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Comprehensive Review of Aquaponic, Hydroponic, and Recirculating Aquaculture Systems

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KEYWORDS

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Aquaponics

Types

Vegetables

Recirculatory aquaculture system

Applications

ABSTRACT

Hydroponics and aquaponics are emergent agricultural techniques that offer several environmental solutions. It is anticipated that the hydroponic systems will result in a more significant profit from selling vegetables and other plants. The use of new technologies, such as hydroponics and aquaponics, has been demonstrated to increase the number of plants that can be grown. The recirculatory aquaculture system makes it possible to multiply fish production while consuming fewer resources. Essential factors of this technology include higher yield, safety, and water management. In addition, the scope of potential future research in hydroponics and aquaponics has been discussed. Furthermore, the paper identifies and discusses the various applications of hydroponics and aquaponics in agriculture.

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1 Introduction

The need to continuously develop alternative farming methods has always been important, especially in response to the multiple problems faced by conventional agriculture (Manos and Xydis 2019). Various organizations such as European Union, the Environmental Protection Agency, and the WHO often recommend the use of recycled water for irrigation, as a suitable solution for formulating water management strategies. According to studies, Hydroponic systems can be utilized to both produce food and treat wastewater (Sundar et al. 2021). They are a simple technology that enables the soil-free growth of plants in water (Jayachandran et al. 2022). Plants get the nutrients they need for growth from the aqueous solution (Shubham and Shrimanth 2020). Because plants can absorb nutrients, toxic metals, and emerging pollutants, the hydroponic system may also be utilized as a management technique before partially treated effluent is released eventually into the environment (Cifuentes-Torres et al. 2020).

Aquaponics means the co-cultivation of fish and plants together and it is widely used as a solution to the growing food demand in urban landscapes. The combination of aquaculture and hydroponics provides an environment where both can flourish. Filtered aquaculture effluent is supplied into the hydroponic technique for giving food to bacteria along with the roots of plants. This water is reused back into the fish farming tanks once the accumulated nutrients have been removed. To increase the nitrogen utilization rate in aquaponics systems, this analysis investigates the significant consequences of nitrate nitrogen from influent to output, including NH_3, nitrogen generation, nitrogen removal, nitrate absorption, and nitrogen transport (Schmautz et al. 2021).

Most people believe aquaponic farms to be a superior opportunity to hydroponic farms as a soilless growing method. Controlled-farming techniques such as aquaponics and hydroponics have become a great method for feeding the world's population, which is rapidly expanding while using minimum land and water. The hydroponic system, however, might be more environmentally friendly than the aquaponics system if the energy source were switched to renewable sources of energy. This life cycle assessment research can give control to environmental agriculturists with the foundation work to decrease the price of manufacturing (Chen et al. 2020).

The manufacturing system is depending on a stable equilibrium among the bacterial, plant, and fish groups (Figure 1). Compared with aquaculture systems, the core microbial communities of the decoupled and connected systems share other widespread operating systematic groups (Eck et al. 2019).

Aquaponics is a system in which fish waste feeds plants, which in turn cleans the water; when fish produce waste (ammonia) which is converted to nitrate by bacteria so that the plants can take it up (Figure 2) (Puteri Edaroyati et al. 2017).

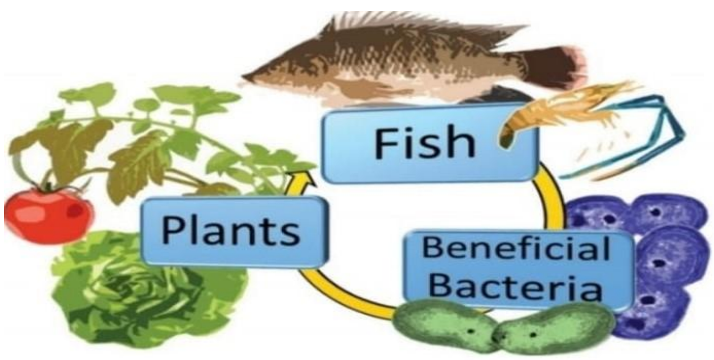


Figure 1 Components of an aquaponic system (Pattillo 2017a).

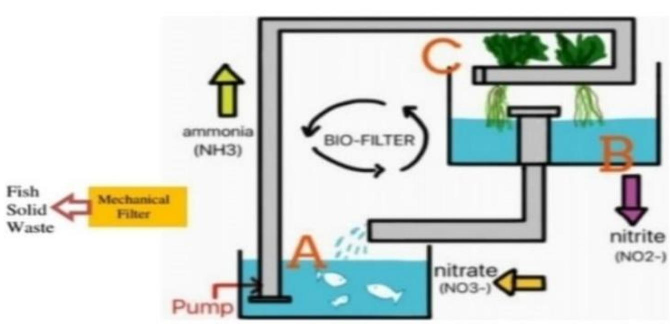


Figure 2 Schematic diagram of the Aquaponic cycle (El-Essawy et al. 2019).

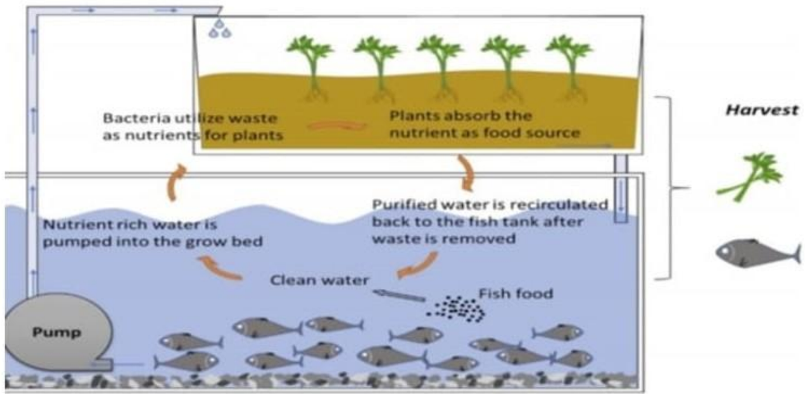


Figure 3 Schematic diagram of Aquaponics (Wei et al. 2019)

This technology makes it possible to use coastal areas, nutrient reuse, reduced pollution, great production, and more effectively. Future aquaponics systems will grow smarter, more efficient, and more effective as a result of technological advancements (Wei et al. 2019) (Figure 3). The futuristic farms have developed the right technology for automated hydroponics, making them pioneers in the hydroponics scene. Monitoring of automated aquaponics technology, the internet of things (IoT), and intelligent systems claimed to have high water efficiency, and consume 90% less water than traditional farming (Bawiec et al. 2018). The technology is environmentally friendly since it uses fewer fertilizers and nil pesticides (Yanes et al. 2020).

The principal objective of aquaponic systems is to stimulate plant growth by employing aquatic animal waste. As a result, aquaponics uses fish waste as plant fertilizer whereas the plants clean the fish's water.

2 Plants used in aquaponics and hydroponics

Herbs like sweet wormwood (*Artemisia annua*), gotu kola (*Centella asiatica*), and especially greens such as spinach (*Spinacia oleracea*), lettuce (*Lactuca sativa*), spearmint (*Mentha spicata*), basil (*Ocimum basilicum*), chives (*Allium schoenoprasum*), and watercress (*Nasturtium officinale*) are perfectly suitable for aquaponics systems. The edible plants like carrot, pumpkin, amaranth, swiss chard, bell peppers, sweet peppers, pak choi, tomatoes, mustard green, kai lan, and cucumbers have an advanced nutritious demand and its efficiency improved in an extensively provided safe aquaponic system.

2.1 Tomato production

Compared to conventional tomato cultivation, evaluating the economic effectiveness of multi-tiered narrow-rack hydroponics showed inherent advantages (Balashova et al. 2019). Askari-Khorasgani and Pessarakli (2020a) observed that in the vermin hydroponic system, the most important thing is in the vermiponic units, the most effective tomato (*S. lycopersicum*) cultural customs provide the best economical and environmentally friendly method of horticultural crops.

2.2 Tomato, basil, and lettuce production

Yang and Kim (2020a) evaluated the phosphorus and nitrogen accumulation stability for tomatoes, lettuce, and basil established in hydroponic and aquaponic technology. The research revealed that the distribution of N and P is mostly affected by these plant species. However, due to its increased biomass output, the tomato was more successful than lettuce and basil at extracting nitrogen from sewage and minimizing denitrification (Yang and Kim 2020a). Their investigation further demonstrated that the profitable give of tomatoes was alike between hydroponics and aquaponics, as lettuce and basil had relatively higher yields (Yang and Kim 2020c).

2.3 Kale production

Kale (*Brassica oleracea l.)* is one of the vegetables produced quickly in hydroponics systems and can be supplied to the market. Kale was cultivated with various stages of natural nutrients in the total hydroponic system to determine its yield, pigment composition, and chemical characteristics. The study showed that Acacia and moringa ferments can be used as nutrient solutions to support kale production in a total hydroponic system and can significantly impact promoting climate-smart organic agriculture (Salas et al. 2020).

2.4 Carrot production

A healthy and manageable root environment is offered by hydroponics. Sakamoto et al. (2020) reported that hydroponic carrots (*Daucus carota*) could be shaped differently based on partially removed early taproots. They observed how partial removal of early hydroponic carrots' early taproots influences their growth mechanisms.

2.5 Swiss chard production

The effects of microelement addition to aquaculture effluent on the swiss chard development (*Beta vulgaris L. spp. cicla*) were found in an aquaponic system using saline groundwater. When microelements were supplied, Swiss chard grown with aquaculture effluent produced sufficient production without chlorosis (Kaburagi et al. 2020).

2.6 Cherry and Tomatoes production

Organic hydroponic fertilizer should be used if certain plants require mineral nutrients supplementation. Hydroponically grown cherry (*Prunus avium*) and fresh tomatoes (*Solanum lycopersicum*) respond to limited fertilization and reduced nutrient concentration when grown in shade nets. Studies on cherries and tomatoes, may minimize nutrient expenditure and result in cost savings of 25% and 50% on fertilizer input costs, as well as decrease the risk of water contamination (Maboko and Du Plooy 2017).

2.7 Mini-Cucumber production

Researchers investigated the nutrients of hydroponically grown mini-cucumbers (*Cucumis sativus* L.) Maboko et al. (2017) studied that the nutritive value was heightened by the condensed nutrient concentration and foliar fertilization. An analysis of the study showed that a reduced nutrient concentration of 75% is enough to maintain cucumber yields and quality, whereas foliar fertilizer has little effect.

2.8 Mint and mushroom herb production

Mint (*Mentha piperitta* L) and mushroom (*Agaricus bisporus*) have excellent nutritional value, making them suitable for aquaponic farming due to the small amount of complement addition required. Hence the modest management effort was causing costs to be raised (Nozzi et al. 2018).

2.9 Pak Choy production

A household-scale aquaponics system was used to optimize the growth of Pak Choy (*Brassica rapa L. var. Chinensis*). Priadi et al. (2019) reported that in the vertical design, Pak Choy's growth parameters were advanced compared with the horizontal one, though the differences were not statistically significant.

2.10 *Nigella sativa* production

Hydroponically grown *Nigella sativa* was studied to determine if additives affected its growth. Using standard plant growth stimulants is a viable alternative to chemical fertilizers. It has been shown that plants treated with *Tricoderma harzianum* spores (fungus) have improved in essential oil and NPK. In hydroponic plant growth, all treatments resulted in an increased yield of seeds, oils, and plants (Nosir et al. 2017).

2.11 Lettuce production

Lettuce is one of the most popular vegetables grown in aquaponic systems. The study showed the potential for year-round lettuce making in the flow-through aquaponic system. Standard yield in the Spring period was the maximum, while productivity in the summer season is elevated than that in spring (Johnson et al. 2016).

Utilizing various growing media, lettuce was produced in hydroponic and aquaponic methods. In both aquaponic and hydroponic systems, the cocopeat-based substrate produced higher yields, making it a better choice for growing lettuce. Lower average harvests were seen in both of the examined production systems when the phenolic foam was used as a medium for agriculture (Jordan et al. 2018). The application of a technique for butter crunch lettuce (*L. sativa*) vertical flowing hydroponic systems coupled with zeolite restoration to create a reusable nitrogen protection system is suggested. The research proved the possibility of fertilizer purification units to concurrently decrease anaerobic membrane bioreactor ammonia-nitrogen concentration while supplying a long-term source of nitrogen for use in hydroponic systems (Calabria et al. 2019).

The study found that fertilizer injection allows a more significant addition of nutrients than water supply treated with chemical fertilizers. Conversely, water supply without supplemental nutrients leads to diminished biomass and nutrient deficits in the vegetation (Mahlangu et al. 2016; da Silva Cuba Carvalho et al. 2018). At the same time, conventional cultivation was done with direct irrigation by using hydroponic solutions, natural irrigation with aquarium waste and wastewater, and managed examination using fresh water with fertilizers. Particularly since the farming region has insufficient water resources, systematic farming is also approximately 80% more water-efficient than topsoil farming (Sayara et al. 2016). The organic hydroponic method was used to study the effects of magnetic field treatments on nutrition solutions on lettuce plant growth (Youssef and Abou kamer 2019). Similarly, Moraes et al. (2020) worked on three lettuce cultivars in a hydroponic system with plants grown below the greenhouse and reported that the cultivar is preferred for the development of leaf length compared with supplementary cultivars.

2.12 Lettuce and water spinach with koi fish and Rainbow trout

Lettuce (*L. sativa L.*) along with rainbow trout (*Oncorhynchus mykiss w.*) crops were grown within a recirculating aquaponic method. According to the study, the lightweight expanded clay aggregate section of a new aquaponics system removed more ammonium, nitrate, and orthophosphate than the raft portion of the plan (Velichkova et al. 2019). Based on the study, the combination of water spinach plants with koi fish formed the maximum yield and determined the maximum complete development of fish and a survival rate of hundred percent (Andriani et al. 2019).

2.13 Lettuces and lambari fishes

Bianchini et al. (2020) demonstrated that sanitation procedures before consuming vegetables must be achieved, regardless of the agriculture technique. The study showed by slurry that total and thermotolerant coliforms were present in all phases of aquaponics (system combining lettuces and lambari fishes).

Further, to estimate the water quality of an aquaponic system, lettuces and lambari fishes were collected and this study showed that total coliforms and thermotolerant coliforms were present in all phases of aquaponics, demonstrating that sanitation procedures before the consumption of vegetables must be achieved. It suggested that the shrimp concentration was unsuitable, which made the system incapable of raising the concentration of nutrients inside vegetables with reduced yields. It was initially believed that domestic lettuce hydroponic cultivation produced organic wastes, but commercial lettuce production was enhanced to make use of components in the water, including magnesium, potassium, and calcium (Lima et al. 2019).

2.14 Gotukola with koi carp

In aquaponics, phytoremediation wastewater was used to grow gotukola (*Centella asiatica*) and koi carp (*Cyprinus carpio var. koi*). By evaluating the proportions of nutrients removed and biofilter performance, aquaponics was evaluated for its effectiveness. It was determined that aquaculture wastewater treated with phytoremediation could be recycled for fish and plant production in aquaponics (Nuwansi et al. 2019).

2.15 Mint with common carp

In hydroponics with an aquaculture system, healthy typical koi (Cyprinus carpio) were grown using various hydroponic media for mint (*Menthaar vensis*). According to this study, compressed sandstone and balanced raft were significantly more competent than river stone in nutrient removal and maintaining satisfactory water quality for fish culture (Shete et al. 2017). Similarly, in a combined system, the production activities of various plants must be measured on the best levels. This best water application flow value inside hydroponics with aquaculture method by healthy typical koi (*C. carpio*) along with *Menthaar vensis* bio-integration was determined (Mint). The aquaponic recirculation system proved a successful method for carp and mint production and an advantageous method for recycling fish farming effluent to preserve its water wealth (Shete et al. 2016).

2.16 Pumpkin with catfish

Similarly, an aquaponic Catfish-pumpkin system illustrates the impact of various growing mediums both water excellence along with vegetation productivity. Water excellence and the proportion of reduction of mineral nutrients (Ammonia, Nitrite, as well as Nitrate) throughout the structure including in dissimilar growth stages are significant (Oladimeji et al. 2020b). Analyzed the growth of fingerling striped catfish (*Pangasianodon hypophthalmus*) in an aquaponics system with fine bubbles. A study found that aquaponics with fine bubbles led to increased fish growth, fish survival, and the highest plant growth (Naomi et al. 2020).

2.17 Goldfish with microgreen

Kizak and Kapaligoz (2019) monitored changes in the growth of goldfish (*Carassius auratus*) and aquatic habitats in microgreen recirculating aquaponic systems. Their study found that when the pH was high, Arugula micro-greens primarily used ammonia instead of nitrate nitrogen.

2.18 Spearmint with Tilapia production

Aquaponics can also be used for plants high in nutrients like Spearmint. The growth of herbal plants is suitable for a good environment, and they could be employed as biofilters within hydroponic aquaculture production technologies. Spearmint plant has a maximum production rate, which indicates its ability to effectively absorb nutrients within that method (Espinosa-Moya et al. 2018).

3 Hydroponic systems in domestic wastewater treatment

Integrating hydroponic systems with household wastewater treatment can lower expenses by removing fewer contaminants and using less energy and maintenance than traditional wastewater treatment. The decentralized system is employed for vegetable production, home wastewater treatment, and municipal agriculture. A hydroponic system is acceptable for wastewater treatment if it can reduce the health concerns that come with contact with wastewater for farmers, harvested crops, and customers (Magwaza et al. 2020).

It is suggested to treat wastewaters with a high concentration of organic matter and nutrients and poor biocompatible to produce an effluent that may be utilized as a nutrient solution for lettuce hydroponic production (*L. sativa var. crisp*). The generated effluent gives a high pH and nutritional level (nitrogen & phosphorus) for lettuce growing in the hydroponic system. The procedure had a 100% success rate in removing all coliforms (Da Silva Correia et al. 2018). This study's objective was to assess how biologically active component levels in greywater were treated using the hydroponic technique as a treatment system. According to the findings, whether or not the third stage of purification is used, the efficacy of purifying will be comparable (Bawiec 2019).

Eregno et al. (2017) measured the health risk of using grey water recycled for hydroponically growing lettuce in an eco-friendly wall. It was shown that greywater treatment systems could be made better by adopting suitable research techniques and growing plant varieties capable of capturing less heavy metals and removing them from the greywater.

Hydroponic root mats be a green technology used for various wastewater decontamination. The Vetiver grasses (*Chrysopogon zizanioides*) were suitable for nutrient and organics removal in the bio-remediation of brewery wastewater utilizing hydroponics. The results showed that the phytoremedial ability of the vetiver grass is used in improving wastewater quality (Worku et al. 2018). This study showed that making hydroponic root mats are sustainable. It was found that harvesting before the plants fade is more successful in removing nitrogen and retaining a sustainable structure (Sun et al. 2019).

4 Modern commercial aquaponic systems

4.1 Coupled aquaponics systems

There are two main types of aquaponic systems - coupled and decoupled. Typically, coupled aquaponics systems have an unidirectional flow of water that begins in the fish culture unit, passes through solids and biological filters, and then through the hydroponic unit and sump tank before returning to the fish to complete the cycle. Plant nutrition, solids, biological filtration, and feed consistency are vital to the product's continued and predictable production (Figure 4).

4.2 Decoupled aquaponic systems

A decoupled aquaponics system provides a separation between the fish and plants in the farming process, treating diseases in one part of the system without completely disrupting the entire system (Pattillo 2017a). These methods can develop to be the most successful, long-lasting workflows for the growth of plant and animal resources. The study shows that it decreases carbon dioxide released in a vegetable growing place by 72% by reducing the power of a waste reduction and reprocessing system (Abbey et al. 2019). A statistical study was carried out to improve the system using a multi-loop decoupled aquaponics system (Figure 5). The results showed that nutrient concentration ranges significantly change the presentation of several aquaponic methods within conditions of longevity (Dijkgraaf et al. 2019).

Maucieri et al. (2017) showed that the intercropping technique is a possible solution to improve vegetable quality in an aquaponic system. The multiple cropping of vegetables did not control the oxidation–reduction potential, electric conductivity, pH, temperature, water, nor O_2 content.

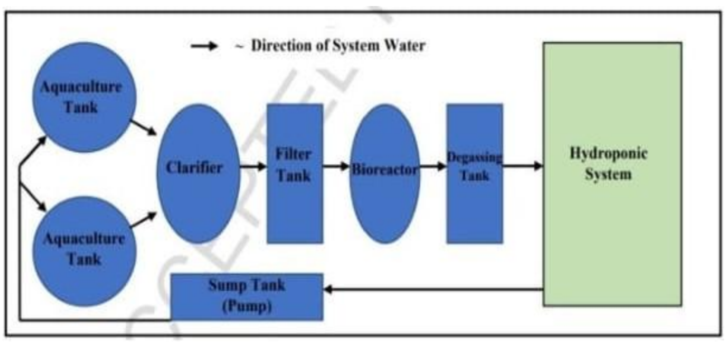


Figure 4 Example of coupled Aquaponics system (Rakocy 2012; Palm et al. 2018)

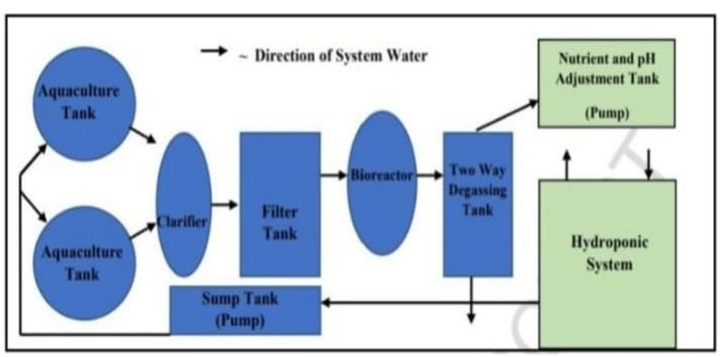


Figure 5 Example of decoupled Aquaponics system (Kloas et al. 2015; Rakocy 2012)

Figure 6 Dutch Bucket hydroponic system for cultivating tomatoes (Osei et al. 2019).

Figure 7 Drip irrigation system (Sahubawa et al. 2020).

4.3 Double recirculating aquaponic system

To cultivate tomato crops that are similar to those in a hydroponic system, dual recirculation aquaponics containing 2 self-regulating phases is necessary. This system lowers the reasonable costs of plant production and recycling of aquaculture effluent along with a related decreased amount of nitrogen production (Suhl et al. 2016).

Studies on low-tech aquaponics systems with different fish-supplying densities by Maucieri et al. (2020) showed that aquaponics systems on modest providing mass-improved crop production, related to hydroponics, but not reducing the quality of the vegetables. Compared to hydroponics, aquaponics gives a higher supply volume and is better economically valuable.

4.4 Aquaponics with subsystems

Macrophytes in the media bed system and NFT are used to remove dissolved phosphorus, total ammoniacal nitrogen, nitrite-nitrogen, nitrate nitrogen, and total nitrogen (Li et al. 2019). Aquaponic systems with two different hydroponic subsystems were used to analyze the development with a yield of fish organisms. This study demonstrates that, throughout the entire process of testing the statistical significance, the aqueous spinach cultivars' proliferation and productivity were not enhanced by hydroponic components (Quí et al. 2020). Hydroponic and immobilized biofilm technology were produced for controlling water quality and increasing feeding effectiveness in pilot-scale aquaponics systems, including mass biosystems.

4.5 Dutch bucket hydroponic system

This system utilized buckets (of varying sizes, filled with inert medium) to grow plants. Plants with extensive roots, such as tomatoes, cucumbers, etc., can be grown in this system. The Dutch bucket works based on the principles of ebb and flow. It is just a variation of that method. The nutrient is forced into a bucket, where it is automatically drained back into the reservoir. The Dutch Bucket is the easiest and most effective way to grow hydroponically indoors or outdoors (Buckets 2018) (Figure 6).

4.6 Dripping method for hydroponics

Irrigation water employs a motor to regularly supply plants with fertilizer and water, making it a dynamic hydroponic design. It is also known as a trickle irrigation system or micro irrigation system. Small emitters are used to drip-wise feed the fertilizer solution onto the plants. Tangune et al. 2016 assessed *Brassica oleracea's* reaction to groundwater concentration below dripping irrigated agriculture during confined surroundings (Figure 7). This study revealed that the soil water tension could not extensively affect water use effectiveness or height of marketable heads.

4.7 Automated hydroponic system

Automated methods will be investigated to provide consistent nutrients in hydroponic solutions by automatically adding nutrients and nutrient concentrations. The automated hydroponic modular system (Figure 8) showed the methodology based on components

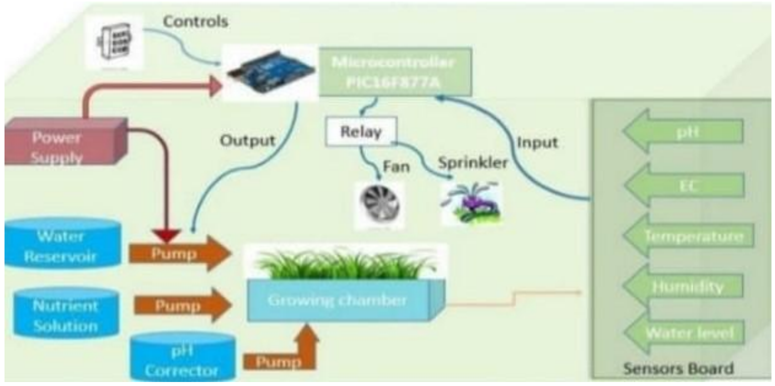


Figure 8 Fully Automated hydroponics system (Shetty et al. 2021).

and provides the pH value of the liquid fertilizer; if the level is insufficient, it will immediately activate the absorption of the solution into the container storage to afterward run the automated irrigation system for hydroponics (González-Linch et al. 2019). Similarly, a computerization system is planned using raspberry microcontrollers and Arduino as a comparative management technique, and it could manage the water temperature and pH (Supriadi et al. 2019). The dissolved oxygen content in an aquaponics system is increased by modifying the aquaculture water and the greenhouse environment (Ren et al. 2018).

The hydroponics by nutrient film technique is a technology for the agriculture of green fodder. This research confirms it is important for agriculture for its extremely used vegetation growth space level and closed-loop water management to plants, which enables it to be readily automated depending on solution conditions. It is beneficial to develop NFT equipment and process management systems in maximizing hydroponic food production methods (Grigas et al. 2020). A hydroponic system integrating pH sensors is suitable for small space areas such as high-rise buildings. The research demonstrates that the computerized method is appropriate for the internet of things and that the user may integrate this information into a created computer to get the best output (Esa et al. 2019).

5 Hydroponic growing methods used in aquaponics

Recirculating nutrient film technique, vertical felt, floating raft, deep floating technique, flood-and-drain system, and aeroponics system are the hydroponic growing techniques utilized in aquaponics systems.

6 Important parameters for Aquaponics and Hydroponics

The environment for the aquaponic system should be patently chosen to avoid pollution factors. The water physicochemical analysis of pH, temperature, dissolved oxygen, nitrate, nitrite, ammonia, calcium, magnesium, and phosphorus should be performed for the maintenance of the aquaponic system (Gavrilă et al. 2019).

6.1 pH and Temperature

Water quality is a very significant parameter for aquaponics and hydroponics cultivation systems. The major factors include total nitrogen, pH, water temperature, dissolved oxygen content, and water hardness. The pH range for hydroponics is 5.5 to 6.5 (Trejo-Téllez and Gómez-Merino 2012) and the optimal pH range for aquaponically grown crops is between 6.5 and 8.0 (Goddek et al. 2015). In hydroponics, it is advised to keep the temperature below 70°F, while in aquaponics, it should be around 82 and 86°F. According to Yang and Kim (2020b), stream speed plays a significant role in the construction of aquaponic crops because it influences the temporal and spatial water quality parameters, which in turn determines the development and productivity of the crops. Aquaponic production requires good water management. A freshwater flow-through fish culture system was used to evaluate the aquaponic crops. The researchers found nutrient recruitment from accumulated solids in the aquaponic channels was responsible for the slightest improvement in water quality (Buzby et al. 2016).

Numerous necessary components for crops are lacking in aquaponics, and the pH of the water can either make these nutrients more or less. To study more about the nutritional kinetics of this mechanism, the investigation into other nutrients offered by the system (such as solid particles conveyed with irrigation water) is recommended (Blanchard et al. 2020). Hydroponic food production is also used to improve crop quality, including taste, sensory attributes, and post-yield durability (Walters et al. 2020).

It was determined through water quality analysis that the aquaponic system's warmth, alkalinity, dissolved oxygen concentration, the total suspended particles have all been within the allowable limit and adequate for the development of Tilapia fish, everlasting greens, green mustard vegetables, and nitrification bacteria. Several necessary economic and fruit cultivation trades can be developed using aquaculture wastewater as part of a large-scale development program (Sahubawa et al. 2020; Alam et al. 2020).

Table 1 Types of Aquaponics and subsystems

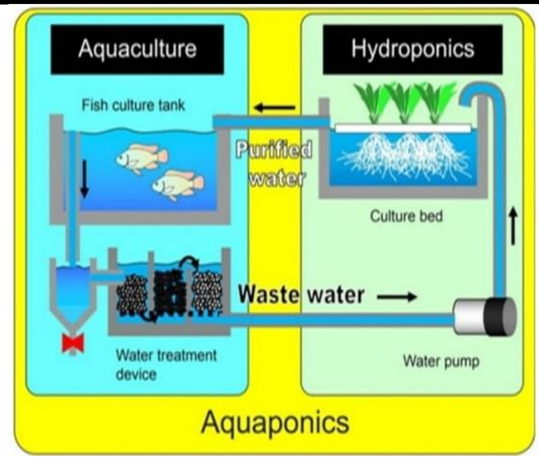
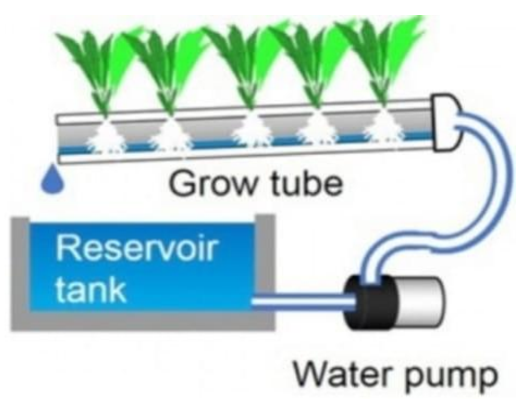
S. No.	Types	Aquaponics and subsystems	Figures
1	Aquaponic system.	In the municipal areas, there are some possibilities for producing supportable seafood and plant production using aquaponics. In this case, some research gaps exist related to the following aspects such as 1. Variety of aquatic and plant species studied. 2. Miscellaneous distribution of the environmental and economic impacts to the co-products. 3. Transportation of formed food 4. Presence of heavy metals, pests, and pathogens with human health consequences (Figure 9) (Wu et al. 2019).	 Figure 9 Aquaponics system (Endo 2018)
2	Aquaponics with subsystems	The comparative studies carried out between deep water culture and integrated aqua vega culture systems at the pilot scale showed that profitability and water conservation were higher in aquaponic systems. This is due to the higher fish production in deep water culture. It is possible to practice by making additional investments in aquaponic system industrial design for reducing expenses and consequently, it is further appropriate for interior agriculture production. (Figure 10) (El-Essawy et al. 2019). This allows an understanding of gaps in product design.	 Figure 10 Aquaponics with sub-systems (El-Essawy et al. 2019).

Table 2 Methods of aquaponic hydroponic gardening

S. No.	Types	Aquaponics uses hydroponic growing techniques.	Figures
1	Nutrient film method	An innovative method of farming known as the "nutrient film method " distributes nutrients by bare roots to provide the nutrients needed by plants for proper growth and development (Qadeer 2020). The studies related to Peppermint (*M. piperita*) and Coriander (*Coriandrum sativum*) performed well as secondary biofilters within a recirculating aquaculture system based on the nutrient film system (Ogah et al. 2020). Suhl et al. 2019 demonstrated that fish wastewater is utilized to nourish NFT hydroponic systems developed vegetation to manage the oxygen assimilation is extremely suggested, particularly at high levels of conductivity (Figure 11). This provides a chance to understand variations in nutrient concentration for various plants.	 Figure 11 Recirculating Nutrient film techniques (Endo 2018)

<table>
<tr><td>2</td><td>NFT hydroponics system and NFT aquaponics system.</td><td>Jordan et al. 2018 designed Lettuce cultivated on different substrates in hydro and aquaculture systems (Figure 12). The cocopeat medium produced higher yields in both hydroponic and aquaculture systems, making it a preferable option for producing lettuce.</td><td>
Figure 12 (a) Nutrient film techniques hydroponic systems (Pattillo 2017b)

Figure 12 (b) Nutrient film techniques aquaponic systems (Pattillo 2017b).</td></tr>
<tr><td>3</td><td>Different hydroponic subsystems NFT vertical felt and floating raft.</td><td>Different hydroponic subsystems were made (nutrient film technology, vertical felt, and floating raft) (Figure 13). Those are evaluated using the United States alimentary and agricultural agencies that serve as models to produce goldfish (C. auratus) and lettuce (L. sativa).
The study showed similar results in fish production (Pérez-Urrestarazu et al. 2019).</td><td>
Figure 13(a) Nutrient film techniques: Vertical felt (Pattillo 2017b)

Figure 13(b) Nutrient film techniques: Floating raft (Pattillo 2017b).</td></tr>
</table>

Table 3 Other Types of Hydroponics

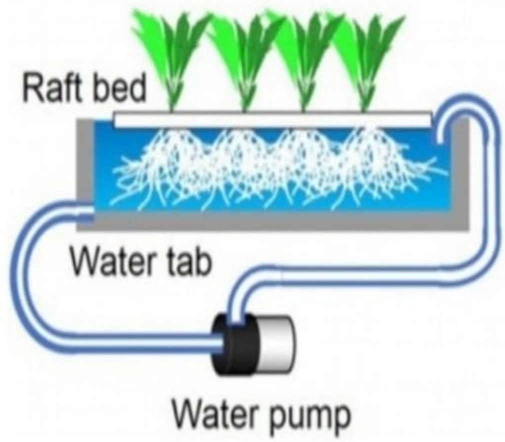
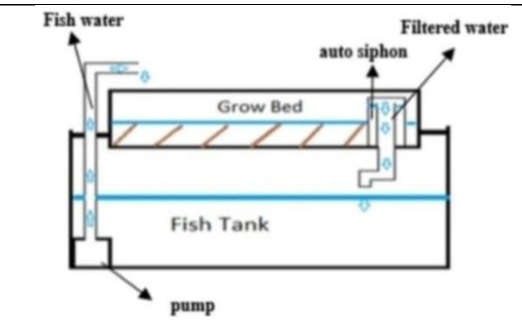
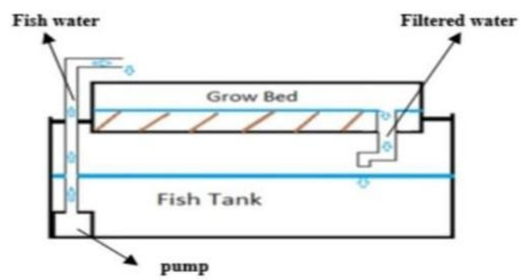
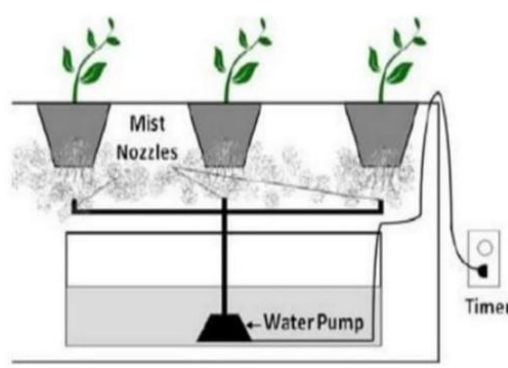
S. No	Types	Other Types of Hydroponics	Figures
1	Deep water culture / Deep floating technique. • It is a hydroponic technique in which plant roots are submerged in nutrient-rich, highly oxidized water (Series and Science 2021).	Triyono et al. (2019) showed how 3 distinct hydroponic containers like a hydraulic cooler, a Polystyrene box, and a bucket affected the growth of three hydroponically grown vegetables such as pak choi, mustard greens, and kai lan. (Figure 14). This study shows that using polystyrene boxes for fertilizer storage did not significantly boost production for tropical locations and that plants growing with nutrients stored in the cooler performed the best for various testing conditions. (Triyono et al. 2019). In bigger commercial-scale systems, it is frequently used (Janni and Jadhav 2022).	 Figure 14 Deep floating technique (Endo 2018)
2	Systems for flooding and drainage and continuous flow. • Drains nutrient solution back into the reservoir after rapidly flooding grow tray by using a submersible pump.	For carps (*C. carpio*) and basil, the flooding and water steady flow methods were examined for variations in water condition, carp production, and plant growth measures (*Ocimum basilicum*). This study showed that both the flooding and drainage and steady flowing methods are suitable for the growing of carp and basil (Homoki et al. 2020) (Figure 15).	 Figure 15 (a) Flood- and- drain system (Homoki et al. 2020)  Figure 15 (b) Constant flow system (Homoki et al. 2020)
3	Aeroponic system	Plant roots are continuously or intermittently in a deeper air or development tank elevated while nutrient solution in droplets is periodically supplied for plant growth. The process provides high aeration (around 100%) and consumes very little water (Biswas et al. 2022). Reena Kumari and Kumar (2019) studied that organic agriculture and hydroponics are both used in aeroponic agriculture. These methods have successfully produced crop potatoes, leafy vegetables, culinary herbs, and reproduction for economic uses. Aeroponics is a very practical way of growing root systems and aerial portions (Figure 16).	 Figure 16 Aeroponics system (Saxena 2021)

Table 4 Merits and Demerits of aquaponic, hydroponic, and related systems

S. No	Aquaponic, hydroponic and related systems	Merits	Demerits
1	Aquaponic system	1. Organic manufacturing method of aquatic organisms and vegetables. 2. Reduce damage from pests and diseases. 3. Significant reduction in the use of water.	1. It is not used for commercial production. 2. There is insufficient lengthy research (Tyson et al. 2011). 3. Reduced efficiency, particularly on the plant side.
2	Aquaponics with subsystems	1. Water quality control and improved nourishment effectiveness. 2. Produced high quality safe organic food. 3. Provide an artificial filtration system for the fish culture environment.	1. High demand for monitoring and control. 2. Lack of skillful technicians and laborers.
3	Wick system	1. Regulates the container's base humidity at a steady level. 2. Simplicity and space efficiency. 3. According to the permeable mat, uses less water.	1. For the manufacture of major commercial crops, the technique is not yet established. 2. It works well for tiny, non-fruiting vegetation, like herbs. 3. It is impossible to maintain slow procedures and crops which require additional water. e.g., tomato
4	a) Recirculating nutrient film technique	1. Perfect for large-scale commercial endeavors. 2. Don't require growing media. 3. Plants grow faster.	1. Purify the culture medium. 2. It is expensive and complicated.
	b) NFT hydroponics system and NFT aquaponics system	1. The potential exists for the general aquaponics technology to provide crop growth at least equal to that of conventional hydroponics. 2. Easy to build & maintain. 3. Low water and nutrient consumption.	1. NFT technology might not be the best technological advancement for an aquatic system. 2. Pump failure can cause the depth of crops to in a few hours.
	c) NFT vertical felt and floating raft are two different hydroponic subsystems.	1. Similar results in fish production. 2. Successful production of leafy vegetables. 3. Very easily adaptable to different spaces & plant requirements.	1. Constant monitoring is required. 2. The roots in the channels can become blocked by blocks of vigorously growing plants (Gaikwad 2020)
5	Deep water culture / Deep floating technique	1. Conservation of water and Fish growth. 2. Used to cultivate a single crop such as lettuce, basil, or other green leafy plants. 3. Does not require farmland with fertile soil.	1. Lack of oxygen in water can happen easily. 2. Nutrient solution needs to be checked frequently. 3. It may be challenging to control the temperature.
6	Drip irrigation system	1. Maximum crop yield. 2. It reduces weed growth. 3. No soil erosion problem.	1. Responsiveness to clogs. 2. Difficulty with humidity dispersion. 3. Risks associated with saltiness (Manda et al. 2021).
7	Flood and drain system and constant flow system	1. Equally suitable for carp and basil cultivation. 2. Efficient with space, relatively low cost. 3. It is easy to build up the structure.	1. Unstable pH levels. 2. Creation of toxicities that are harmful to the crop; this brings losses to the farmer. 3. It is inappropriate for plants that require additional irrigation.
8	Aeroponics system	1. It produces healthier root systems 2. It provides us with a valuable research tool. 3. It is easy to replace old plants with new ones. 4. Due to the abundant oxygen available to plant roots, crops grow quickly.	1. It requires constant monitoring to be successful. 2. It is an expensive growing method to set up initially. 3. It is highly susceptible to power outages. 4. We must have a certain level of technical knowledge.

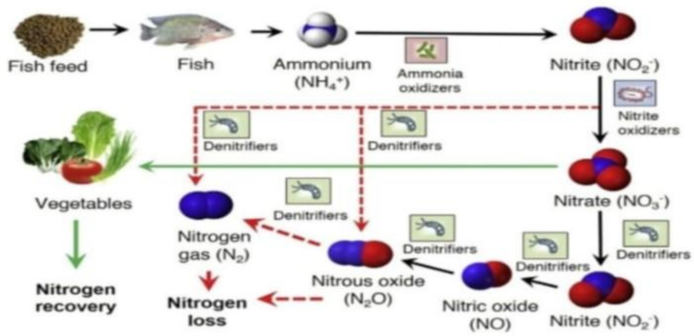


Figure 17 Nitrogen transformations in aquaponics systems (Wongkiew et al. 2020).

6.2 Nitrogen and phosphorus removal by Aquaponics

Nitrogen and phosphorus compound removal efficiency is essential in the hydroponic and aquaponic systems. Aquaponics can be an alternative to reduce inorganic nitrogen and phosphorus accumulation, which can interfere with fish growth. The static tests were conducted to investigate nitrogen removal performance by hydroponics and immobilized biofilm units in an aquaponic system. It was reported that the concentration of total ammoniacal nitrogen and nitrate nitrogen in the aquaponic method satisfied the requirements for fish-friendly water. Equally fish and vegetables are produced well (Zhang et al. 2018). The present study introduced a form of an aquaponic method for minimizing the need for water, electricity, and nitrogen. Nutrients like nitrogen, which can and should be recycled to meet future regulatory discharge requirements, are present in wastewater from industry activities (Lastiri et al. 2016).

6.3 Nitrogen utilization efficiency in Aquaponics

Various studies assessed the nitrogen utilization of the efficiency of aquaponics and suggested ways to boost their effectiveness (Fang et al. 2017; Wongkiew et al. 2017). The nitrogen use efficiency can be used to understand the relationship between the total nitrogen input and the nitrogen output. Aquaponic uniform feeding increased N use efficiency (nitrate nitrogen and nitrite nitrogen) by 30% to 600% compared to those in aquaponic increasing feeding and hydroponics, because it improves the production and yield of herbs and vegetables grown in aquaponic systems by enhancing the quality of the water and nitrogen availability for greater plant production (Yang and Kim 2019).

For increased nitrogen consumption efficiency in aquaponics, it was advised to keep the pH around 6.0, and more research on nitrous oxide reduction strategies is required. In a media-based aquaponic system, the hydroponic bed, where the majority of microorganisms proliferated, was where nitrous oxide release mostly transpired. Advanced nitrous oxide production from aquaponics on lower pH be identified for the prevention of microbial action (Zou et al. 2016b). The lesser nitrifier concentration in the root system and biofilter caused nitrogen removal, which reduced the aquaponic system's ability to use nitrogen effectively. These discoveries about microorganisms and nitrate alterations offered alternative methods to enhance the aquaponic effects in terms of the degree of nitrogen removal from aquaculture wastewater and the quality of the water (Wongkiew et al. 2018a).

To increase the effectiveness of nitrogen utilization in aquaponics methods with a decrease in the discharge of ecosystem-damaging pollutants as well as wastewater, it is important to have a basic knowledge of nitrogen converted in aquaponics. The research demonstrates the rising of dissolved oxygen concentrations by air mixture does not recover nitrogen utilization efficiency and reduce N_2O emission simultaneously (Figure 17) (Wongkiew et al. 2018b).

7 Recirculating aquaculture systems

The recirculating aquaculture system provides a controlled and consistent environment for the optimal production of freshwater aquariums by reusing water in the manufacture. Aquaculture is an industry where various species are grown, such as fish, shrimp, clams, etc., using mechanical and biological filters as part of the irrigation process. Water from the fish tanks is filtered throughout the recirculating process and used again inside the tanks. There is also a need for some other facilities such as pH regulators, heat exchangers, and denitrification units. Aquaponic systems are natural and automatic filters used in aquaculture as techniques for improving water quality. Results showed that the system is more efficient in plant growth than the captive fish supply, so it is not harmful to aquatic life. In this study, biofiltration demonstrated its effectiveness in removing ammonia from water and reducing nitrate formation (Estim et al. 2019).

Nutrient recruitment procedures were investigated by measuring dissolved elements using the spectrophotometric method in the management tanks (nitrate nitrogen, nitrite nitrogen, ammoniacal nitrogen, phosphorus, potassium, magnesium, & iron). Thus, there is a possibility for enhancing crop production with the oxidation

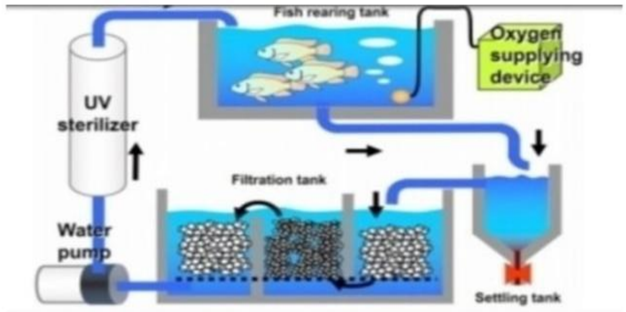


Figure 18 Schematic diagram of recirculating aquaculture system (Endo 2018).

process of the aquacultural waste mixture (Monsees et al. 2017). Recirculating farming practices are more beneficial than conventional agricultural systems in terms of nutrient usage since the fish in these systems give fertilizer to the plants, while the plants remove excess nutrients from the water (Figure 18).

Hydroponic tomato production has been compared to the impact of effluent as a pikeperch recirculating farming practices. Recirculating aquaculture water consists of microorganisms and dissolved organic matter; these act as plant biostimulants and mitigate the salinity pressure and physiological disorders like blossom-end rot symptoms (Delaide et al. 2019). Butterhead lettuces are employed because of their large root systems and aquaponic growing methods. According to the study, analytical calculations were created to relate root development to shoot or root fresh weight and design the nitrification process for an integrated aquaponic system that includes recirculating fish farms (Schwartz et al. 2019).

The goal of the hydroponic filter media project was to design an aquaponic system on a pond scale while treating the nutritional wastewater from the concentrated fishpond. It combined artificial wetlands and suspended grain hydroponic systems. This study demonstrated the feasibility of using rice hydroponic biofilters as an effluent treatment system and producing food plants in an aquaponic method that employs pools with recirculating water (Li et al. 2018). In a laboratory investigation, the impacts of membrane technology remediation on Tilapia and spinach growth (*Ipomoea Aquatica*) and water circulation were examined. The research showed that the sludge tank's sediments and microorganisms were successfully maintained by the membrane treatment, speeding up the nitrification process (Wang et al. 2016). The farming system's hydroponic component proved sufficient for regulating the nitrogen levels during aquaponics within the necessary values for fish farming (Supajaruwong et al. 2020). Fish waste is treated and recycled in an intensive aquaculture system to lower waste concentration in the water and lessen environmental contamination (Calone et al. 2019). There are studies on the effectiveness of removing nutrients from a small-scale recirculating aquaponic system to grow amaranth (*Amaranthus dubius*), sweet wormwood (*Artemisia annua*), and pumpkin (*Cucurbita pepo*). Plants in aquaponic systems take up dissolved nutrients from wastewater from aquaculture. Nutrient removal enables water reuse and lowers wastewater discharge to the residential environment (Gichana et al. 2019). Sustainable food is the source of future water conservation and resources. According to Endut et al. (2016), the aquaponic recirculating system produces crops with a good source of protein and is attaining a sustainable environment.

Aquaculture systems that are concentrated highly controlled, and recirculate waste from fish are treated and recycled to increase fish harvests while saving water. As a separation of recirculating aquaculture systems, aquaponics systems improve water consumption effectiveness along with decrease pollution through a hydroponic technique to facilitate produces good fertilize crops (Medina et al. 2016).

8 Challenges in aquaponics and hydroponics

Even when they are properly designed and successful aquaponic systems, there are major problems in employing the method for crop cultivation. Aquaponics' major agriculture challenge is providing balanced nutrients for substantial nourishing vegetation. According to much research, condensed molasses soluble could be employed as a novel natural fertilizer for crop production to circumvent this nutritional limitation (Li et al. 2020). The countries like India, Nigeria, and Bangladesh are facing a massive loss of nitrogen in the field of aquaculture due to struggling with nutritional and food production security. Thus, aquaponics can be used to evaluate nitrogen transfer by analyzing isotopic signatures or stable isotopes (Adhikari et al. 2020).

In a hydroponic system with artificial lighting, the nitrogen removal efficiency was observed to be elevated in wastewater with exposure to air. Distillation is more efficient in wastewater supplemented with carbon dioxide at the same time, artificial lighting had no significant effect on the reduction of nitrogen forms (Bawiec et al. 2020). Here, the plant is nourished by nutrient-rich fish waste, and the crops help purification by removing toxins harmful to fish (Kumar Sharma et al. 2018).

Few studies have reported that the microorganisms that promote plant growth (sweet peppers, tomatoes, and cucumbers) are likely to be why aquaponics plants can obtain yields similar to those of hydroponics; However, the nutrient level is significantly reduced, and future research in this field is essential for the beneficial use of microorganisms in all plants (Yep and Zheng 2019). With just a basic EC control of the nutrient solution content, vegetables could be grown using recycled hydroponics sustainably (Chowdhury et al. 2021). In protected agriculture, soilless cultivation is significantly employed to maintain the quality of the product while enhancing control over the growing environment and avoiding uncertainties in the soil's water and nutrient condition. In addition to allowing for soilless cultivation and water conservation, soilless methods help for the proximity of food production to urban spaces like residential rooftops (Fussy and Papenbrock 2022).

9 Applications

Aquaponics advanced technologies help to create more sustainable food systems (Krastanova et al. 2022). Aquaponics is beneficial for sustainability in food production as an indirect factor that controls the motivation of environmental awareness and green consumption. Variables impacting the motivation to spend higher ecological production in industrial and theoretical model approaches were studied (Eichhorn and Meixner 2020). Vertical farming utilizes less space for growing extra food. Unlike traditional farming, several novel agricultural techniques such as hydroponics and aeroponics have elevated food production in less space and additional yields in less time (Kumar et al. 2020). Grey water from the bioretention method will be used for the hydroponics of spinach, water spinach, and lettuce, which the community can consume. Thus bioretention plots can decrease the capacity of greywater to have a pollution grade without a pollution index (Widiyanti et al. 2020).

The growing vegetation in hydroponics, like the irrigation of lettuce and beets (rice crops), is measured with phenological conditions like the amount of mixed wastewater collected from domestic effluents, pharmaceuticals, fabric, and fuel discharges. Experiments on seed germination and plant development demonstrate that combined wastewater can be recycled for farming (Egbuikwem et al. 2020). This study aims to examine the efficacy of morning glory in the phytoremediation of hydroponic sewage effluent for use as an alternative to wastewater treatment. The study indicates that the morning glory (*Ipomeaasari folia*) plant can help manage aquaculture effluent to allowable limits, and the treated effluent is safe for reuse (Kiridi and Ogunlela 2020).

Since irrigation water is so limited in desert regions, it is crucial to use alternate water sources, such as tertiary processed wastewater, to cultivate crops. Effluents from hydroponic systems are a key source of fertilizer. It has been suggested that using treated wastewater to irrigate wheat crops using hydroponic systems is an alternate wastewater disposal strategy that poses no risk of heavy metal accumulation in the soil (Al Hamedi et al. 2021). Different aquaponic production systems' degrees of melon (*Cucumis melo L.)* fruit quality were investigated. The study showed that the bioactive compounds in melon should be measured to maintain well-being with age (Piñero et al. 2020).

Strategies for the sustainable and economic development of co-culture and hydroponic systems were studied. This study aimed to discover the possible benefits associated with adopting recirculating aquaculture techniques to avoid over-accumulation of toxic elements while improving nutrient recovery; water exchange and filtration periods were discussed to analyze how these technologies might be used for recirculating aquaculture (Askari-Khorasgani and Pessarakli 2020b). Tomato was produced in aquaponics and evaluation of three hydroponic methods. This study found that the production and fruit quality were comparable among three systems (nutrient film technology, drip irrigation method, and floating raft culture). However, the drip irrigation system gave better results (Schmautz et al. 2016). Healthy amounts of spinach were produced by both the aquaponic and hydroponic spinach treatments, however, the aquaponic system outperformed the hydroponic system in terms of fish development and feed conversion ratio, most likely due to the system's better water quality (Atique et al. 2022). Therefore, aquaponics effectively mobilizes nutrients that are both economically appropriate and ecologically sustainable, not just for a balanced ecosystem but also for humans (Shreejana et al. 2022).

10 Automation

Automation is the hydroponics industry's last challenge. This will allow a single person to employment multiple jobs and cultivate multiple farms simultaneously (Modu et al. 2020). Likewise, the production of catfish and pumpkin using aquaponics and traditional methods was compared. The aquaponics system proved more efficient in producing catfish and pumpkin than other production methods in this study (Oladimeji et al. 2020a).

Aquatic food production from aquaponics systems showed high efficiency and was suitable for production scale. This study confirmed that aquaponics could primarily be used in regions facing water scarcity (Estim et al. 2020). Hydroponic systems for crop production are currently essential to maximize yields. The study reported correct and modernized information about the different nutrients and compositions used hydroponically compared to the traditional production model. They are rationale, nutrient solution technique, and work on fruit crops (Kumar and Saini 2020). Nutrient elimination and growth of arugula were evaluated in the recycled aquaponic method for freshwater fish. The study discovered that biweekly gathering compared with fewer

Table 5 Applications of Aquaponic plants

S. No	Aquaponic plants	Applications
1	Lettuce and beets (*Lactuca sativa* and *Beta vulgaris*)	Seed germination and plant growth experiments showed that mixed wastewater could be reused for farming
2	Morning glory (*Ipomoea purpurea*)	It can be useful in managing aquaculture effluent to allowable limits and the treated effluent is safe for re-use
3	Broccoli microgreens (*Brassica oleracea*)	It is used to enhance the success of farmers and retailers selling microgreens
4	Melon fruit (*Cucumis melo*)	The bioactive compounds in melon are used to maintain well-being with age
5	Tomato (*Solanum lycopersicum*)	It is used to avoid over-accumulation of toxic elements while improving nutrient recovery and water exchange in recirculating aquaculture
6	Watercress (*Nasturtium officinale)*	It can be used to reduce the nitrogen removal effectiveness of aquaponic systems by reducing the ammonia and nitrite removal

than 25 percent of the mass of the developing arugula is advised for nitrification and the economic progress of both the arugula and the carp in aquaponics (Irhayyim et al. 2020).

The cultivation of fish can increase the productivity of fishing technologies. The purpose of the study was to evaluate the entrepreneur's sustainability. Zainal et al. (2021) showed that catfish and mustard greens cultivation in aquaponics yield a high level of profitability and economy. Aquaponics is a system of producing fish using the deep flow technique (DFT) with the result that the partners get an additional income while the environmental improvement makes the area more pleasant and attractive for tourists (Gunawan et al. 2021). An aquaponic system's economic and social benefits in support of the combined trout and water crops were examined. It is used in business models to generate benefit data, which contributes to achieving the multiple potentials of the technology and enabling the development of sustainable food systems from production to consumption (Rizal et al. 2018).

11 Research challenges

Building and sustaining an aquaponic system can sometimes be challenging, as many essential variables need to be measured. The possibility of fish farming developing into a significant sector in the development of environmentally friendly nutrition is restricted by technical constraints and economic challenges. The study highlighted the significance of particular instance analysis taking place in customer choices, financial concerns, and previous marketable advantages in aquaponics (Greenfeld et al. 2020).

The technical challenges of an automated hydroponic system are pH maintenance, nutrient equilibrium, and pest and disease management. Natural cultivating, being a need of great significance, is usually the selected system to overcome the central problem (Devvrat and Ratan 2019). Similarly, the socio-ecological challenges of aquaponics are mineral recycling and overfishing. A review of the fish farming improvement in aquaponics systems was conducted. The potential for fish farming to be a viable technique for the treatment of nitrogen-rich pollutants with year-round principal cultivation of high-quality vegetables and fish while preserving the water is quite high (Oniga et al. 2018).

The optimized aquaponic systems were produced to improve sustainability using Project OASIS. The project's goals were to reduce energy use and construction expenses while using universally available equipment (Nigam and Balcom 2016). The objective of artificial climate-controlled hydroponics farming is to cultivate an electrically controlled environment that encourages plants' growth. Hydroponically grown plants with automatic processing can be used smartly to decrease crops' growth period and save resources such as workforce, water, and fertilizers, thus increasing their productivity (Sanjay and Balasaheb 2021). The buildup of inhibitory allelochemicals that reduce yield and quality due to the autotoxicity phenomenon is a significant concern for recycled hydroponics (Asaduzzaman et al. 2022).

Conclusion

Aquaponics has the potential to be a huge, healthy food production sector, but is constrained by technical issues as well as financial and logistical problems. There is a high demand for green vegetables and small amounts of fish at a relatively high prices. Hydroponics is a profitable technology anywhere there is a shortage of water and poor soil quality. This review article has provided an overview of the various types of aquaponic systems, including those that incorporate standard hydroponically production technology like nutrient film technique, deep water culture, flood and drain systems, aeroponics, and the use of vertical processes. Aquaponics determines the higher removal of nitrogen regaining from aquaculture wastewater through nitrate reduction and nitrogen absorption into organic vegetables and plants. Green leafy vegetables like different varieties of spinach, peppermint, and herb appear to be the best successful species of plants in the aquaponic system because of their low nutritional needs, widespread demand, and usefulness in aquaponics. Aquaponic produce exists to be healthy food that is sustainable and eco-friendly, but it is equally important for the general public to recognize that this product requires a particular level of skill and procedure to function well.

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Conflicts of Interest

The authors declare no conflict of interest.

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