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Aquaponics system for sustainable water, energy, and food nexus: A review

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ABSTRACT

Climate change, population expansion, water shortages, soil erosion, and food security are some of the primary concerns facing the world today. Hydroponic, aquaponic, and aquaculture systems may help to address these difficulties. Hydroponics is a closed-loop system for growing plants in nutrient-rich water rather than soil. Aquaponic systems combine hydroponics and the growing of fish or other aquaculture species in addition to plants. This review aims to evaluate the challenges encountered by aquaponic and aquaculture farming operations and identify which issues still need to be addressed. The review is organized as follows: recent previous studies on hydroponics, aquaponics, and aquaculture were collected and investigated; water quality and energy issues were addressed; technologies to improve water quality in these systems were discussed; and challenges to the implementation of large-scale aquaponics were discussed. The study found that a commercial reverse osmosis filtering system that provides excellent water quality control is a good method for removing harmful contaminants from water in small-scale aquaponics and aquaculture. Recirculation systems are more sustainable and effective in managing the volume of effluent in aquaculture units because only 10% of the total volume of water is refilled daily. Constructed wetland systems are a low-cost, high-efficiency treatment solution for nitrogen-containing wastewater, with removal efficiencies of up to 98% for NH_4-N and above 98% for NO_2-N. The use of aquaponics in desert settings with water constraints constraint is viewed as a possible sustainable food production approach.

Keywords: Aquaponics, Sustainability, wetland treatment system, Water quality, Wastewater integrated system.

1 INTRODUCTION

Aquaculture, the world's fastest-growing food-producing sector, uses a variety of production strategies. Aquaponics is regarded as one of the most efficient and environmentally sustainable methods of the twenty-first century [1]. Aquaponics is a novel and environmentally friendly agricultural approach that blends aquaculture, or the production of aquatic creatures such as fish, with hydroponics, or the cultivation of plants without soil. This integrated system fosters a symbiotic relationship in which fish waste feeds the plants and the plants, in turn, filter the water for the fish [2]. Aquaponics saves water, has a low environmental effect, offers economic opportunities, and is a sustainable way of food production. However, concerns such as disease outbreaks and system maintenance necessitate cautious planning [3].

Aquaponics has numerous benefits over traditional farming methods. It consumes less water, occupies less land, and necessitates fewer pesticides and fertilizers. Aquaponics systems can also be found in metropolitan locations, making them more accessible to city dwellers. Aquaponics can increase agricultural yields, making it an appealing solution for current farming practices. One of the key objectives of aquaponics is to design systems that close nutrient cycles. Therefore, water recirculation saves water, and mineral transfers from aquaculture to hydroponics help with nutrient recycling. Among the components are fish tanks, grow beds, beneficial microorganisms, water pumps, and aeration systems. Effective resource management, crop diversification, space optimization, and nutrient recycling are all advantages [4]. Disease control, pH adjustment, balanced system design, optimal plant selection, periodic maintenance, and ongoing monitoring are all critical considerations [5]. This novel solution exemplifies sustainability by offering access to local, fresh fruit while minimizing environmental effects. Aquaponic plant nutrition comprises a variety of important nutrients such as nitrogen, potassium, micronutrients, and phosphorus. Aquaponic nutrient availability is affected by parameters such as temperature, pH, and light intensity. While nutrient concentrations delivered by fish in aquaponic systems are lower than in hydroponic systems, plants can nonetheless grow in low-nutrient solutions [6,7]. The intermittent discharge of considerable amounts of nutrient-rich water in non-recirculating aquaculture systems causes excessive water consumption and surface pollution [8-10]. Recirculating aquaculture systems reuse a high percentage of water (95-99%), with water use falling below 100 L/kg of fish produced [11,12]. Instead of being eliminated in gaseous form in denitrification units, surplus nitrate in aquaponics is utilized to produce beneficial plants [13,14]. Environmental problems are raised by aquaculture wastewater and the catastrophic overfishing of wild fish populations for use as ingredients in fish feed [15,16]. Unused feed and feces, which are organic components of aquaculture effluents, harm the ecosystem by degrading recipient water bodies and sediments. The main components of aquaculture wastewater that can hurt fish growth and the environment include dissolved and particulate organic matter, total dissolved solids, and nutrients including phosphorus and nitrogen. The enhanced metabolic activity of aerobic bacteria is the main result of the significant volumes of decomposable organic waste in aquaculture effluent. Aerobic nitrification and denitrification reactions are simultaneously inhibited by the anaerobic sulfate reduction reaction that predominates in anaerobic environments [17,18]. The death of sediment macrofauna, which is necessary for bio-irrigation in natural water streams, will result from oxygen deprivation in both processes, further lowering the aeration levels in the receiving water bodies. The environment is severely harmed by the organic enrichment in river sediments caused by an insufficient microscopic animal population. Such an ecosystem is dominated by sulfur-fate reducers and methanogens, which also disrupt the relationship from the river basin to the subsequent level of the food chain [19]. To improve the sustainability of aquaculture units, all these environmental effects of dumping untreated aquaculture effluent into receiving water bodies should be minimized. The nutrient enrichment of aquaculture wastewater through the feedstock can also result in the eutrophication of lakes and discharge channels, which therefore requires environmentally acceptable treatment methods. Aquaculture systems also use traditional wastewater treatment techniques that combine physical, chemical, and biological approaches. For the oxidation of organic matter, nitrification, or denitrification, biological processes such as submerged biofilters, trickling filters, rotating biological contactors, and fluidized bed reactors are utilized [20]. Traditional wastewater treatment techniques are expensive in terms of initial outlay, energy use, and upkeep. In this case, the development of sustainable solutions is crucial for the treatment of aquaculture wastewater. This paper assesses the obstacles faced by aquaponic farming systems, indicates which concerns need to be solved, and makes recommendations for further research. Different approaches to each barrier are described. In addition, the latest technology possibilities for treating wastewater from sustainable aquaculture have been thoroughly examined in the review, which is necessary to maintain a sustainable connection between the water, food, and energy chains. The work is organized as follows: recent previous studies on hydroponics, aquaponics, and aquaculture were collected and investigated; water quality and energy issues were addressed; and various technologies to improve water quality in these systems were discussed, as well as the challenges to large-scale aquaponics implementation. Figure 1 depicts the study process.

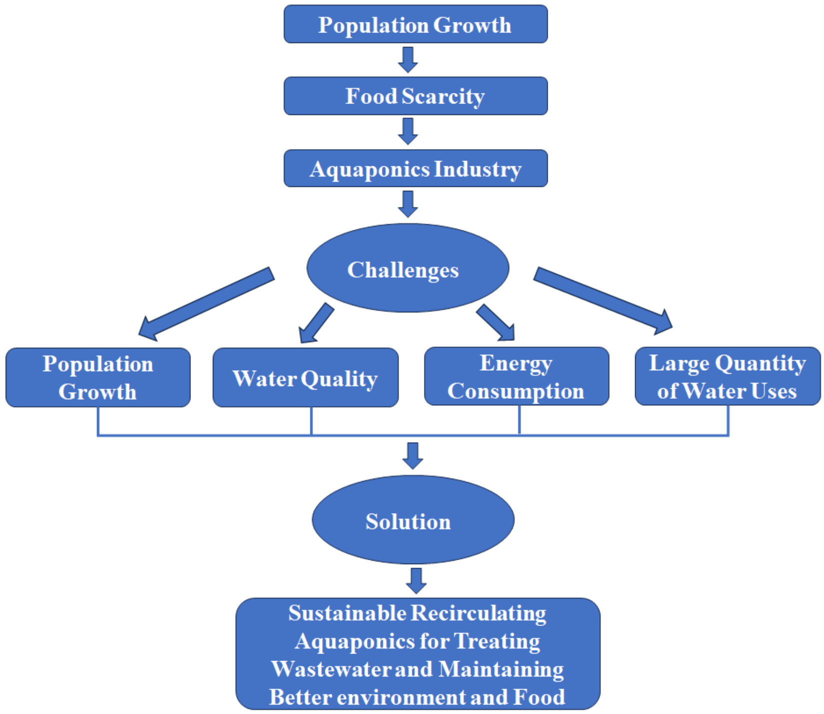


Figure 1: Study methodology.

2 LITERATURE REVIEW

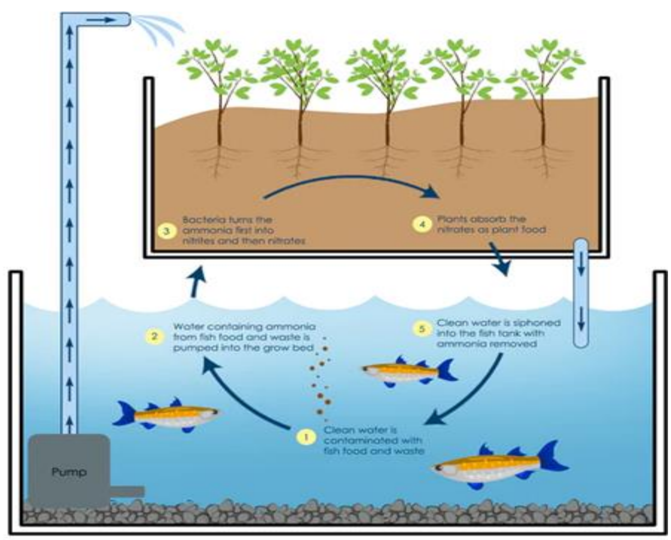
Several research efforts provide insights into the scientific and technical elements of aquaponics [21-24]. Ibrahim [25] does a thorough literature study on multiple-use water in pond-based aquaculture-integrated agriculture systems in terms of legal regulations and water salinity. Scenarios for pond-based aquaculture-integrated agriculture and their environmental implications were presented and explored. They found that pond-based aquaculture-integrated agriculture could help increase productivity, food producer revenue, soil fertility, ecosystem management, and adaptation to environmental change. aquaculture-integrated agriculture systems contribute to climate change adaptation and mitigation by lowering waste and greenhouse gas emissions, relieving pressure on water resources, and recycling nutrients. Theresa and Oliver [26] investigate the elements that impact consumer willingness to pay for aquaponic products. Structural Equation Modeling was used to test relationships, both direct and indirect. We collected primary data from 315 Austrian respondents. The study found a direct correlation between buying intention and willingness to pay for aquaponic products. To successfully adopt aquaponics in the market, consumers must have access to relevant information. They proposed that to improve willingness to pay for aquaponics, it is necessary to highlight its value as a sustainable food production method. Other factors influencing willingness to pay include environmental awareness and green consumption. The construction of a solar-powered aquaponics prototype as a sustainable, cost-effective, and environmentally friendly approach to food production was presented by [25]. They determined that operating a low-cost aquaponics setup powered by renewable energy has the potential to be a sustainable way of food production. Zugravu et al. [28] investigated consumer perceptions and images of aquaponics in Romania. These studies imply that people perceive aquaponic items based on product opinion, price, and value. Demographics, financial status, and third-party influence all have an impact on purchasing behavior. Zugravu et al. [28] found that indigenous aquaponic items received more attention and were preferred over international products. Specht et al. [29] studied Berlin residents' choices for productive urban space, acceptance of urban agriculture, and views of agricultural products. According to Specht et al. [30], an agricultural production system that integrates commercial, environmental, and social aims has the highest level of acceptance. According to a study [31], profit-oriented and technologically intensive systems were increasingly rejected, while aquaponic systems received poorer evaluations. Only 28% of respondents supported aquaponics as a fish and vegetable production technique, and only 27% would buy these items. Miliˇci'c et al. [30] conducted a Europe-wide survey and found that consumers were generally positive and prepared to pay more for items devoid of antibiotics, pesticides, and herbicides, as well as those from local providers. Tamin et al. [31] examined Malaysian customers' reactions to aquaponic products. The outcome was positive buying interest.

3 MATERIALS AND METHODS

3.1 Hydroponics and aquaponics systems

The practice of growing plants in a nutrient-rich water solution rather than in soil, known as hydroponics, is well known. Hydroponics systems are closed-loop, which means that they cycle the water solution to use less water overall. Hydroponics can be utilized in the home and garden, as well as for small-scale crop production, such as salad greens, cannabis, and ornamental plants (Figure 2A). Many people are unfamiliar with aquaponics, an agricultural technology. Aquaponics, like hydroponic systems, uses water solutions with the optimal nutritional balance. Fish or other aquatic animals are cultivated alongside plants in aquaponic systems, which is the fundamental distinction between them and hydroponic systems. In aquaponics, plants and animals coexist in a symbiotic connection where the plants feed the aquatic creatures and aid in water filtration while the animals create nutrients in the form of waste that the plants need to grow (Figure 2). The growing method known as aquaponics combines hydroponics and aquaculture in many ways [32]. Aquaponics has great promise as a way to increase food harvests while reducing water consumption in both residential and commercial agriculture. Aquaponic systems can be used to grow a variety of plants, but the most popular ones are cannabis, tomatoes, leaf lettuce, peppers, cucumbers, strawberries, cabbage, broccoli, cauliflower, and Chard.). Aquaponic systems give growers the chance to produce and harvest aquatic organisms, which is an additional benefit. In the closed system, these animals flourish alongside the plants. Even if not all aquatic animals cultivated in a reverse osmosis aquaponics system are harvestable. Growers must ensure the right water composition for their crops, making filtration systems like reverse osmosis very important.

A



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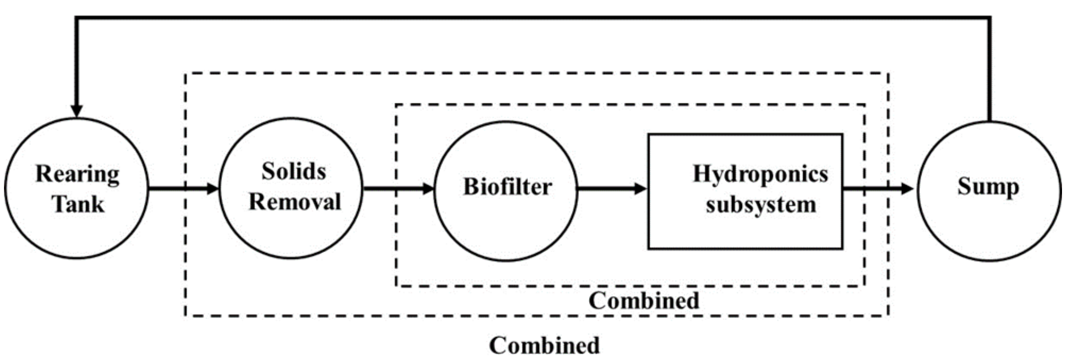

C

Figure 2 A: Hydroponics, B: Aquaponic system, and C: Aquaponic system layout [32].

3.2 Principles of aquaponics

Recirculating aquaculture and hydroponics are combined in aquaponics. Traditional hydroponic systems need mineral fertilizers to provide plants with the nutrients they need, but aquaponic systems employ readily available fish water that is nutrient-rich in fish waste instead. Another benefit of this combination is that excess nutrients do not need to be eliminated by the regular replacement of fresh water with enriched fish water, as is done in aquaculture systems [33]. Fish, bacteria, and plants all coexist in harmony as a result of the system, which also promotes the recycling of nutrients and water (Figure 3) [34].

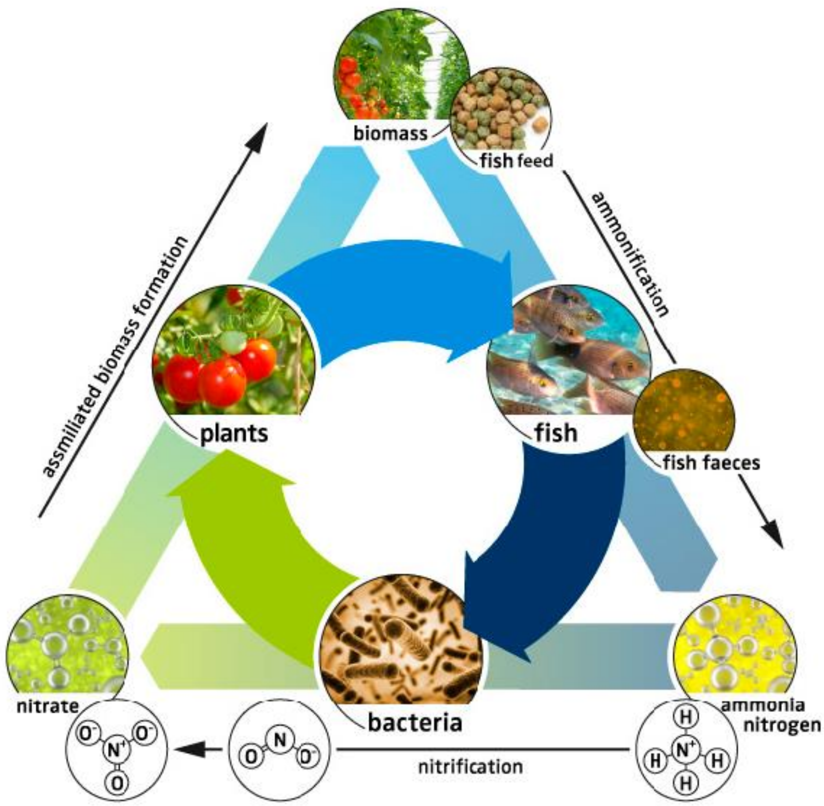

Figure 3. Interdependent aquaponic cycle [34]

For proper growth, plants require macronutrients like C, H, O, P, N, Ca, K, Mg, and S as well as micronutrients like Fe, Mn, Cl, B, Zn, Mo, and Cu. Except for C, O, and H, which are obtained from air and water, these elements are present in hydroponic solutions in predetermined ratios and are added in the form of ions [33]. In aquaponics systems, fish waste (gill discharge, urine, and feces), which contains both soluble and solid organic compounds, is dissolved into nutrient-rich ionic form in the water and fed to plants as a source of nutrients. Monitoring the concentrations of micro- and macronutrients is necessary to ensure proper plant growth. Monitoring micronutrient and macronutrient concentrations is essential for optimum plant growth. Some nutrients' concentrations may need to be modified regularly, for example, iron is frequently insufficient in fish waste [35]. Different microorganism communities that are engaged in the processing and solubilization of fish waste must be able to live in aquaponic systems. If the ammonia (NH_4) from fish urine and gill discharge is not eliminated from the system, it can accumulate to dangerous levels. Step-by-step microbial conversion to nitrate can accomplish this. The nitrifying autotrophic bacteria consortium, which forms a biofilm on solid surfaces in the system and is primarily made up of nitroso- and nitro-bacteria (such as Nitrosomonas sp. and Nitrobacter sp.), is one of the most significant microbial components. The nitroso-bacteria in the system first turn the ammonia in the system into nitrite (NO_2), which is then turned into nitrate (NO_3) by the nitro-bacteria [36]. Nitrate, the final byproduct of this bacterial conversion, is far less hazardous to fish and serves as the primary nitrogen source for plant growth because of its bioconversion [37]. Most systems require a specialized biofiltration unit with extensive nitrification. To achieve the optimal balance between fish nutrient production and plant uptake in each system, the appropriate fish to plant ratio must be calculated. This may be based on the feeding rate ratio, which is the quantity of feed consumed daily per square meter of plant variety, according to Rakocy

[38]. For leafy greens growing in raft hydroponic systems, a value of between 60 and 100 g/day/m^2 has been advised [39]. For eight water spinach plants (Ipomoea aquatica), Endut et al. [40] discovered an ideal ratio of 15–42 grams of fish feed m^2 of plant growing with one African catfish (Clarias gariepinus). Therefore, to strike the correct balance, the following factors must be understood from the ground up and experienced: (1) Fish species and food consumption rates; (2) Fish food composition, such as the percentage of pure proteins converted to Total Ammonia Nitrogen (TAN); (3) Feeding frequency; (4) Hydroponic system type and design; (5) Types and Physiological Stages of Cultivated Plants (Leafy Greens vs. Fruity Vegetables); (6) Plant Sowing Density; and (7) Chemical Composition of Water Influenced by Fish Waste Mineralization Rate. Furthermore, because fish, bacteria, and plants all share a water cycle, it is important to maintain environmental variables like pH, temperature, and mineral concentrations at a compromise that is as close as possible to each organism's ideal growth conditions.

3.3 Quality of Water in Aquaponic Systems

In aquaponics systems, the quality of the water affects both the plants and the animals. Agricultural runoff contains ammonia, chlorine, heavy metals, and excessive levels of TDS, which are toxic for crops and people. As a result, farmers must ensure that irrigation water is within the permissible limits of these parameters. [41]. Along with the possibility of impurities getting into the aquaponics system's water supply, aquatic animals that grow alongside plants produce waste. As this waste builds up more quickly than plant roots can use it, the quality of the water decreases with time. The water solution in the system could turn hazardous to plant and animal life if it is not controlled. The water in aquaponics systems can be filtered using a variety of techniques. In most systems, the biological filtering action of plant roots and animal activity is supplemented by some kind of chemical or mechanical filtration. Water filtration and a reverse osmosis aquaponics system provide unmatched control over the system's water quality. Reverse osmosis (RO) is a mechanical procedure that imitates the osmosis that occurs naturally in cells. Water travels through cell walls in live cells to create a balance by moving from areas of lower concentration to those of higher concentration. When water is forced through a semipermeable membrane by pressure, reverse osmosis removes sediments, debris, dissolved minerals, and solid waste thanks to the membrane's small pores. The reverse osmosis aquaponics system requires an incoming water supply, which could be a well or a public water source. Impurities from the RO filter is flushed away through a drain. Sustainability in aquaculture treatment technologies

3.3.1 Reverse Osmosis role in the aquaponics

For individuals who use hydroponic or aquaponic systems to raise aquatic plants and animals, RO systems are effective at eliminating dangerous chemicals from water. A commercial reverse osmosis filtration system that provides outstanding water quality control is often used in a reverse osmosis aquaponics system [42]. The biggest commercial RO systems include automatic controllers and can handle 1000 gallons or more of water each day. Precision valves allow aquaponic farmers to regulate the flow and chemistry of both treated and untreated water. As a result, gardeners can maximize the water's concentration of TDS and ammonium nitrate, which are essential for the development of both plants and animals. Up to 99% of contaminants, such as heavy metals (mercury, lead, and arsenic), chlorine, fluoride, suspended particles, and pathogens (bacteria and protozoan cysts), may be eliminated using commercial reverse osmosis aquaponics systems. The reverse osmosis systems are effective, efficient, and simple to keep up with aquaponics. These systems provide clean water for the fish and plants that are raised in the system, which enables aquaponics growers to achieve high yields. Additionally, these strong water filtering systems are employed in bakeries, food processing plants, pubs and restaurants, and pharmaceutical manufacturing facilities. The finest comprehensive, portable, light-commercial reverse osmosis system such as the PRO-RO-I was built with the simplicity of installation, usage, longevity, and peak performance in mind.
[https://proaquawater.com/products/pro-aqua-commercial-reverse-osmosis-system-1000-gpd].

3.4 Wetland recirculating aquaculture system

Wetlands have proven to be a viable and cost-effective method of wastewater treatment [43-46]. Constructed wetlands technology is becoming increasingly important in the RAS. Energy is only needed to pump and distribute wastewater in developed wetland systems. By combining plants with aquaculture water, the symbiotic process can be employed to create a mutually profitable and environmentally favorable system in RAS systems. The advantage of constructed wetland systems is their great efficacy in treating sewage containing nitrogen compounds (Table 1). Wetlands, on the other hand, are more effective in large-scale treatment systems at removing some nutrients, such as nitrites and ammonium, whereas nitrate and phosphorus elimination is occasionally negatively impacted by wetland passage. As a result, a long retention period is required to remove the required nitrogen [47]. They require a considerable amount of land, up to 2.7 times the area of the pond, which is another drawback [48]. Wetland systems may be less economically viable as a result, as they require a lower hydraulic loading rate and a longer hydraulic retention time to effectively remove pollutants. This problem can be mitigated by effective pre-treatment in small, commercially feasible artificial wetlands with high hydraulic loads that remove 80% of total suspended solids (TSS) [49]. An additional strategy for overcoming the limits of the built-in wetlands in the RAS system is the inclusion of aquaponics.

3.5 Recirculating aquaculture system

The recirculation aquaculture system cleanses wastewater by reintroducing dangerous pollutants and recirculating purified water. As a result, RAS systems use a very modest volume of water to produce high numbers of fish. Recirculation of the wastewater into the fish tanks is possible in some or all cases. Depending on the supply and feeding rates, recirculation aquaculture systems typically replace 5 to 10% of the water each day [50,51].

Table 1 pollutant removal efficiency in constructed wetlands [49]

Parameter	Average removal efficiency
Suspended solids	47-86%
COD	25-55%
Total phosphorus (TP)	71.2-31.9%
Total inorganic nitrogen	95-98%
NH_4	86-98%
NO_2	More than 99%
NO_3	82-99%

With the use of recirculating aquaculture systems, fish aquaculture is less polluting and utilizes less freshwater, making it more environmentally beneficial. Recirculating aquaculture systems must be developed, and this requires the removal of solids, organic debris, ammonia, and nitrite [52]. Fish can be produced in recirculating aquaculture systems alongside other species, converting nutrients that would otherwise be wasted into valuable goods [17]. This makes the system more resilient than pass-away systems. Aquaculture systems that use recirculation recycle the cleaned water while also relocating hazardous particles are used to remediate wastewater. Because of this, RAS systems only need a relatively modest amount of water to produce big amounts of fish. Recirculating the wastewater to the fish tanks might be done in part or whole. Recirculation aquaculture systems typically have a daily water replacement of 5 to 10%, depending on the supply and feeding rates [52]. RAS is available to mitigate the impact of fish farming on the environment and reduce the need for freshwater. The growth of recirculating aquaculture systems depends on the removal of sediments, organic debris, ammonia, and nitrite.

4 DISCUSSIONS

Aquaponics allows for the recirculation of nitrogen-rich water while producing crops and raising fish [53]. Aquaponics systems provide numerous advantages over traditional farming methods. First, it can be used in a variety of sizes, from indoor units to large-scale ponds. Second, the system is sustainable and capable of producing two agricultural products (vegetables and fish) from a single nitrogen source. Finally, such a system generates little waste, is soil-free, and does not require the use of any fertilizers or chemical pesticides [54]. The concept of aquaponics fulfills one of the global sustainable development goals (SDG8) [55] by creating opportunities for long-term growth and quality jobs. Small-scale farmers could earn more money, those living in urban areas with limited water and land could grow their food (e.g., rooftop aquaponic setup), and commercial farmers would be able to start a viable business in food production through large-scale aquaponics setup [56]. Despite the benefits emphasized in recent aquaponics evaluations, some difficulties persist, impeding researchers and producers in this field. These issues include the necessity for more precise processes for running and supporting aquaponics, as typical insecticides and medicines are not employed, making it difficult to avoid diseases and pests in both fish and plants [57]. Furthermore, integrating the hydroponic and aquaculture components to optimal nutrient consumption remains a difficulty [58], aquaponics suffers from a lack of societal recognition, high initial investment prices, and a lack of programs to offset these expenses. There is also a need for more data, information, training, and education, as well as a viable marketing strategy. Integrating Industry 4.0 into aquaponics faces numerous challenges, including difficult system integration, high prices, skill shortages, compatibility, cybersecurity threats, and environmental adaptation. Implementing smart technology is expensive and complex, necessitating specific kills. Data security, privacy, and interoperability remain top priorities. Future research in aquaponics (i) the need for more comprehensive nutrient management by researching other elements such as phosphorus, potassium, and sulfur distribution in aquaponics; (ii) the application of aquaponic techniques in dry areas where traditional agriculture is limited due to groundwater salinization; (iii) an investigation of alternative fish feeds and polyculture benefits; and (iv) more research on influencing factors, nutrients, and microorganism communities in aquaponics. Furthermore, (v) aquaculture solar energy applications,

(iv) a better understanding of the degree and nature of competition in the market, (vii) exchanging practical experiences globally, (viii) the creation of low-cost aquaponics, (ix) technological developments that cut investment costs and demand less technical knowledge, and (x) continual research and development leading to new crop types and optimum yields.

4.1 Water polishing in aquaponics

Disease outbreaks, pH variations, and system maintenance, among other things, are three key obstacles that aquaponics practitioners frequently face. Understanding these obstacles and applying effective techniques are critical for aquaponics success. Disease outbreaks in aquaponics can be disastrous for both fish and plants. Pathogens can spread quickly in closed aquaponic systems due to their limited nature [15]. Understanding how each aspect affects fish, plants, and microbes is vital. However, the best values for these characteristics vary for each fish. Plants and microbes. To meet the needs of all species in an aquaponic system, compromises are made on certain water quality factors. Table 2 summarizes the permissible water quality parameters in aquaponics.

Table 2 Permissible water quality parameters in aquaponics [59].

Parameters	Permissible concentration
Water Temperature	64–86ºF
pH	6–7
Ammonia	0 ppm
DO	5–8 ppm
Nitrite	0 ppm
Nitrate	5–150 ppm
Water Hardness	60–140 ppm

In aquaponics, preventing nutrient imbalances and maintaining optimal conditions necessitates a combination of proactive activities and continuous monitoring. Numerous ways have been successfully used in aquaponics. One strategy is to use desalination technologies such as reverse osmosis to reverse nutrient concentrations within the system without hurting plant growth-promoting. To ensure sustainability, it is crucial to maintain adequate water quality for good marketable goods and to manage the negative consequences brought on by aquaculture wastewater. Several technological issues need to be resolved before commercial aquaponic systems can be developed that are socially, ecologically, and environmentally sustainable. (1) customized pest control; (2) higher nutrient solubilization and recovery for improved nutrient utilization and elimination of extra-mineral addition, such as phosphorus recycling; (3) Significantly reduced water uses by minimizing the need for water exchange (4) Utilization of alternative energy sources in hot, cold, and desert locations; and (5) using fluidized lime-bed reactors, revolutionary pH stabilization techniques that have been successfully applied in natural waters [60]. Constructed wetlands (CWs) are a green technology for effectively removing nitrogenous waste. The CW system uses less energy (0.1 kWh/m^3) than aerobic filters (0.28 kWh/m^3), Brix [61], making it a more environmentally friendly choice [62]. The main challenge for the CW system is that as the treatment system is scaled up, it has been discovered that nitrate removal effectiveness decreases. The CW method also has to deal with the need for a vast amount of land [63]. Pre-treatment was proven to increase the effectiveness and cost-effectiveness of CWs. Aquaponics is a symbiotic method of growing plants and fish that upholds the idea of sustainability. However, this system's energy needs are far higher than that of CWs, making it difficult to justify economically. By utilizing renewable energy sources and lowering the number of water pumps in the system, it can be made more economical and energy-efficient. The rafter aquaponics system has a 46.8% energy demand, making it more environmentally friendly. On the other hand, by substituting freshwater for wastewater in the traditional pass-away system, it is possible to retain the quality of the water while avoiding the expense of wastewater treatment equipment. The replacement of wastewater, which necessitates a significant amount of fresh water, is a crucial problem that the conventional wastewater treatment system must address. Here, the valuable freshwater resource is abused, and untreated effluent can harm the environment. Recirculating aquaculture systems (RAS) get around the drawbacks of the traditional system, which uses less fresh water because the wastewater is reused. For the production of huge amounts of fish, the RAS system employs an additional 10% of the total water volume as fresh water, making it more sustainable. The accumulation of nitrate in water, which may impact water quality, is the RAS system's main weakness. The current solutions to this issue include installing aerobic filters and external carbon sources, however, there are significant drawbacks, including increased cost and energy requirements when treating nitrate-enriched wastewater. The efficiency of nutrient and water utilization in multi-loop aquaponics systems was enhanced by [64]. Nutrients currently tend to accumulate in the RAS portion of decoupled aquaponics systems while being somewhat scarce in the hydroponics system. Only by switching the subsystems' concentrations in the opposite direction can this issue be resolved from the standpoint of mass balance. The critical factor in this reverse-engineering process is the amount of water that needs to be released daily because it determines the process and concentrates flows. Because it affects the concentration factor of the process water obtained from the RAS, the RO efficiency ratio is crucial. A 4:1 ratio would result in 4 m^3 of demineralized water and 1 m^3 of RAS concentrate from 5 m^3 of RAS process water. The system is provided with a moving bed biofilm reactor which is a very efficient biological treatment method that combines biofilm media with the traditional activated sludge process [64]. Within the aeration and anoxic tanks of the moving bed biofilm reactor process, floating High-Capacity organism chips medium are used. In addition, an up-flow anaerobic sludge blanket reactor schematic creates a layer of granular sludge that suspends in the tank using an anaerobic process. The anaerobic bacteria in the blanket digest (degrade) the wastewater as it moves upward through it. To remove organic substances from water, such as food and waste particles, utilize a protein skimmer or foam fractionator. Another factor limiting aquaponics productivity and profitability is power (for water pumps, aeration, sensors, and lighting, among others). Aquaponics has been proposed as a means of alleviating hunger and malnutrition while also offering an additional source of income [65,66].

4.2 Sustainable aquaponics measures

Aquaponics systems are frequently distinguishable from their hydroponics grower cousins. There are four different types of hydroponics growers: media-filled (grow bed), floating raft or deep-water culture, nutrient film technique, and vertical grower. Aquaponics with grow bed hydroponics, for example, is the simplest method that does not require the installation of a dedicated water filtering unit. The domestic media in the grower, such as light expanded clay aggregate, serves as a surface area for the nitrification process and mineralization to occur, as well as facilitating solid filtration in aquaponics systems and plant growing [67-70]. The nutrient film technique and vertical grower are hydroponics methods using horizontal and vertical pipes respectively where a stream of nutrient-rich aquaponics water is flowing through it. Plants are placed within holes in the top of the pipes for nutrient film technique or at the side of the pipes for vertical growers. These techniques have very low evaporation because the water is completely shielded from the sun. The deep-water culture technique involves suspending plants on polystyrene sheets, with their roots hanging down into the water. This type of grower is the most common for large commercial aquaponics because it can be scaled up to larger operations at a reasonably lower cost compared to other types of growers [71-74]. Aside from the necessary installation cost, which is a one-time investment in the purchase of tanks, pipes, and other discrete components to set up the aquaponics system, numerous non-sustainable components to its operation have a significant impact on the aquaponics operational cost. These include daily fish feeding, water consumption, and the amount of electricity required to run the pumps [75,76]. Electricity consumption for pump running is an unavoidable operational cost in an aquaponics system. For a 6 x 2 m^2 aquaponics unit, a single 100-watt submersible pump is required for water circulation, which typically runs for 24 hours. In addition, air pumps are required to provide appropriate aeration for the fish and plants within the system where the dissolved oxygen level is 5 mg/L. An aquaponics system requires electricity to operate the pumps and so will not function without a consistent source of power. In Malaysia, price and electrical consumption tariffs normally range between 30 and 50 cents per kWh, depending on whether the electricity is used for residential, commercial/industrial, or agricultural reasons. These rates may not be an issue for small-scale operators running a backyard (or rooftop) aquaponics system. However, for a bigger commercial aquaponics farm (i.e., an area greater than one acre) and/or for low-income farmers in rural areas (i.e., a group with a monthly family income of less than 600$), such prices may be a strain on their aquaponics operation [77,78]. However, the electricity supply in third-world countries is unpredictable and epileptic. Aside from a few users of solar and wind energy (which serve as supplements to fossil fuels), there has been no documented commercial usage of other alternative power sources; consequently, it has remained a difficulty. As a result, more research is needed to assess the usefulness and efficacy of intermitted recirculation time on the production characteristics of fish and crops in an aquaponics production system, which might assist in reducing the cost of power utilized in production.

4.3 Challenges to the Implementation of Large-Scale Aquaponics

Despite its obvious benefits, large-scale aquaponics deployment presents several problems. A complex balance of critical parameters—such as water quality, pH, temperature, and oxygen levels—is required for the optimal growth of fish, bacteria, and plants in the system [79]. It is vital to regularly monitor these elements. The rise in aquaponics research covers a wide range of themes, including system types, hydroponic aspects, species variety, management strategies, environmental concerns, and energy efficiency [80,81]. The multidisciplinary character of aquaponics, which involves numerous fields such as agriculture, aquaculture, microbiology, and others, presents a challenge for comprehensive evaluations [82]. While existing assessments are extensive, they typically lack in-depth insights into energy use efficiency (EUE) and greenhouse aquaponics' energy demands. Aquaponics' energy requirement, particularly in greenhouse and indoor settings, is predominantly driven by artificial lighting, which accounts for a major share of electricity usage [83]. According to reports, lighting significantly increases the output expenses of indoor farming [84]. Despite several studies on lighting efficiency, a definitive light response spectrum for various plant growth phases remains elusive [84]. Managing the energy consumption of artificial lighting in large-scale aquaponics entails improving lighting systems to balance efficiency and crop demand. Lighting, a major contributor to production costs in indoor farming, lacks a definite spectrum for distinct plant growth phases, despite several efficiency studies.

Using technology such as LEDs, regulating intensity based on plant demands, and automating with smart systems are all part of the optimization process. Integrating renewable energy and efficient designs promotes both sustainability and cost-effectiveness. Efficient management promotes growth while decreasing costs, necessitating a holistic approach that includes technology adoption, smart controls, renewable energy, and customized lighting schemes. Reduced costs and environmental impact are critical for long-term success in large-scale aquaponics. Aquaponics performance varies greatly between urban and rural settings due to economic viability, environmental sustainability, and technological control levels [85]. Land-efficient, urban-based aquaponics systems provide benefits in high-density areas by lowering transportation costs and improving supply chain management [86]. In contrast, rural and peri-urban locations lacking special benefits such as renewable energy sources may face constraints in constructing commercially effective aquaponics plants.

5. CONCLUSIONS

The aquaponics production system, which combines soilless plant cultivation (hydroponics) with a recirculatory aquaculture system, is without a doubt an environmentally benign solution for food production. Despite years of progress, there are still numerous study areas to be explored to produce information that can help concurrently increase plant and fish productivity. While many of these study fields have been included in this review, it is crucial to note that identifying allied aquaponics technologies is an important method for increasing the system's functionality. Given that aquaponics is based on the reuse of nutrients and water, it appears to be a viable option for sustainable hydroponic and aquaculture practices. However, as seen by the difficulties mentioned in this work, more study and advancements are required. A commercial reverse osmosis filtration system that offers excellent water quality management is an efficient way to remove harmful chemicals from water for small-scale aquaponics. Constructed wetland systems have demonstrated excellent efficacy in the treatment of nitrogen-containing wastewater, with removal efficiencies for NH_4-N exceeding 98% and NO_2-N exceeding 98%. Recirculation systems are demonstrated to be more sustainable and efficient in regulating the volume of effluent in aquaculture units because only 10% of the total volume of water is refilled daily. While we have underlined the potential of the aquaponics production system as a solution for solving various challenges in developing countries and ensuring food security, it is unfortunate that domesticating this technology is inadequate. As a result, the additional expense of solar plants may be spent on the building and operation of the aquaponics system in Africa and the Middle East region. The long-term viability of this type of setup, as well as the venture's profitability, could be the focus of future research.

Author Contributions

Conceptualization, Mohamed Elsayed Gabr and Nawaf S. Alhajeri; methodology, Mohamed Elsayed Gabr and Nawaf S. Alhajeri, data collection, Mohamed Elsayed Gabr, Nawaf S. Alhajeri, Fahad M. Al-Fadhli, and Salem Al Jabri, validation, Mohamed Elsayed Gabr and Fahad M. Al-Fadhli, formal analysis, Nawaf S. Alhajeri and Salem Al Jabri, investigation, Mohamed Elsayed Gabr and Salem Al Jabri, write—review and editing, Mohamed Elsayed Gabr, writing—original draft preparation, Mohamed Elsayed Gabr, editing—original draft, Mohamed Elsayed Gabr, Nawaf S. Alhajeri, Fahad M. Al-Fadhli, and Salem Al Jabri. All authors have read and agreed to the published version of the manuscript.

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Declaration of competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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