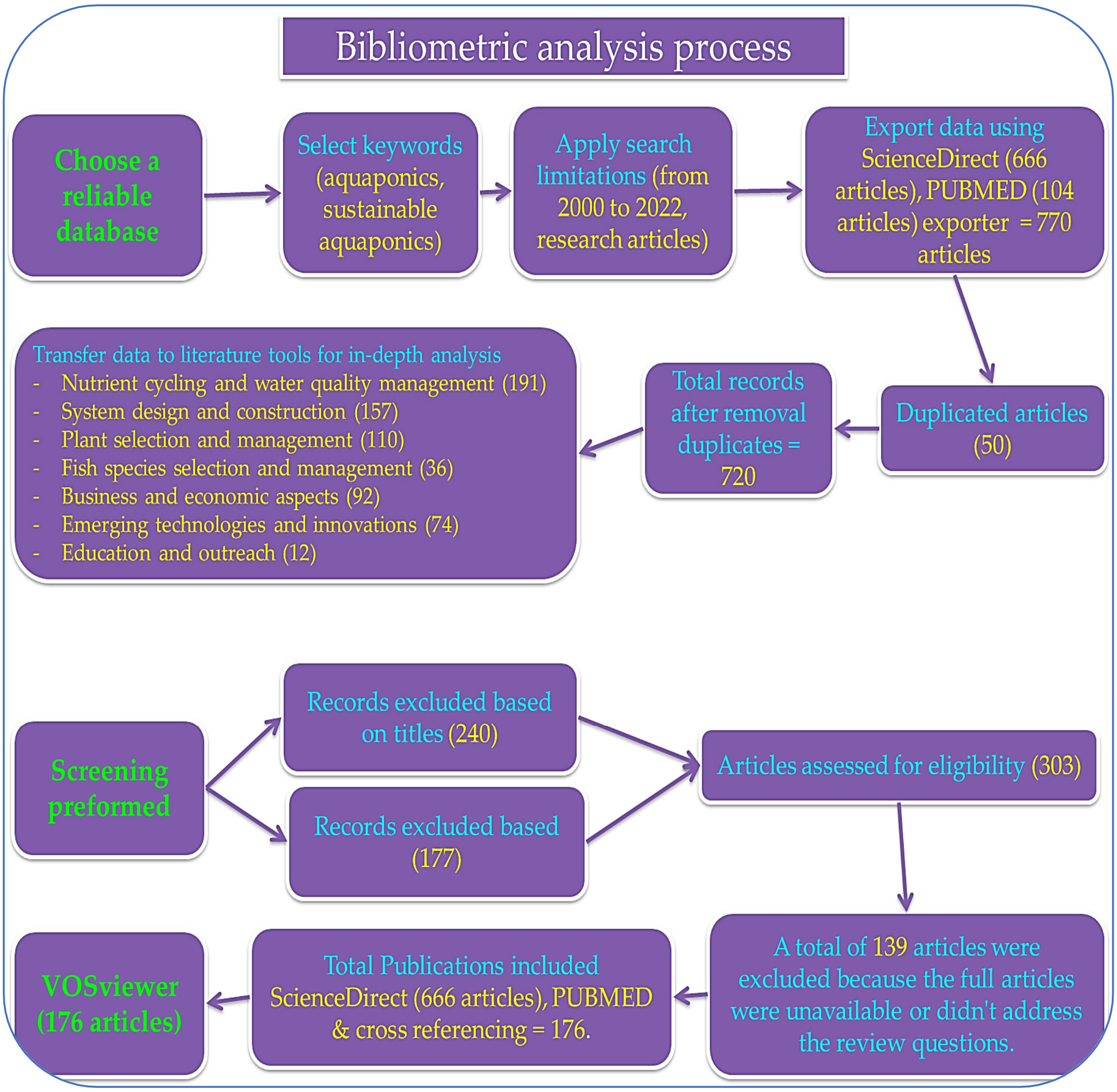

Figure 2. Flowchart illustrates the sequential steps involved in the bibliometric analysis process and presents key findings derived from the study.

The keyword "aquaponics" was used to retrieve every publication, from the oldest in 2000 to the newest in 2022, from ScienceDirect (666 publications) and PubMed (104 publications), as shown in Figure 3. It is worth noting that the number of publications retrieved from ScienceDirect (666) is considerably higher than that from PubMed (104), possibly due to ScienceDirect's broader range of scientific disciplines and publication outlets, while PubMed's focus is primarily on biomedical research. Out of the 666 publications on ScienceDirect, 540 were research articles, and 126 were review articles. Between 2016 and 2022, ScienceDirect published 603 research and review articles. The number of publications increased gradually from 2000 (one article) until 2022 (179 articles). Additionally, freshwater aquaponics received more attention in publications than marine aquaponics.

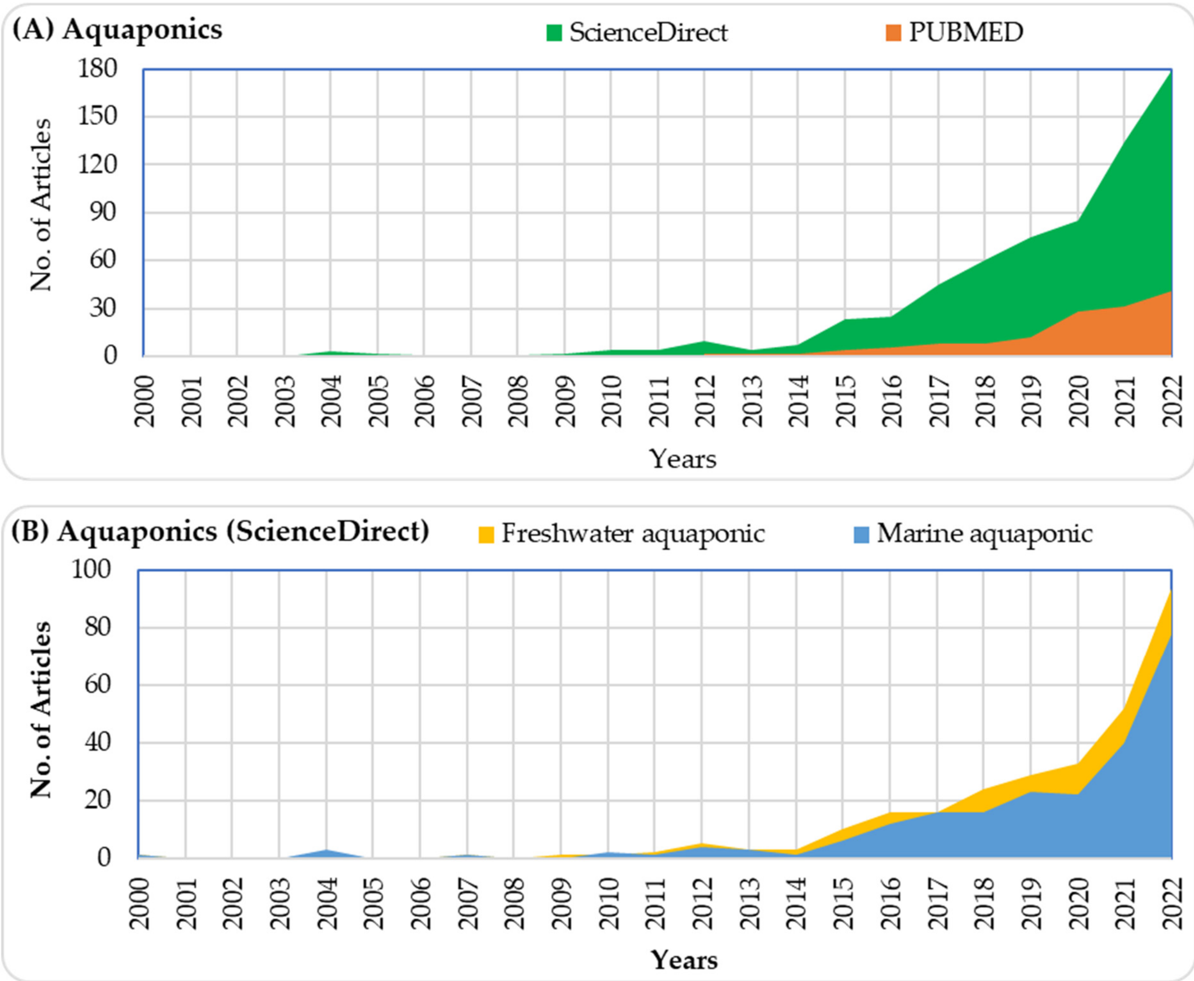

Figure 3. (**A**): Science report for search terms by ScienceDirect, and PubMed. (**B**): Classification of aquaponics environments according to ScienceDirect.

Based on the analysis of the literature review, it appears that the publications retrieved from ScienceDirect are likely to focus on various key topics in the field of aquaponics, including nutrient cycling and water quality management (191 articles), aquaponic system design and construction (157 articles), plant selection and management (110 articles), fish species selection and management (36 articles), business and economic aspects of aquaponics (92 articles), emerging technologies and innovations (74 articles), and education and outreach (12 articles). Furthermore, there seems to be a growing interest in the use of aquaponics as a sustainable and efficient approach to food production, particularly in urban and peri-urban environments. These trends reflect the ongoing efforts to develop and refine aquaponics systems for commercial use, as well as the increasingly acknowledged potential benefits of aquaponics for addressing food security and sustainability challenges.

After this initial screening, 303 articles were thoroughly reviewed for eligibility, with 411 being excluded for various reasons such as not addressing research questions or unavailability of the full text. Ultimately, the VOSviewer analysis included 139 eligible articles from the databases, supplemented by additional cross-references, totaling 176 publications for the analysis. Based on the degree of correlation between the keywords "aquaponics" found in the titles and abstracts of 176 articles, the entire co-existence network can be categorized into three distinct groups or clusters, shown in Figure 4. Cluster 1 (blue) centers around "aquaponics" as the hub, primarily delving into research related to aquaponics technology, productivity, challenges, and sustainability. In Cluster 2 (red), "water quality" and "growth" serve as the central themes. This cluster involves an in-depth exploration on the effect of water quality parameters on growth (fish and plant species) in aquaponics.

Key mechanisms within this cluster include "nitrification", "denitrification", "selection of fish species (oreochromis niloticus tilapia)", "selection of plant species (lettuce and lactuca sativa)", and bacteria. Cluster 3 (green) is predominantly focused on monitoring aquaponics applications through the utilization of IoT (Internet of Things) for dissolved oxygen (DO) and temperature (T). Therefore, the main pillar of this review is aquaponics, revolving around technology, productivity, and sustainability.

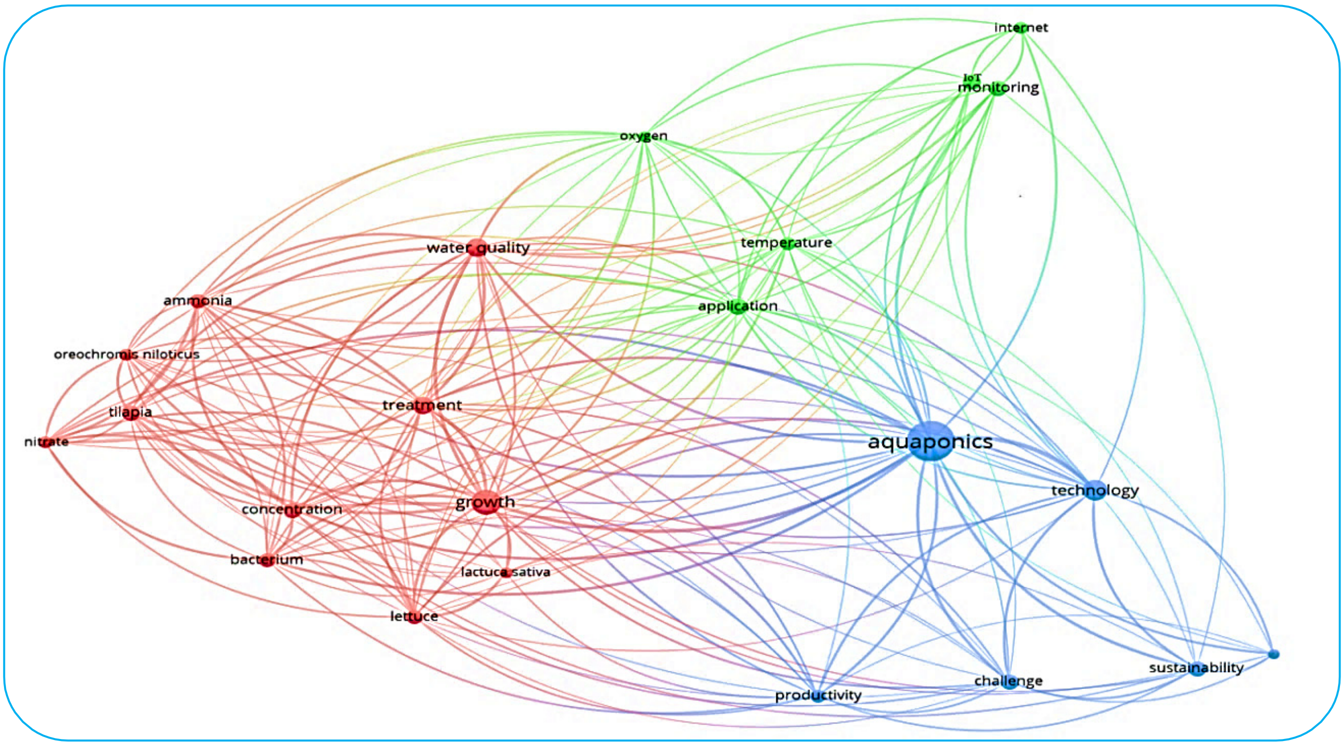

Figure 4. Commonly occurring terms related to "aquaponics" in abstracts and titles of influential publications, sorted into three distinct colored clusters: blue, red, and green.

3. Aquaponics

3.1. Nomenclature in Aquaponics and Legislation

Rakocy [15] explains that aquaponics involves the cultivation of aquatic organisms alongside plant growth without soil. However, to avoid confusion, the term "aquaponics" should specifically refer to hydroponic plant cultivation without any substrate. Lennard [16] proposes a revised definition where the waste generated by feeding aquatic organisms must supply at least 50% of the necessary nutrients for optimal plant growth. This specific approach, known as aquaponics sensu stricto (s.s.), solely utilizes hydroponic methods (aqua-farming techniques without soil or substrates like sand or rock or gravel). Fish production combined with algae production in photobioreactors or separate tanks is now a common feature of integrated systems for aquaculture. Aquaponics sensu lato (s.l.) is employed in both indoor and outdoor substrate aquaponics, incorporating horticultural strategies for growing herbs, cultivating or gardening plants, and conventional soil-based agricultural crop production. This approach leverages the buffer, nutrient storage, and mineralization processes of different substrates.

Aquaponic systems can be broadly classified into four types: open pond, domestic, demonstration, and commercial, each serving different purposes and functions. In modern commercial aquaponics, the three main designs are: one-loop "coupled aquaponic systems (CAS)", two-loop "decoupled aquaponic systems (DAS)" [17], and multiloop decoupled aquaponic systems (DAPSs) [18]. CASs are utilized at various scales, including domestic systems for personal use, social projects like school aquaponics [19], and commercial production exceeding 100 m^2. Open-pond aquaponics encompasses system variations that combine a hydroponic component with free surface waters like lakes or ponds, either on-pond or on land. Domestic aquaponics encompasses all types of systems used for private purposes, ranging from small-scale systems for personal consumption to hobby/backyard systems for home production. Aquaponic demonstration systems are specifically constructed to showcase the food chain in aquaponic production, and are often used in classrooms or workshops. Commercial aquaponics serves diverse purposes such as urban gardening, roof aquaponics, living towers, vertical aquaponics, and small to semi-commercial systems (>50–100 m^2). Larger-scale commercial operations (100–500 m^2 and beyond) trend towards industrialized, highly mechanized production.

Aquaponics, aligning with the UN Sustainable Development Goals, faces hurdles in organic certification due to EU Regulation's strict guidelines [19]. Proposed changes, such as incorporating soil in hydroponic areas and enhancing fish welfare, require collaborative efforts from horticulture, aquaculture, and organics. Despite challenges, the industry garners significant interest, hinting at promising market opportunities. Notably, aquaponics lacks specific inclusion in Europe's agricultural policies [20]. South Africa also lacks dedicated aquaponics policies [21], and in Egypt, aquaponics lacks legal recognition. Certainly, investigating organic certification for aquaponic production is crucial for its acceptance as a healthy and sustainable local food source, even though it may not be a mandatory requirement for the industry to flourish.

To enhance organic aquaponics, revising legislation in line with statutory organic certification standards (as seen in the USA and the EU) is crucial. According to the UK's DEFRA (Department of Food and Rural Affairs), organic farming avoids the use of human-made fertilizers, pesticides, growth regulators, and GMOs (Genetically Modified Organisms), promoting environmentally, socially, and economically sustainable production [22]. Current rules might lack scientific bases and favor existing hierarchies. Embracing innovations like controlled aquaponic greenhouses is environmentally friendly. Certification should adapt to these advances, emphasizing science-based, ethical, and nature-oriented production. To achieve these goals, outlined below are specific policies for organic aquaponics. Proposed policies prioritize environmental, social, and economic sustainability while excluding basic regulations on water quality, organic fish feed, antibiotics, or pesticides.

Crops regulations: Plants can be grown in various hydroponic systems, with soil-based substrates allowed. Fertility in coupled aquaponic systems should come from aquaculture water, while fish waste enhances soil fertility in both coupled and decoupled systems.

Aquaculture regulations: Fish and aquatic organisms must meet welfare standards, considering habitat, diurnal cycles, and environmental stimulation. Tanks should include species-specific enrichments like structures, shelters, or sandy substrates. Local species fitting water parameters should be chosen to reduce the need for artificial heating or cooling. Regular checks for distress signs are essential.

Systems regulations: Organic aquaponic systems must primarily rely on fish water and waste for nutrients. Any additions, like seaweed extracts, must be organic and sustainable. Coupled systems should avoid substances harmful to fish health. The use of alternative energy systems and water harvesting is encouraged, especially in water-deficient areas.

3.2. Aquaponic Systems Development

Coupled aquaponic systems (CASs) operate as single continuous loops, with water flowing in a single direction or towards an outlet in each tank [23], shown in Figure 5. In contrast, decoupled aquaponic systems (DASs) have two separate loops between which solutions can flow [24], shown in Figure 5. This allows for greater control over water parameters in the hydroponic portion without affecting the aquaculture portion, resulting in superior filtration and better manipulation of nutrient concentrations and pH level [25,26]. Nutrient supplementation can enhance plant quality and reduce the risk of nutrient deficiencies [27]. Double recirculation aquaponic systems (DRAPSs) optimize fish production while allowing for dynamic adjustments in nutrient concentrations and pH levels [28], shown in Figure 5.

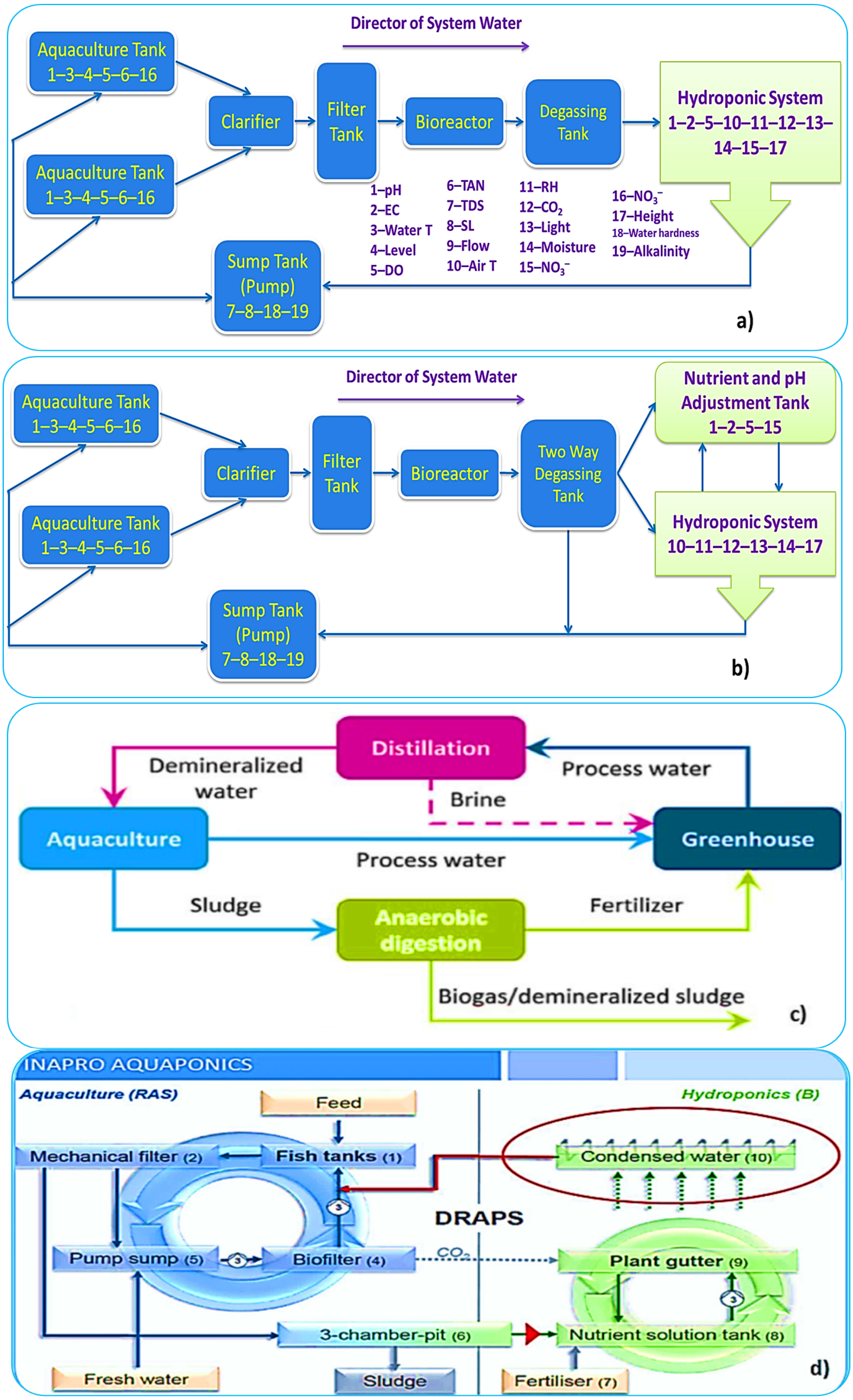

Figure 5. (**a**): The CAS represents a coupled aquaponic system, and (**b**): the DAS illustrates a decoupled aquaponic system. Both CAS and DAS designs were introduced by Palm et al. [23] and Kloas et al. [24]. (**c**): Decoupled (multiloop) aquaponics (DAPS), adapted from Goddek et al. [20]. (**d**): Concept of the double recirculation aquaponics system (DRAPS) [25,28]. The numbers (1–19) in (**a**,**b**) indicate the sensor locations.

Decoupled multiloop aquaponics systems (DAPSs) separate the RASs and hydroponic units, providing inherent benefits for both plants and fish [24,29], shown in Figure 5. CASs are popular due to their ease of setup and adaptability, while DAS and multiloop systems can be more efficient but require more expertise and management. Examples of CASs include UVI aquaponics and the Integrated Aqua-Vegeculture System [23,24,30–32], with varying systems described in Table 1 [33–38]. Aquaponics technology is constantly evolving, with a current focus on enhancing the effectiveness of decoupled multiloop aquaponic systems [30,31,38–43], as indicated in Table 1.

Table 1. The historical development of aquaponic systems.

Main Finding	Reference
The initial instance of a DAS was introduced in Germany.	[33]
In the DAS, plants favor a hydroponic (water) root zone pH of 5.8–6.2, whilst a pH of 6.5–9.0 is suitable for most aquatic organisms (USA).	[34]
The inaugural documented DAS emerged in 2015 from the "Leibniz Institute of Freshwater Ecology and Inland Fisheries, Berlin, Germany"—the system has been named aquaponics for tomato and fish free from emissions.	[35]
Various hydroponic components were added to change their system from a CAS to a DAS. The benefit of utilizing various hydroponic components is to expand water quality stability and increase the versatility for cultivating and comparing various crop types.	[36]
Various up-to-date DASs have been reported in Europe, including the Tilamur, IGB, and Inagro facilities. Among them, the NerBreen facility in Spain boasts an impressive area of 3500 m^2. While it seems that aquaponics is gaining momentum with DASs, particularly in Europe, there are certain disadvantages associated with this system when compared to the CAS. The primary challenge faced by the DAS is the significant upfront construction costs involved.	[37]
The re-mineralization and desalination loops were inserted in the design of DAS, whilst the nutrient loop was closed. The technical solution of the DAS involves a separate hydroponics section and aquaculture section, each optimized to provide specific benefits for plants and fish, respectively. This segregation allows for targeted management of the environment, promoting optimal growth and health for both components of the system.	[31,37]
DRAPSs combine a hydroponic system (HS) and a Recirculating Aquaculture System (RAS) in a one-way setup with separate water circuits (multiple loops). This approach optimizes the RAS for fish production, ensuring animal welfare, while enabling the hydroponic system to regulate pH and adjust nutrient concentrations dynamically, creating an ideal environment for plant growth.	[28,36]
DAPSs present greater potential for incorporation with renewable energy technologies.	[29]
The double (dual) recirculation technology facilitates the establishment of ideal conditions for both fish and plants.	[38]

Nevertheless, a significant hurdle in modern aquaponics is the high cost and complexity of devices such as the DAS, DAPS, and DRAPS, along with their maintenance requirements. Decoupled multiloop systems have more loops and components, which necessitate greater monitoring to ensure optimal performance. Additionally, scaling up these systems can be difficult as their complexity increases with size, which limits their potential for large-scale commercial production. Growers must evaluate the costs and technical requirements of these systems carefully before deciding whether they are suitable for their operations.

3.3. Recirculating Aquaculture Systems (RASs)

The RAS is crucial for land-based fish production in aquaponic systems and for rearing aquatic animals such as shellfish, crabs, and shrimp [41], shown in Figure 5. RASs employ mechanical and biological filtration, gas exchange, and production tanks to cultivate fish. Mechanical filtration eliminates solid waste, while beneficial bacteria convert toxic ammonia into nitrate. Oxygenation and carbon dioxide removal are performed before water recirculation. By employing mechanical filtration, water quality can be improved by up to 85% [44], and waste removal can be enhanced by increasing the recirculation rate [45]. Biofilters consisting of media-filled strata replace the need for biological filters.

The RAS significantly reduces water exchange by 90–99% and occupies less than 1% of the space required by conventional aquaculture [46]. Table 2 summarizes the historical development of the RAS worldwide [47–54]. Compared to traditional aquaculture, the RAS reduces water exchange by 90–99% and occupies less than 1% of the area [55]. Daily water consumption varies from 250% for extensive aquaculture to less than 1% for the RAS [23,56].

Table 2. The historical advancement of RASs (Recirculating Aquaculture Systems) around the globe.

Time Period	Key Developments	Reference
1950s	Initial research on RASs (Recirculating Aquaculture Systems) conducted in Japan	[47]
1970s	The foundation of modern RASs laid through German programs focused on intensive carp production, along with developments in Australia	[48]
Mid-1970s	Denmark nurtured the first commercial idea for a RAS as a means for commercial fish production	[49]
1980	Denmark witnessed the establishment of the first commercial RAS for European eel production	
Early 1980s	The Netherlands adopted the RAS design and innovation for catfish production, while North America initiated innovative work on RASs	[50,51]
1980s	China ventured into marine RAS development	[52]
1980–1990s	Ongoing improvements in RASs were observed in various European countries such as Denmark, Iceland, Norway, and Finland	[53]
2000–2020	Continuous advancements in RASs were witnessed in Australia, Europe, and North America	[54]

3.4. Hydroponic Components

Hydroponics is a soilless agricultural technique utilizing a nutrient-rich solution for crop cultivation. It can be implemented as a closed or open system [57]. Among hydroponic methods, the NFT (nutrient film technique) system yields lower lettuce and nitrate elimination compared to clutter DWC (deep water culture) [58]. A review by Maucieri et al. [59] highlights that the NFT in hydroponics has a comparatively lower success rate and representation in research compared to media culture and DWC systems in aquaponics. NFT systems also have limited surface area for beneficial microbes, necessitating the use of a biofilter.

Media beds provide an ample surface area for nitrifying bacteria growth and function as physical filters, eliminating the need for a separate biofilter [56]. However, Pattillo [60] noted that the maintenance cost of media bed culture is a significant drawback. Sediment accumulation disrupts water flow, resulting in uneven fertilization and the formation of anaerobic zones. Media bed culture is more suitable for smaller-scale aquaponic operations, while low-maintenance hydroponic components like DWC are better suited for larger-scale projects [23].

Studies indicate that DWC systems have a lower environmental impact compared to media culture systems, despite their higher water demand [61]. DWC systems exhibit improved water use efficiency (WUE) [58], with Love et al. [62] having found that they use only 1% of their water daily. Silva et al. [63] observed a 10.3% reduction in energy costs in a small-scale DWC system, resulting in an 11% decrease in total electrical costs for the growth cycle of pak choi over 32 days. Schmautz et al. [35] reported comparable yields in NFT (17.5 kg/m^2) and DWC (17.4 kg/m^2) systems, slightly lower than drip irrigation (18.7 kg/m^2), for tomatoes. Khandaker et al. [64] investigated hydroponic towers in aquaponics, assessing different substrates for tower cultivation. In conclusion, media beds suit small-scale and research-based aquaponic systems by fostering diverse plant growth and eliminating the need for an additional separate biofilter. Meanwhile, DWC systems are well-suited for commercial applications due to their minimal environmental impact and improved root–water contact.

4. Aquaponics Systems Performance

The evaluation of aquaponics systems involves assessing several aspects, including fish and plant growth, water quality, consumption rates, nitrification, and the presence of specific bacteria, such as assessing ammonium and nitrate concentrations, as well as microflora.

4.1. Fish Species, Feed, and Growth Indicators

Aquatic organisms tolerant of high population densities and elevated levels of TN, TP, TSS, and potassium are crucial for productive aquaponic systems [34]. Species capable of thriving near densities of 0.06 kg/L are suitable, while fish above this threshold should not be stored [65]. Nile tilapia are widely used and considered excellent for aquaponics due to their adaptability, followed by carp and African catfish [66,67]. Nile tilapia can tolerate high TSS and nitrite levels up to 4.67 mg/L and survive at dissolved oxygen levels of 0.5–1.0 mg/L, allowing for higher stocking densities to meet plant nutrient requirements [68]. In a comparative analysis, Palm et al. [69] found that the Nile tilapia system yielded more lettuce, basil, and cucumber than the African catfish system. Effluent from African catfish, Nile tilapia, and common carp contained nitrate and phosphorus at values fluctuated between 20 mg/L and 42.9 mg/L and 8.2 mg/L and 17 mg/L, respectively [70]. Knaus and Palm [71] showed that using common carp effluent wastewater boosted cucumber yields, while tilapia wastewater increased tomato yields. These findings suggest that tilapia released more feces (nutrients) into the water.

Fish feed constitutes 70% of aquaculture costs, but only 20–30% of the nitrogen (N) content is consumed by fish, while 70–80% is released into the water as waste or utilized in aquaponics [72,73]. Fish meal, despite being rich in amino acids and phosphorus, lacks essential micronutrients and potassium for plant growth [74]. Polyculture, involving different aquatic species, shows potential for enhancing plant growth in aquaponics but requires further research [46,75,76]. The impacts of excretion from different fish species on nutrient levels in aquaponic solutions and plant yields remain uncertain. Exploring alternative fish feeds that generate wastewater with higher levels of potassium (K) and magnesium (Mg) and maximizing nutrient conversion into plant biomass requires additional investigation.

4.2. Plant Species, Nutrients, Growth, and Indexes

Leafy vegetables are ideal for aquaponics due to their fast growth, short growth period, low nutrient demands, and nitrogen tolerance [77]. Commonly grown crops include basil, herbs, tomatoes, lettuce, salad greens, chard, pepper, kale, and cucumbers, chosen based on fish density and nutrient levels [46,62,76]. Nutrient absorption varies throughout plant growth stages, with an optimal uptake of P, K^+, S, Ca^{2+}, and Mg^{2+} at pHs from 6.0–8.0. Other nutrients like Fe^{2+}, Mn^{2+}, B^{3+}, Cu^{2+}, and Zn^{2+} are best absorbed at a pH below 6.0 [78]. Leafy greens require higher nitrate levels than fruiting vegetables, and larger root areas enhance nitrate absorption. Flowering crops are more valuable but have greater nutrient needs and longer growth cycles, posing challenges in aquaponics [79].

Combining a trout farm with a NFT culture for lettuce and basil can yield a 12.5% ROI and lower water remediation costs [80]. Leafy greens and herbs are popular due to their year-round availability and restaurant demand [71,73]. Li et al. [75] considered plant number, height, fresh weight, and fish-to-plant ratios to estimate FCR and SGR. Researchers have analyzed plant yields, leaf nutrient content, and plant quality indexes to assess productivity [81–83], while others have incorporated microalgae bacteria to increase nitrogen use efficiency and reduce N_2O emissions [84]. Leaf quality is assessed visually using a 1–4 scale for color, known as the PQI [78,79,84]. Leaf yellowing may result from nutrient deficiencies or inadequate fish feed. Aquaponics productivity is evaluated through plant, water, and fish performance, while increased yields are measured by assessing biomass growth in plants and fish [59,78,85].

More research is needed to explore the aquaponic cultivation of flowering plants and assess their nutritional content and effectiveness in floriculture. Limited information is available on the estimation of vitamins, lipids, ash, protein, moisture, and ash matter in aquaponically grown flowering plants. Lettuce's nutritional content is well documented [62]. Future studies should investigate aquaponics' viability for floriculture and determine the necessary nutrient content for optimal growth.

4.3. Nitrifying Bacteria and Microflora

Aquaponics involves nitrification, converting TAN to nitrites and nitrates through two steps [86], shown in Figure 6. Ammonia-oxidizing bacteria (AOB) and nitrate-oxidizing bacteria (NOB) facilitate this process. TAN is produced by fish through their waste and gills [44]. AOB use TAN as an energy source, while plants prefer NH_4^+. Nitrosomonas bacteria transform ammonia to nitrite, while Nitrobacter bacteria convert nitrite to nitrate [78]. Nitrite, a byproduct of ammonia processed by AOB, poses a threat to aquatic life when it exceeds 0–1 mg/L. Maintaining nitrite levels within this range is crucial for the well-being of fish, plants, and bacteria. Nitrates, generated through NOB's nitrification process, serve as a nitrogen source for plants and are fish-safe when kept below 90 mg/L. To ensure proper biofilter design, maintaining levels between 50 and 100 ppm is recommended.

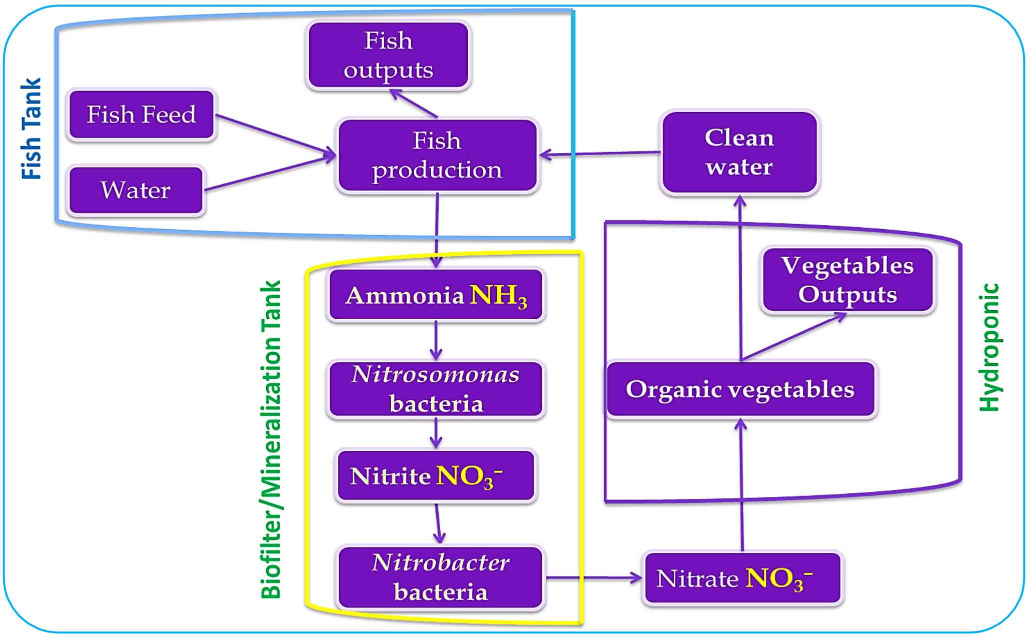

Figure 6. Nitrification process during a time period spent in three main aquaponic systems.

Optimal nitrification conditions include temperatures of 25–30 °C, pH levels of 7–9, and oxygen levels below 20 mg/L [65]. Nitrates should be within the safe range of 150–300 mg/L [26]. Nitrospira, Nitrobacter, and Nitrosomonas are the primary nitrifying bacteria, and microalgae can reduce ammonia levels [87–89]. Fish retain only 20–30% of nitrogen from their feed, releasing 70–80% into the water [26,44]. Plants utilize only 10–37% of this released nitrogen, with the rest lost. Studying Nitrospira strains in aquaponics biofilters can improve Nutrient Use Efficiency (NUE) [26,44,73,90]. Biofilms and interactions between nitrifying bacteria and other organisms enhance nutrient availability for plants [34]. Aquaponics' NUE ranges from 34.4% to 46.6%, comparable to or lower than conventional agriculture [80]. Enhancing NUE can improve aquaponics efficiency, but nutrient availability for plant absorption remains a challenge.

Exploring "plant growth-promoting microorganisms (PGPM)" in aquaponics offers opportunities. PGPMs, like Pseudomonas, Bacillus, Enterobacter, Streptomyces, Gliocladium, or Trichoderma, enhance nutrient uptake by plants [91]. Aquaponics reduces waterborne diseases through biofilters with Rhizobiales and Actinobacteria, while roots contain Burkholderiales, Flavobacteriales, and Pseudomonadales for disease protection. Adding nitrifying bacteria like B103 (BIOZYM, USA) enhances aquaponics.

4.4. Water Quality, Consumption, and Use Efficiency in Aquaponics

Aquaponics is a sustainable farming method that conserves freshwater and promotes water stress alleviation [92,93]. Maintaining appropriate water chemistry parameters is critical for system stability and the well-being of plants and fish. Factors such as pH, dissolved oxygen levels, temperature, and nutrient concentrations require vigilant monitoring and control. pH affects nutrient availability and microbial activity, while dissolved oxygen is vital for the respiration of both fish and beneficial bacteria. Temperature influences metabolic rates and the efficiency of biological processes. Water quality is crucial, monitored using sensors for DO, pH, and temperature [86]. Weekly water samples are collected and analyzed for nutrients and minerals [26,87,94,95]. Optimum conditions for fish and plant growth are determined through environmental and physicochemical parameters as depicted in Table 3 [86,96–98].

Furthermore, water quality management is essential in preventing the accumulation of harmful substances and maintaining a healthy environment. Regular monitoring of parameters such as ammonia, nitrite, nitrate, dissolved solids, and trace elements is necessary to detect imbalances and take corrective actions promptly. Research focuses on improving fish and cash yields, considering the initial capital cost [96–98]. Geographical location affects optimal parameter ranges [99]. Aquaponics using RASs is suitable for arid areas with water shortages [100]. Microbial systems can reduce waste and improve water quality [75].

Table 3. Quality ranges for the parameters of water and impacts in aquaponics systems.

Parameter	Aquaculture	Nitrification	Hydroponic	Impacts	References
pH	6.5–9.5	7.0–9.0	4.5–7.0	At low pH levels, reduced plant reproduction, root injury, and nutrient deficiencies occur, while at high pH levels, plants experience nutrient deficiencies and potential ammonia buildup.	[96]
Temperature	5–32 °C	17–34 °C	18–30 °C	Risk of fish diseases increases at both low and high levels of temperature.	[86]
Water level	1000 L/20 kg	-	-	Fish stress leading to health issues at low levels; plant nutrient inadequacies at high levels.	
Dissolved oxygen	4–5 mg/L	4–8 mg/L	>3 mg/L	At lower levels, occurrences include fungal growth, cessation of fish feeding, interrupted nitrification processes, and root death.	
Total ammonia–nitrogen	0–2 mg/L	<3 mg/L	<30 mg/L	At lower levels, there are no specified impacts, while at higher levels, toxicity to fish and detrimental health effects occur.	
Nitrates	50–100 ppm	-	-	At lower levels, plants may face nutrient deficiencies, whereas at higher levels, the concentration becomes harmful for fish.	
Flow	-	-	1–2 L/min	At lower levels, there is a reduction in nutrient accessibility, while no specific impacts are listed at higher levels.	
Air temperature	-	-	18–30 °C	At lower levels, there is incorrect crop transpiration, premature flowering, and decreased water efficiency. At higher levels, there is an alteration in the chemical composition of plants.	

Table 3. *Cont.*

Parameter	Aquaculture	Nitrification	Hydroponic	Impacts	References
EC	100–2000 mS/cm	-	-	At lower levels, there is nutrient loss and unbalanced systems, while at higher levels, it leads to water pollution and potential fish fatalities.	[97]
Water hardness	50–150 mg/L$CaCO_3$	-	-	At lower levels, fish experience stress, while at higher levels, there are elevated pH, reduced nitrification, and decreased nutrient uptake.	
Alkalinity as $CaCO_3$	50–150 mg/L	-	-	At lower levels, there are poor water conditions, inadequate acid neutralization, and a risk of high pH. At higher levels, there is ammonia toxicity leading to fish respiratory issues.	
Nitrites	0–1 mg/L	0–1 mg/L	0–1 mg/L	Detrimental effects are observed for fish, plants, and bacterial activity at both low and high levels.	
Relative humidity	-	-	50–80%	Curled and dry leaves along with mold growth are observed at lower levels, while at higher levels, there is a potential for plant organisms due to water scarcity.	[98]
CO_2	-	-	340–1300 ppm	At lower levels, plant photosynthesis is reduced, while at higher levels, there is an alteration in the chemical composition of plant tissues.	

Water use in aquaponics is influenced by factors like fish sludge removal, evaporation, evapotranspiration, and fish feeding, shown in Table 4 [60,101–113]. Total water usage includes mechanical pumping, rainfall, and runoff, while water consumption is the amount reduced due to discharge, evaporation, and seepage losses [27,114]. In aquaponics, water consumption varies, ranging from 0.05% to 5% in floating systems and from 1.2% to 41% in medium-based systems like gravel beds [51,115,116]. The type of hydroponics does not significantly impact water loss [117].

Table 4. Characteristics of aquaponics and water consumption per day.

Hydroponic Type	Fish Species	Plant Species	Water Flow	Water T (°C)	Water Consumption (%)	Reference
Floating *	*O. niloticus*	*I. aquatica/ water spinach*	Constant	27.4–27.5	1.40	[101]
					1.50	
				26.1–26.3	1.60	[102]
		L. esculentum		26.0–26.2	2.20	[26]
		B. ampestris L. subsp. *Chinensis*			0.70	
	Oreochromis spp.	*O. basilicum/Basil*		26.5–27.9	2.40	[79]
		A. esculentus			0.36	[103]
	O. niloticus, O. aureus	*Crop succession* for 2 years		>22	1.00	[66]
	Oreochromis sp.	*I. aquatica*	Root in fish tank	25.4–29.6	0.10	[104]
	M.s anguillicandatus	*A. nidus*				[105]

Table 4. *Cont.*

Hydroponic Type	Fish Species	Plant Species	Water Flow	Water T (°C)	Water Consumption (%)	Reference
Medium-based *	*M. peelii peelii*	*L. sativa*	Reciprocal	22.0	2.43–2.86	[106]
	C. carpio var. koi	*B. vulgaris var. bengalensis*	Constant	22.0–26.9	4.00	[107]
	C. carpio	*B. chinensis*			1.20–1.80	[46–90]
	M. peelii peelii	*L. sativa*			1.83	[58]
	T. mossambicus x 0. niloticus	*L. esculentum, C.sativus*		>25	2.80	[108]
	Tilapia mossambicus x 0.	*niloticus L. esculentum*			2.08	[117]
					2.42	
					2.84	
					3.89	
NFT *	*O. niloticus*	*L. esculentum*	Constant	22.0–29.1	3.83	[24]
		C. sativus			0.90	[109]
		L. sativa			1.40	[110]
	M. peelii peelii				1.97	[58]

*: The hydroponic-to-fish ratio ranges from 1.3–8.7, 2.1–7.0, and 0.9–3.83 for floating, medium-based, and NFT types, respectively.

Aquaponics achieves a WUE of approximately 90% compared to conventional agriculture [27,62,116]. In the Northern Nile Delta, conventional agriculture has a WUE range of 0.29 kg/m^3 to 13.79 kg/m^3 for winter crops, 3.40–10.69 kg/m^3 for winter vegetables, 0.29–6.04 kg/m^3 for summer crops, 2.38–7.65 kg/m^3 for summer vegetables, and 1.00–5.38 kg/m^3 for autumn season crops [117]. Delaide et al. [27] found that 0.49 cubic meters of water were needed to produce 1 kg of vegetables and 0.878 kg of Nile tilapia fish over 30 days, while Love et al. [62] reported a need for 0.40 cubic meters of water. In the comparison conducted by Lefers et al. [116], freshwater usage per kg of vegetables produced in the field was compared to that in an aquaponics system installed in a seawater-cooled CEA system, revealing that the CEA system saved around 90% of freshwater.

5. Technology

Automation technology plays a significant role in maintaining optimal water chemistry conditions. Automated systems can monitor and adjust parameters in real time, ensuring stable and precise control. This reduces the risk of human error and enables efficient resource management. In the 1970s, advancements such as robotics, IT, embedded systems, and software engineering were combined with aquaponics to create a more precise farming method, known as aquaponics 3.0 [118–127]. Towards the end of 2016, research began to incorporate Industry 4.0 concepts into aquaponics, giving rise to aquaponics 4.0—a digital farming approach involving remote monitoring, extensive automation, and smart decision making for optimal crop yield and quality [125]. Industry 4.0's evolution has significantly revolutionized efficiency and automation in farming. Digital twin technology, replicating plant production lines virtually, stands as a notable advancement, enhancing overall system performance. Table 5 illustrates how smart systems aim to leverage cutting-edge information, collection, and computing technologies for production improvement [118–124]. Industry 4.0 technologies applied in aquaponics are described in the subsequent sections. Achieving this advanced digitization demands smooth data integration, a seamless information flow, and effective knowledge management. This allows the system to adjust and learn from past experiences, enabling it to adapt to diverse situations.

Table 5. Summary for different control degrees for the aquaponic systems.

Control	Technique or Method	Component	Time of Data Measurement	Data Acquisition	Control Unit	Effect	Reference
Smart monitoring and control system for aquaponics	OpenWRT and WRT nodes for data acquisition, mobile exchange, and interactive intelligence		Collect constant natural information	The system measures temperature, light, water level, oxygen, *E. coli* levels, and humidity	Components such as water pumps, air pumps, lamps, and feeding devices are controlled by a central unit	The system allows remote observation, monitoring, and control of the aquaponics system, enabling collaboration between humans and machines.	[118]
	pH and water temperature are monitored and controlled through a web socket		Measurements are taken in the morning and afternoon for water temperature, pH, and level		The lights, water pumps, lamps, and fan	The system is designed to control more devices and monitor more parameters. IoT enables automatic water supply and fish food feeding.	[119]
	Internet of Things (IoT)	Automatic water supply; automatic fish food feeder	The water level is put away at fixed time periods in the monitoring	Temperature, water level, and moisture content	Oxygen pump, fish feeder; water pump and LED light	Aquaponics provides a cost-effective and water-efficient solution for vegetable production.	[120]
	Source node; sink; database server; visualization on mobile application	Data are collected using ultrasonic, temperature, pH, and ammonia gas sensors	Automatic control of the component's parameter with mobile application	The control unit manages parameters such as pH, temperature, ammonia gas levels, and water depth	Coolant, heater, control motor (for H_3PO_4 and KOH), fish feed actuator, and ammonia warning procedure	Controlled NFT aquaponic systems optimize vegetable growth compared to NFT hydroponics.	[121]
	Fuzzy logic is employed with Arduino Uno, fuzz inference system, and relay control		Data are measured every 25 s for water, pH, luminance, and air/water temperature		Components include lights, heaters, and alarms	The system is accurate, low-maintenance, low-cost, and convenient.	[122]
	Arduino (Mega)	-		Water level; temperature; amount of food	Pump; feeder; dimmer	An Arduino Mega is used for a closed-control system, effectively maintaining fish health and promoting plant growth.	[123,124]

5.1. Smart Aquaponic Systems

Smart systems in aquaponics use machine learning to predict and optimize parameters. For example, (1) predictive analytics software [125] can optimize fish feed rates, and sensors can predict and prevent disease outbreaks. (2) Autonomous wireless aquaponics uses regression techniques to make smart decisions based on sensed parameters. (3) "Convolutional Neural Networks (CNNs)" are used to assess crop quality and growth rate [128]. They can recognize patterns and features indicative of high-quality crops and help farmers optimize crop productivity for improved profitability and sustainability. In summary, parameters prediction, developing an autonomous wireless aquaponics system, and quality and growth rate are all important aspects of smart aquaponics. Still, they represent different areas of focus that are all important for optimizing the performance of the system.

5.2. Internet of Things (IoT) Systems

IoT systems can monitor and control aquaponics remotely, using sensor-based, actuator-based, or hybrid systems. Remote monitoring and control, as well as wireless sensors, are crucial elements of IoT in aquaponics. Remote monitoring allows farmers to track water quality, temperature, and nutrient levels, while remote control enables them to adjust settings like water flow rates, lighting, and temperature [93,125,129,130]. Wireless sensors collect data on multiple parameters and can detect issues before they become serious problems [131,132]. By combining these components, farmers can optimize their aquaponics systems, improving efficiency and productivity. Odema et al. [93] developed sensor-based modules enabling real-time data collection for informed decision making and remote control of aquaponics systems [118], showcasing a remote ChlF sensor that optimizes artificial lighting for improved energy efficiency and crop growth [118,119]. In Sub-Saharan Africa, the integration of an IoT water quality sensor system with local farms has doubled fish length prediction accuracy and enabled the achievement of a 99% accuracy rate for fish weight prediction in a mobile aquaponics system, significantly enhancing efficiency and management [133]. Nayak et al. [134] explore Ag-IoT (IoT-based agriculture) applications, utilizing WSN, RFID, cloud technology, and end-user apps to offer automated, cost-effective solutions for monitoring irrigation, soil, weather, disease control, and smart farming applications such as those involving cattle, poultry, aquaponics, and beehive monitoring, benefiting farmers. In summary, remote monitoring, remote control, and wireless sensors are all important components of IoT in aquaponics. Remote monitoring allows for real-time tracking of important parameters, remote control allows for remote adjustment of system settings, and wireless sensors allow for real-time data collection and analysis. Together, these components can help farmers to optimize their aquaponics systems and improve efficiency and productivity.

5.3. Big Data

Big data significantly enhances aquaponics, enabling data-driven decisions [38]. Sensors collect diverse data on water quality, nutrients, environment, and crop/fish health. Analyzing these data uncovers trends, optimizing systems for efficiency, productivity, and sustainability. It aids in predictive modeling, disease detection, and overall management, advancing modern aquaponics [38,135,136]. It optimizes fish quality, water conditions, and predicts plant outcomes while analyzing sensor data for fish health, ensuring quality and timely interventions [136]. Algorithms monitor water parameters, maintaining stable conditions and preventing contamination. Predictive analysis forecasts plant growth, aiding cultivation decisions for consistent production. This integration boosts efficiency and offers sustainable insights for aquaponic ecosystems [135].

5.4. Artificial Intelligence (AI)

AI, employing machine learning and neural networks, analyzes sensor data in aquaponics, optimizing water quality, crop growth, and fish health [137]. It drives data-driven decisions, enhancing efficiency and resource use. AI aids in predictive modeling, disease detection, and system management, boosting productivity and sustainability. It optimizes fish quality and water conditions and predicts plant outcomes while estimating maturity levels [135,137]. Analyzing sensor data, AI guides optimal harvest and breeding times for fish and aids decisions on crop harvest cycles and rotations based on plant growth stages and nutrient absorption. In a previous study by Abbasi et al. [135], they developed the "AquaONT" ontology model using semantic technologies. This comprehensive model contains data about different diseases, detailing their causes and treatments. It is integrated with a disease detection system through an interface on a cloud-based application. This AI-driven maturity estimation enhances decision making, ensuring timely actions for sustainable aquaponic success. Digital technologies used in fish farming encompass AI, big data analytics, and blockchain for data collection and analysis [138]. Web-based apps offer real-time sensor data visualization, alerts, and remote water pump control [139]. Additionally, machine learning algorithms, such as logistic regression, predict fish disease by analyzing IoT water quality data [140].

Finally, the integration of Industry 4.0 tech into aquaponics faces hurdles like complex systems integration and data management due to extensive sensor-generated data. The high initial cost of technology acquisition and the need for specialized expertise also pose challenges. Standardizing diverse technologies for compatibility remains critical. Overcoming these hurdles requires ongoing innovation tailored for aquaponics, promising more efficient and sustainable agricultural practices.

6. Economic Feasibility, Energy Consumption, and Benefits

6.1. Economic Feasibility

An aquaponic farm with a 76 m^3 tilapia fish tank and a 1142 m^2 DWC lettuce plant growth bed (LPGB) has an initial venture cost of USD 217,078 [141]. Small UVI systems cost USD 285,134, while large UVI systems cost USD 1,030,536 for aquaponic foundations [142]. The annual net revenues of smaller systems range from USD 4222 to USD 30,761, with IRR and MIRR rates varying from 0 percent to 27 percent [142]. The UVI system [77], with a growing area of 214 m^2, could generate USD 110,000 per year by selling only basil, whereas the revenue from selling okra would be only USD 6400. Basil had the highest value per kg (USD 8.80–11.03), and Boston lettuce generated more income per week per m^2 (USD 7.50–9.20) than basil (USD 3.96–4.96) due to higher returns and higher planting density. Not all fruit crops, such as melon, zucchini, and cucumber, had a weekly income per m^2 above USD 1.32. Morgenstern [143] found that a small-sized aquaponic farm with a 3 m^3 European catfish fish tank and a 59 m^2 DWC LPGB would require an initial investment cost of EUR 151,468. A medium-sized aquaponic farm with a 10 m^3 European catfish fish tank and a 195 m^2 DWC LPGB would have an initial investment cost of EUR 304,570. A commercial-scale aquaponic farm with a 300 m^3 European catfish fish tank and a 5568 m^2 DWC LPGB would have an initial investment cost of EUR 3,705,371. According to Lobillo-Eguíbar [144], aquaponic infrastructure costs range from EUR 2266.27 to EUR 2252.13 for two small-scale aquaponics systems, generating a family farm income per FWU (family work unit) of EUR 3090.41 and EUR 153.50. A total of 62 kg of tilapia and 352 kg of 22 distinct vegetables and fruits were produced, with a typical net farming value-add of EUR 151.3 and EUR 91.34. The results showed positive accounting benefits and negative economic profit when labor costs were included. The level of commoditization was around 44%, allowing for some specific independence. A study conducted in Egypt [145] found that the total capital expenditure (CAPEX) and operational expenditure (OPEX) for the first year per square meter in aquaponics amounted to EGP 469/m^2. This cost was deemed relatively high when compared to land reclamation for the same area (aquaponics farm located on a 400 m^2 area along the Cairo Alex desert road in Egypt). Delaide et al. [78] argued that suboptimal environments in the aquaculture and hydroponic subsystems result in lower yields that are not compensated for by savings on fertilizer to support plant growth. According to Rupasinghe and Kennedy [112], an aquaponics farm that grew lettuce and barramundi had a higher annual economic return of USD 22,800 compared to the two independent systems. Over the course of a year, the aquaponic farm saved USD 3391 on total variable expenses, USD 1269 on effluent removal, and USD 1320 on nitrogen and phosphorus fertilizer.

Location plays a crucial role in the profitability of aquaponic projects, with acquiring land at low costs contributing to cost savings [146,147]. Setting up the system near urban and peri-urban areas reduces transportation costs to markets, resulting in lower emissions of fossil fuels and a smaller carbon dioxide (CO_2) footprint. Ultimately, the economic feasibility of aquaponic technologies is a crucial consideration for their widespread adoption.

6.2. Energy Consumption

Energy consumption in aquaponics systems holds immense significance due to its pivotal role in ensuring system functionality and the well-being of aquatic organisms and plants. As per studies, aquaponic systems in the Midwest and Arkansas reflect annual energy costs ranging from USD 5991.06 to USD 7337.04 within total operating expenses [115]. Notably, heating constitutes nearly 50% of these costs, albeit subject to significant variability based on farm location [146,147]. Conversely, lighting costs are comparatively lower and can potentially decrease, especially through rooftop farming, which particularly suits densely populated urban settings. Aquaponics systems incur energy expenses stemming from various sources such as lighting, water filtration, and circulation and temperature regulation.

LED lighting stands out in aquaponics for its superior energy efficiency and plant growth promotion compared to other options. Studies highlight LEDs for higher yields, energy savings, and environmental benefits, making them ideal for large-scale aquaponic setups [148–150]. Tailored LED treatments have been effective in enhancing plant growth, improving energy efficiency, and boosting specific plant characteristics [151]. Studies note that specific LED combinations, like far-red light in red plus blue LEDs, significantly enhance plant growth in lettuce [152,153]. Optimizing artificial lighting parameters like DLI (daily light integral) and PPFD (photosynthetic photon flux density) play a crucial role in enhancing plant growth and yield [154–156]. Utilizing controlled switching frequencies to shift lighting into pulsed modes significantly improves energy efficiency in aquaponics. These customized "light recipes" yield substantial energy savings compared to continuous lighting while maintaining plant characteristics [157,158]. In the realm of smart agriculture, real-time monitoring through sensors and IoT devices in aquaponics aims to optimize energy usage and enable automation. Tailoring LEDs to plant needs—considering types, wavelengths, schedules, and intensity—can slash energy use by 75% [158]. This innovation in aquaponics holds promise to bridge economic and environmental sustainability gaps by enhancing efficiency. Yet, challenges like interoperability, costs, and security must be addressed for broader commercial adoption.

The continuous circulation of water is fundamental to aquaponic systems, facilitating the distribution of nutrients essential for plant growth and maintaining optimal conditions for aquatic life. Goddek et al. [11] underscore energy-intensive issues in aquaponics, particularly within indoor systems that consume significant electrical and heating energy, while also emphasizing challenges in nutrient recycling, pathogen control, and supply chain management. However, the operation of pumps required for this circulation demands a significant amount of energy. The need for a consistent and uninterrupted flow of water throughout various system components contributes substantially to overall energy consumption. Energy-efficient pumps reduce your environmental footprint and save you money on energy costs in the long run. In an aquaponics system, where the water pump runs continuously, the impact of energy efficiency is significant. Efficient pumps consume less electricity while delivering the required flow rate, helping you achieve a more sustainable and cost-effective operation.

Regulating temperatures within an optimal range is crucial for the well-being of both fish and plants in aquaponics. This often involves the use of energy-intensive systems like heaters or air conditioning units, especially in regions with extreme temperature fluctuations. While essential, these systems contribute significantly to the overall energy demands of aquaponic setups.

To address resource conservation, a process engineering approach targets water and energy usage in hydroponics [159]. Integrating renewable energy boosts system ecological performance. Aquaponics holds potential for efficient and sustainable technology, welcoming integration possibilities like biogas and solar power (reference [14]). Additionally, Goddek et al. [160] underscore the crucial need to improve energy consumption in aquaponics.

The substantial energy requirements for pumping systems and temperature regulation directly impact the operational costs of aquaponics. High energy consumption not only affects the economic viability of these systems but also raises concerns regarding their environmental sustainability. Minimizing energy consumption is critical for reducing operational costs and aligning aquaponic practices with broader sustainability goals, thereby reducing the carbon footprint associated with energy production and operation.

Efforts to enhance energy efficiency in aquaponics systems involve exploring alternatives such as renewable energy sources (e.g., solar power), employing smart technologies for precise control, and researching more energy-efficient equipment and methodologies. Balancing efficient system operation with energy conservation remains pivotal in ensuring the economic feasibility and environmental sustainability of aquaponic systems.

6.3. Social, Economic, and Environmental Benefits for Food Security

The integration of agriculture in urban areas brings about social, economic, and environmental advantages, contributing to both food security and sustainable development. It also promotes the growth of cities while fostering scientific and cultural knowledge [161]. From an economic perspective, urban agriculture, including the production of crops, fisheries, and livestock, provides raw food that can be distributed to the city's residents, maximizing conservation efforts [161]. While this concept had previously posed environmental challenges, it has now evolved into an environmentally friendly strategy within city centers [161]. Aquaponics systems, utilizing the principles of the 4Rs (source, rate, time, and place), play a crucial role in enhancing productivity, stability, and profitability, thereby ensuring food security. The four pillars used to assess and measure the status of food security include food availability, accessibility, utilization, and stability [162]. Evaluating aquaponics' sustainability reveals that while its infrastructure, electricity usage, and feed pose environmental impacts, this closed-loop system offers a sustainable means of producing fish and plants. Moreover, it aligns with various United Nations Sustainable Development Goals (SDGs) as outlined in Table 6 [147,161,163].

Aquaponics addresses food sovereignty (FS) for food abundance. Food sovereignty is described as the entitlement of local peoples to manage and adjust their own food systems, food cultures, markets, ecological (environmental) resources, and production patterns [18]. It advocates prioritizing food production policy and practices that are environmentally, socially, and economically sustainable [164]. With the right infrastructure and support, aquaponics can contribute to a more sustainable and equitable future. It provides a sustainable source of food, promotes healthy lifestyles, and creates jobs and economic growth [165]. Ensuring access to food worldwide is a pressing concern, especially in regions where conventional farming is not viable. Aquaponics offers a promising solution to achieve food security and food sovereignty while being environmentally sustainable [166]. Nonetheless, it is crucial to safeguard the interests of local and small-scale farmers against larger corporations and prioritize sustainable agricultural methods [167]. Achieving food security and food sovereignty requires a personalized approach to the development of food systems that cannot be prescribed [168].

Table 6. Contributions of aquaponics to achieving several SDGs.

SDGs	Contribution
SDG1	Aquaponics offers income and food security using less land and water, is accessible in urban areas for impoverished communities.
SDG2	Aquaponics enhances food security and quality and mitigates health hazards by enabling year-round cultivation.
SDG3	Aquaponics produces fresh, healthy food without chemicals, promoting healthy lifestyles.
SDG3 and SDG14	Aquaponics ensures fish health, welfare, and end-user safety, reducing the need for anti-infective agents.
SDG4	Aquaponics provides learning and education facilities.
SDG6 and SDG14	Aquaponics minimizes water consumption, enhances water quality, and has cultural, educational, and tourism potential [137,140].
SDG7	Aquaponics conserves energy and supports alternative energy sources.
SDG8	Aquaponics creates jobs and fosters entrepreneurship in aquaculture and hydroponics.
SDG9	Aquaponics combines industries and benefits from infrastructure and technological advancements.
SDG10	Aquaponics promotes equality by being inclusive of all ages and abilities.
SDG11, SDG12 and SDG13	Aquaponics reduces transportation needs, minimizes waste, and promotes sustainable consumption.
SDG13 and SDG15	Aquaponics conserves land and soil, producing high-quality food intensively and portably [138].

Aquaponics can help achieve food sovereignty goals by providing fresh, healthy, and locally grown food that is secure, satiating, and socially acceptable. The closed-loop system ensures food safety and reduces dependence on imported food, promoting food independence and addressing food insecurity. Aquaponics uses less water than traditional agriculture, reduces the risk of water pollution, and can grow a variety of crops, promoting the safeguarding of natural resources. By increasing access to fresh, healthy, and locally grown food, aquaponics promotes social harmony and reduces the risk of social unrest. It also allows small-scale farmers to have a voice in agricultural policies, promoting democratic oversight and community resilience.

7. Case Studies

7.1. International Experiences

7.1.1. Freshwater Aquaponics

The popularity of aquaponics is on the rise globally because of its many benefits such as increased crop yields, reduced water consumption, and decreased waste. The utilization of this technology has spread to areas that face water scarcity such as Australia and arid regions like the "University of the Virgin Islands (UVI)", which started its research activity in the late 1970s led by Dr. Jim Rakocy and has been active for over three decades. The aquaponics education program at UVI has been universally recognized. Aquaponics has gained significant popularity in North America, particularly in the United States and Canada, with a few farmers and scientists worldwide following suit. The aquaponics system developed at UVI is a raft hydroponic system that focuses on the production of tilapia [25].

In Europe, aquaponics is gaining traction as a sustainable and eco-friendly approach to food production. Several European countries such as Spain, Denmark, Iceland [26], Norway [168,169], Slovenia, Italy, Switzerland [169–173], and Germany have embraced aquaponics. Although most of these are small hobby or research units, some semi-commercial units have provided excellent information for future developments. For example, in "Spain", the small business Breen developed a 500-square-meter aquaponic system in Hondarribia, while in Denmark, the "Institute of Global Food and Farming (IGFF)" created a decoupled aquaponics unit of 60 m^2. In South Norway, Nibio has been involved in aquaponics development since 2010. Several other startups in Italy, Switzerland, and Germany are currently developing aquaponic systems. Additional startups in Europe are exploring aquaponics, but typically, these systems remain either small-scale or are in the developmental stage. The EU-backed initiative "INAPRO", spanning from 2014 to 2018, spearheaded by the "Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB)" based in Berlin, Germany, alongside 18 partners from eight nations, aims to establish four substantial demonstration facilities, each covering an area of 500 square meters. These facilities are planned for deployment in "Spain", "Belgium", "Germany" and "China". Aquaponics is popular in Asia, especially in China, Japan, and Thailand, for commercial and small-scale operations due to its high yields and low water usage. In Africa, it is gaining popularity for sustainable food production in areas with limited water resources, with small-scale operations established for community projects providing food and income.

Aquaponics presents an eco-friendly method for urban food production, diminishing reliance on distant food transport and storage from rural areas. By doing so, it curbs transportation expenses and cuts down on carbon emissions. This approach can help lower transportation costs and reduce carbon emissions. Moreover, aquaponics can be conducted in smaller spaces and indoors, providing fresh and healthy food options to urban communities with limited access to traditional farming methods. Körner et al. [174] suggest that local vegetable production in urban areas in Northern Europe can outperform imported products in terms of environmental performance. Aquaponics systems are implemented in various regions worldwide, with varying fish biomass and crop yields as presented in Table 7 [38,66,102,175–179].

Several case studies have been conducted on automated aquaponics systems in various locations around the world [13,122,180]. These studies, including those conducted in Indonesia [181], Najaf (Iraq) [182], Morocco [183], Bangladesh [184], Rourkela (India) [185], USA [62], and Germany [39,186] have explored different degrees of control in aquaponics systems, including fully controlled, semi-controlled, non-controlled, and hybrid-controlled systems. These systems utilize sensors and IoT devices to collect data, aiding decision-making processes, predicting plant growth, and optimizing harvest times for precision farming. IoT integration in aquaponics facilitates real-time data collection, monitoring of crop health, and assessment of environmental factors [125–140]. Energy monitoring systems track energy consumption per yield [93], enhancing process efficiency. Learning factories are merging engineering challenges with smart aquaponics to advance skills and knowledge. Recent research emphasizes smart systems for real-time monitoring and prediction of aquaponics' growth and resource efficiency, signifying a shift towards automation and improved energy use in the technology [13,38,93,186]. Smart aquaponics architectures leverage sensors and cloud-based databases for real-time monitoring and control through a "graphical user interface (GUI)" [187]. These advancements enable predictive modeling for estimating growth patterns, harvest times, yield, and profit margins, empowering sophisticated decision making in aquaponics management. Predictive models enhance operational control and crop quality. However, addressing challenges like IoT standards, initial costs, and security concerns remains essential for widespread adoption in large-scale commercial aquaponics. While IoT and smart monitoring offer significant advantages, they also pose challenges. A major issue is the absence of standardized IoT protocols, limiting system interoperability. Initial costs and potential security vulnerabilities in the absence of proper encryption are key hurdles that require addressing before deploying these systems in large-scale commercial aquaponics.

Table 7. International commercial aquaponics systems.

Country	Aquaponics Scale	Fish Species	Crop Grown	Fish Biomass	Crop Yield	Reference
Rakocy/Virgin Islands (UVI)	Commercial	Nile and red tilapia	Basil, lettuce, okra	Fish sales yield was USD 134,245/year and the productivity of water was 61.5 and 70.7 kg/m^3	5.01–5.34 mt/year basil,	[102]
Johns Hopkins University/ Baltimore, Maryland, United States US	Small-raft system (10.3 m^3)	292 L H_2O, 1.3 kg feed, and 159 kWh of energy (USD 12)	104 L H_2O, 0.5 kg feed, and 56 kWh energy (USD 6)	1 kg increase in tilapia	1 kg of crops	[66]
ECF/Germany, 1.3 mill. EUR	1800 m^2	Tilapia	Basil	-	Size 1000 m^2	[38]
NerBreen/Spain, 2 mill. EUR	6000 m^2		Lettuce, straw, barriers, tomatoes, and peppers	–	Size 3000 m^2	
Nigeria	Small	Tilapia and African catfish	Spinach, eggplant, tomatoes, and maize	27.9 kg/year	3 kg/year	[175]
Ghana	Commercial	Nile tilapia	Maize	_	2.3 t/ha	[176]
Cote d'lvoire	Small		Tomatoes	60 kg/month	81 kg/month	[177]
Kenya			*Amaranthus* (Am), *Cucurbita* (Cu), and *Artemisi* (Ar)	-	1.1 kg/m^2 Am, 1.3 kg/m^2 Cu, and 1.6 kg/m^2 Ar	[178]
Nigeria		catfish	Pumpkin	160 kg/m^3	43 kg/month	[179]

The findings demonstrate that aquaponics systems must be tailored to local conditions and resources, and that different control degrees offer varying levels of precision, efficiency, accessibility, and affordability. While fully controlled systems may offer greater precision and efficiency, they may be less accessible to small-scale farmers and require higher initial investments. In contrast, non-controlled systems may be more affordable and accessible, but require more manual labor and may be less efficient. Hybrid and semi-controlled systems offer a balance between these approaches, and they may be suitable for a range of contexts and scales.

7.1.2. Marine and Brackish Aquaponics

Marine and brackish aquaponics are still relatively niche farming techniques compared to traditional agriculture and aquaculture, and their adoption worldwide is limited. However, there are a few notable examples of marine and brackish aquaponics systems in different parts of the world. Both marine and brackish aquaponics have the potential to provide a sustainable source of seafood and fresh produce, but they require specialized knowledge and expertise to set up and maintain. Using water of moderate or high salinity can open up opportunities to grow halophytes with relatively nil impact on the environment. The capability of halophytes to be used as biological filters for brackish water aquaculture effluents bioremediation has been freshly demonstrated by growing them in aquaponics to upgrade the value of these crops. Trials summarized in Table 8 with different halophytes in aquaponics show that halophytes can be grown in aquaponics systems to produce high-value crops for food, energy, or fodder production [188–195].

Table 8. International case studies on marine and brackish aquaponics.

Location	EC	Fish—Brackish	Plant—Brackish	Major Finding
Negev Desert—Israel [188,189]	Two studies: 1st EC 4708–6800 µS/cm 2nd EC (4000–8000 µS/cm)	*Tilapia* sp. ("red strain of *Nile tilapia Oreochromis niloticus*" × "*blue tilapia O. aureus hybrids*")	*"A. ampeloprasum", "A. graveolens", "B. oleracea v. gongylodes", "B. oleracea v. capitata", "Lactuca sativa", "B. oleracea v. botrytis", "B. vulgaris vulgaris", "A. fistulosum", "O. basilicum" and "N. officinale".*	Two separate research studies observed positive outcomes when cultivating various herbs and vegetables alongside Nile tilapia in brackish water systems. The fish exhibited robust health and growth throughout these experiments.
Italy [190]	Reared in environments with 20 parts per thousand (ppt) salinity and freshwater conditions at 0 ppt	45 "European sea bass juveniles" raised in a fish tank of 500 L in volume	*Beta vulgaris* (50 seedling/m^2) Three aquaponics grow beds (2 m^2)	Aquaponic systems integrating euryhaline fish with halophile plants allow for rapid adjustments to environmental variations. Beta vulgaris was grown successfully.
Italy [191]	10–30 g/L	Mullet (*Mugil cephalus* L.)	*Salsola soda*	Mullet performed well at salinity levels up to 20 g/L, while Salsola soda thrived at 10 g/L. Marine aquaponics showed promise.
USA [192]	Salinity of 15 ppt	Red drum	*Sesuvium portulacastrum and Batis maritima*	Red drum production, edible halophytes, and improved drainage were achieved in marine aquaponics at a salinity of 15 ppt. Shrimp and halophytes thrived at this level too.
USA [193]		Shrimp	*triplex hortensis, Salsola komarovii, and nopusPlantago coro)*	
Portugal [194,195]	Coastal lagoon salt marshes	*Solea senegalensis*	*Salicornia ramosissima and Halimione portulacoides*	Incorporating organic-rich effluents altered the lipid profile of halophytes in marine aquaponics, increasing glycolipids with n-3 fatty acids. Enrichment of halophyte-associated bacterial taxa enhanced nutrient cycling.
	Marine fish farm		*Halimione portulacoides, Salicornia ramosissima and Sarcocornia perennis*	

They can be grown alongside marine fish (sea bass, barramundi, and shrimp), as they are compatible with the salinity levels required for marine aquaculture. Halophytes can also be grown using lower levels of nutrients in the edible solution, which can help to reduce the environmental impact of aquaponics. Their high biomass production and nutrient utilization efficiency (NUE) make them valuable for food, energy, or fodder production [196]. Moreover, the substantial revenues generated from halophyte crops present opportunities for developing integrated farming systems that effectively utilize by-products from saline aquaculture. By using the waste products from marine aquaculture as a nutrient source for halophyte crops, it is possible to create a closed-loop system that maximizes resource use efficiency and reduces environmental impact.

7.1.3. Challenges Hindering the Implementation of Large-Scale Aquaponics

Large-scale implementation of aquaponics encounters various challenges despite its numerous advantages. Achieving a delicate balance among crucial parameters—such as water quality, pH, temperature, and oxygen levels—is essential for the optimal growth of fish, bacteria, and plants within the system [13]. Monitoring these factors constantly remains critical.

Aquaponics' performance differs significantly between urban and rural contexts due to economic viability, environmental sustainability, and technical control levels [197]. Land-efficient, urban-based aquaponics systems offer advantages in high-density regions, reducing transportation costs and benefiting supply chain management [198]. In contrast, rural and peri-urban areas lacking specific advantages like renewable energy sources may face limitations in establishing economically viable aquaponics facilities [199].

The surge in aquaponics research spans diverse topics, encompassing system types, hydroponic elements, species variety, management practices, environmental concerns, and energy efficiency [61,71,200–204]. However, the interdisciplinary nature of aquaponics involvement with multiple disciplines—agriculture, aquaculture, microbiology, and more—poses a challenge for comprehensive reviews [115]. Existing reviews, while comprehensive, often lack in-depth insights into energy use efficiency (EUE) and greenhouse aquaponics' energy demands [205].

The energy demand within aquaponics, particularly in greenhouse and indoor settings, primarily arises from artificial lighting, accounting for a significant portion of electricity consumption [149,197]. Reports suggest that lighting contributes substantially to indoor farming's production costs [199]. Despite numerous studies on lighting efficiency, the conclusive light response spectrum for specific plant growth stages remains elusive [206]. Managing the energy consumption of artificial lighting in large-scale aquaponics involves optimizing lighting systems to balance efficiency and crop requirements. Lighting, a major contributor to production costs in indoor farming, lacks a definitive spectrum for specific plant growth stages despite various studies on efficiency. Optimization involves using technologies like LEDs, adjusting intensity based on plant needs, and employing smart systems for automation. Integrating renewable energy and efficient designs ensures sustainability and cost-effectiveness. Efficient management enhances growth while reducing expenses, requiring a multifaceted approach involving technology adoption, smart controls, renewable sources, and tailored lighting strategies. Reducing costs and environmental impact are vital for long-term success in large-scale aquaponics.

7.2. National Experiences

In Egypt, a few practices have been experienced, as displayed in Table 9 [207–216]. Aquaponics as a new technique is highly recommended by various organizations and individuals, including the "United Nations Food and Agriculture Organization (FAO)", the "World Health Organization (WHO)", and many sustainable agriculture advocates and practitioners. Effective commercial aquaponics design necessitates selecting the right scale and structure to achieve optimal outcomes at a minimal cost. Salt water has been used for agriculture and fish farming in aquaponics in many countries in the world [198–205] and has not been applied in Egypt until now except in this study [217].

It is suggested that aquaponics can be utilized in desert areas and coastal regions with brackish or saline water to cultivate a range of crops and fish species like tilapia, catfish, and trout, without any negative impact on the environment. In desert areas, aquaponics can facilitate the growth of crops that are suitable for arid conditions, including cacti, succulents, and desert-adapted vegetables. Similarly, in coastal areas, it can be utilized to cultivate salt-tolerant crops like sea asparagus, samphire, and halophytes, thus enhancing local food production and decreasing dependence on imported food. Furthermore, since aquaponics is an environmentally friendly and sustainable farming technique, it can be implemented with zero environmental impact, lowering the ecological footprint of food production. However, to increase the effectiveness of aquaponics, additional research and pilot-scale implementations are necessary. Integrating aquaponics with home appliances is also crucial, allowing more people to purchase customized aquaponics systems to cultivate vegetables and protein at home. Meanwhile, the high capital and operating expenses of aquaponics must be addressed, and more practical and economical designs must be developed to enable aquaponics to become a part of everyone's lifestyle in the near future.

Table 9. National aquaponics case studies.

Aquaponics/Location	Main Findings/Outputs	Reference
Abassa, Sharkia Goveraorate, Agriculture Research Center	Hydroponics unit improved water quality for fish and yielded peppers meeting economic expectations.	[207]
Small-scale-aquaponic/2006/National Institute of Oceanography and Fisheries (NIOF)	Healthier fish and crops with increased economic returns.	[208]
	"Integrated Multi-Trophic Aquaculture (IMTA)" and "nutrient film technique (NFT)" systems in Egypt had the best net income and economic surplus compared to traditional soil culture systems.	[209]
Bustan aquaponics farm—1000 m^2	The first commercial aquaponic system in Egypt producing pesticide-free tilapia fish and various lettuce types.	[210,211]
Agrimatic Farms (one acre)	The second commercial aquaponic system integrating lettuce, mint, and basil with tilapia production.	[210]
Al-Haggag aquaponic farms—(Harm City/6 October)	The third aquaponic commercial system utilizing waste material to feed insects and producing "mint", "lemon", "herbs", and "olives".	
American University in Cairo	Aquaponics is a viable alternative to traditional farming. IAV (Integrated Aqua Vegaculture) system shows more potential than DWC system.	[212]
	Compared yields in DWC and sand-bed aquaponics systems in Egypt and found that DWC had higher yields with lower water use.	[213]
	Small-scale aquaponic systems in Egypt can generate positive financial benefits within the first five years.	[214]
Ain Shams University and Agricultural Research Center	Basil has a higher capacity than mint to remove nutrients from fish culture water, improving fish yield.	[215]
Al-Azhar University in Cairo	In aquaponics, having 20 fish per aquarium alongside lettuce plants is an ideal stocking density that supports both fish and plant production effectively.	[216]

8. Constraints, Challenges, and Future Aspects

Despite the benefits highlighted in recent reviews of aquaponics, there are several challenges that continue to impede researchers and producers in this field. These challenges include the need for more detailed procedures for operating and supporting aquaponics, as traditional insecticides and antibiotics cannot be used, making it difficult to prevent diseases and pests in both fish and plants [114,218]. Additionally, incorporating the hydroponic and aquaculture components to maximize nutrient usage remains a challenge [219], as does the lack of social recognition for aquaponics, high initial investment costs, and the absence of policies to subsidize these costs. There is also a need for additional data, information, training, and education, as well as a practical and effective marketing plan. Integrating Industry 4.0 into aquaponics faces multiple hurdles: complex system integration, high costs, skill shortages, compatibility, cybersecurity risks, and environmental adaptability. Implementing smart tech is costly and intricate, demanding specialized skills. Data security, privacy, and interoperability remain major concerns. In Egypt, there is a lack of technical knowledge and expertise in aquaponics, which can be a significant barrier for small-scale farmers who do not have access to education and training. Furthermore, the high cost of equipment and infrastructure needed to establish an aquaponics system can pose significant challenges for farmers and entrepreneurs, despite the long-term benefits of this technology.

In the future, several aspects of aquaponics must be considered, including (1) the application of aquaponic techniques in dry areas where traditional agriculture is limited due to salinization of groundwater, (2) the need for more comprehensive nutrient management by researching other elements such as phosphorus, potassium, and sulfur distribution in aquaponics, (3) more research on influencing factors, nutrients, and microorganism communities in aquaponics, (4) investigation of alternative fish feeds and polyculture benefits, (5) the utilization of solar energy, (6) a deeper understanding of the level and type of competition in the market, (7) the development of low-cost aquaponics, (8) sharing practical experiences globally, (9) technological advances that lower investment costs and require less technical knowledge, (10) ongoing research and development leading to new crop varieties and optimized yields and sustainability, (11) urban agriculture, (12) climate resilience in the face of climate change, extreme weather events, and water scarcity, (13) examining organic certification for aquaponic production is essential for recognizing it as a healthy, sustainable local food source, regardless of its mandatory status for industry growth, and (14) Industry 4.0 in aquaponics: using big data, IoT for control, seamless tech, AI maintenance predictions, cost cuts for access, and skilled worker training. This leads to automated, data-driven, sustainable aquaponics.

9. Conclusions

Aquaponics, a promising technology uniting hydroponics and aquaculture, produces high-quality fish protein and vegetables using minimal land, water, and energy. It offers benefits like nutrient recycling, resource efficiency, and alignment with sustainable development goals and food sovereignty. Aquaponics faces challenges in organic certification due to strict regulations, necessitating collaboration among various sectors. Despite hurdles, the industry shows promise, yet lacks specific inclusion in European policies, and faces recognition issues in South Africa and Egypt. Revising legislation in line with established standards is essential. Proposed policies emphasize sustainability and innovation, encouraging environmentally friendly practices. Specific regulations cover crops, aquaculture, and systems, focusing on natural methods and ethical production. Optimizing aquaponic system chemistry enables automated commercial aquaponics to meet sustainable development goals, producing nutritious food with minimal environmental impact, conserving resources, reducing fertilizer reliance, and promoting local food production. Integration of automation enhances efficiency and scalability, empowering communities for self-sufficient food production.

Although aquaponics presents some challenges, such as higher initial costs and the need for more education, information, and marketing, the application of economies of scale can diminish production per unit cost and improve the viability of aquaponics. Moreover, integrating Industry 4.0 into aquaponics brings substantial benefits like precision farming and real-time analysis, despite the challenges. These technologies promise an efficient, automated, and sustainable farming future, calling for ongoing collaboration and tailored solutions to unlock their full potential. The policies of horticultural marketing are fundamental in advancing the suitability of aquaponics systems, and the introduction of rules and regulations to support sustainable food production technologies is essential. Aquaponics can be a valuable tool for sustainable food production in Egypt, and as more knowledge and expertise are developed, and as the costs of equipment and infrastructure decrease, aquaponics could become a widespread and essential component of Egypt's agricultural sector. As technology and research continue to advance, the future prospects of aquaponics are bright, and it has the potential to play a vital role in meeting the growing demand for fresh and organic produce while reducing environmental impact.

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