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AQUAPONICS: A SUSTAINABLE TECHNOLOGY FOR AQUACULTURE AND AGRICULTURE FOOD SECURITY

HIDAYAH MANAN*, MOHAMAD JALILAH, AMYRA SURYATIE KAMARUZZAN, MOHAMMAD MUKMIN AHMAD RAZMAN, NOR AZMAN KASAN AND MHD IKHWANUDDIN

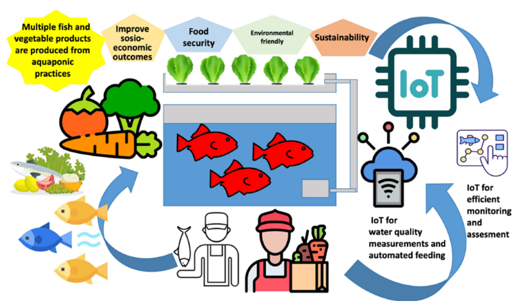
Higher Institution Centre of Excellence, Institute of Tropical Aquaculture and Fisheries, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia.

**Corresponding author: hidayahmanan@umt.edu.my*

HIGHLIGHTS

- Aquaponics is an efficient green farming practice for sustainable food production.
- Aquaculture wastes are recycled into natural bio-fertilisers for plant growth.
- Supports food security initiatives and produces less environmental pollution.
- Potential means of boosting food production for many years in the future.

GRAPHICAL ABSTRACT



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ABSTRACT

Aquaponics are one of green technologies and that would allow for the production of multiple food products like fish and vegetables in one complete system. Aquaponic systems also have potential as a sustainable food security practice as the production of vegetables and fish can be done simultaneously. The process also supports global Sustainable Development Goals (SDG); SDG 1 (no poverty) and SDG 2 (zero hunger), with the implementation of aquaponic systema by local communities. The aquaponic concept is characterised by the recycling of fish waste into beneficial products and as a source of nutrients and natural fertilisers for plant growth. The synergy between the plants, fish and bacteria in the soil and fish waste benefits all components in the system and promotes a circular economy. This review emphasises the types of aquaponic systems, the fish that are suitable for aquaponic cultivation, the types of vegetables that are suitable for aquaponic cultivation and the benefits of the application of aquaponic systems. Aquaponic systems help promote a sustainable environment for the recycling of fish and plant waste into fertilisers that maximise resources use and production yields. In this manner, the system helps the local community improve socioeconomic and income generation as well as supports national and global food security agenda.

Introduction

Aquaponic systems are a potential solution to food production and security issues, especially in the wake of climate change and post-pandemic economic conditions. The system can be set up in small spaces even in an urban area. Aquaponic systems are a complete system that combine aquaculture and hydroponics and pair it with beneficial microbes in a symbiotic relationship. Aquaponics are a sustainable technique for the production of organic food products (Krastanova *et al*., 2022). Aquaponic systems, use a Recirculating Aquaculture System (RAS) with the soilless vegetables to produce environmentally friendly organic products (Vermaeulen & Kamstra, 2013).

Aquaponic systems are a viable solution for producing organic foods. The system can be set up in small spaces with land constraints such as in urban areas (Brewer *et al*., 2021). The system can assist with food security and production issues the system also has potential as an alternative for achieving economic and environmental sustainability targets (Endut *et al*., 2016).

Aquaponics use RAS that integrate hydroponic plant cultivation and aquaculture systems. RAS are more profitable than conventional methods and provide a better yield of fish and vegetables (Tyson *et al*., 2011).

Aquaponics is an innovative method that is being studied by the aquaculture industry in recent years, where fish waste is used as a fertiliser to boost plant growth and effectively solve environmental pollution issues arising from the disposal of aquacultural effluents (Wei *et al*., 2019).

The wastewater from the cultivation of fish provides a nutrient-rich base for vegetable growth. Aquaponic systems allow for the cultivation of various types of aquatic animals including fish, crayfish, as well as plants such as vegetables, herbs, and fruits (Rakocy, 2012).

Aquaponic systems use less energy, less water, and do not require chemical fertilisers to enhance crop yields, which makes it exceptionally environmentally friendly (Bhakar *et al*., 2021).

Vegetables and crops in aquaponic systems do not require outsourced fertilisers and the fish that are cultured in the system do not require water changes as frequently, making the system suitable for high efficiency modern agriculture farming (Mchunu *et al*., 2018).

Aquaponic farming is an excellent solution that eliminates environmental issues associated with modern farming by doing away with chemical pesticides and outside sources of fertiliser (Narvois *et al*., 2022). This review looks at the types of aquaponic systems available, the types of fish that are suitable for cultivation in the system, the types of vegetables that are suitable for aquaponic cultivation, and the benefits of the aquaponic system. Aquaponics are a sustainable and eco-friendly means of resolving water quality, food security, environmental and aquaculture waste issues in one go, and promote sustainable agriculture practices.

Types of Aquaponic Systems

The most commonly used aquaponic methods are the Nutrient Film Technique (NFT), a floating raft known as the Deep-Water Culture (DWC), and the media beds with substrates known as an ebb and flow technique (Knaus *et al*., 2020).

Aquaponic systems are mostly setup and operated in the recirculating loops rather than as independent systems, which include the RAS, hydroponic unit, and through nutrient recovery compartments (Goddek *et al*., 2016).

The types of aquaponic system under review should be clearly differentiated from hobby, backyard aquaponic systems, and aquaponic systems for commercial production, or those used for the urban agriculture as small business or projects (Buehler & Junge, 2016).

Aquaponics employ Recirculating Aquaculture System (RAS) with the hydroponic technologies, where plants are cultured without soil in a closed-loop system (Junge *et al*., 2017).

For commercialised aquaponic models, there are three designs available which are a one-loop system known as Coupled Aquaponic System (CAS), a two-loop or Decoupled Aquaponic System (DAS), and a Decoupled Multiloop Aquaponics Systems (DAPSs) (Goddek *et al*., 2019). CAS is operated in a single continuous loop and flows in a single direction towards the tank outlet, meanwhile DAS has two separate loops for water to flow (Kloas *et a*l., 2015).

Aquaponic systems can be operated coupled in the single closed loop or decoupled in which the plant bed is separated from the fish tank. Usually, most aquaponic systems have a design that includes a fish tank, plant bed, sedimentation tank, and bio-filtration compartment (Ruiz *et al*., 2023).

Smart aquaponic systems usually consist of different types of sensors and devices to monitor the parameters such as temperature, dissolved oxygen, pH, and water level in the fish tank. The use of the smart devices and Internet of Things (IoT) technologies in aquaponic practices would improve monitoring of the fish culture, reduce labour and energy costs, and increase profitability and yield (Narvois *et al*., 2022).

The introduction of technology integrated in the system complies with industrial revolution IR 4.0 requirements. The technology will make the system more precise in farming and harvesting, as well as integrate the automated feeding, sensors in the culture system to allow for sustainable farming (Ibrahim *et al*., 2023).

Large-scale aquaponic practices in the European Union (EU) and United Kingdom (UK) have successfully demonstrated the economic viability of the system and the Willingness to Pay (WTP) for aquaponic products due to an uptick in environmental awareness and green food consumption practices (Baganz *et al*., 2022).

Species of Fish and Vegetables Suitable for Aquaponic Culture

Aquaponic system farming is a profitable type of agriculture method in the United States Virgin Islands (USVI). A commercial scale aquaponic unit developed at the Virgin Islands University was used to cultivate red tilapia and leaf lettuce has seen positive returns on the farming activities conducted (Bailey *et al*., 1997).

Endut *et al.* (2010) built a recirculating aquaponic system to grow African catfish (*Clarias gariepinu*s) and cultivate water spinach (*Ipomoea aquatica*). The plants cultivated did not have any nutritional deficiency or mineral imbalance and the plant yield also increased. There were also improvements in the nitrogenous ammonia removal due to an increase in nitrification in the aquaponic system (Endut *et al*., 2010).

The tilapia fish and lettuce were mostly grown, as a hobby or as cultures by educator using either Deep Water Culture (DWC) or Nutrient Film Technique (NFT) method on a media bed type of aquaponic system (Hussain & Brown, 2024).

Meanwhile, Bulc *et al*. (2012) has turned a small-scale cyprinid fish farm into an aquaponic system and successfully cultivated tomatoes (*Lycopersicum esculentum*) in a vertical model of the aquaponic system.

A variety of fish can be cultivated in aquaponic systems including tilapia, ornamental fish (koi, goldfish, tropical fish), catfish, perch, bass, bluegill, and trout, of which tilapia, catfish, ornamental fish, trout, perch, and bass were the most commonly cultured (Krastanova *et al*., 2022). Tilapia is the most common species cultured in the aquaponic systems due to its omnivorous feeding habits, rapid reproduction rate, and the fact that it grows well in the system (Rakocy *et al*., 2004). Tilapia fish can tolerate a wide range of environments, where water temperatures range between 15 and 30°C and ammonia level are between 0.2 and 3.0 mg/L (Krastanova *et al*., 2022).

The integration of African catfish (*Clarias gariepinus*) with water spinach (*Ipomoea aquatica*) and mustard greens (*Brassica juncea*) showed that the water spinach has an excellent ability to reduce ammonia about 78% to 85% and nitrite about 82.93% to 92.22% removal compared to mustard greens in the aquaponic culture system and also achieve higher survival rates of the fish cultured with a 94% survival rating (Enduta *et al*., 2011).

It was reported that the green oak lettuce (*Lactuca sativa*) grows well in the gravel bed media, followed by the raft and NFT system when cultured with Murray cod (*Maccullochella peelii peelii*). Meanwhile, lettuce that being culture with goldfish was identified growth well in the NFT aquaponic system compared to floating raft system and vertical farming system (Perez-Urrestarazu *et al*., 2019).

African catfish (*Clarias gariepinus*) showed good growth when cultured in aquaponic systems with combination cultures with sweet basil (*Ocinum basilicum*) (Knaus *et al*., 2020). Basil is popular plant to be cultured in aquaponic system and shows good performance when combined with African catfish, Nile tilapia, and common carp (*Cyprinus carpio*) (Palm *et al*., 2014). Basil also shown a good growth performance when cultured with river crayfish (*Procambarus zonangulu*s) in the raft aquaponic system (Saha *et al*., 2019). Meanwhile, cultures of African catfish (*Clarias gariepinus*) integrated with three other type of plants, namely red and green-red amaranth (*Amaranthus* spp.) and water spinach (*Ipomoea aquatica*) in the aquaponic system promoted significant growth in the plants, increased the yields produces and improved a sustainable agriculture farming (Mamat *et al*., 2016).

The integration of catfish and pumpkins in the aquaponic system was more efficient than static or conventional aquaculture systems. The fish survival and water quality also improved significantly (Oladimeji *et al*., 2020).

Red hybrid tilapia and *empurau* (*Tor tambroides*) had higher survival rates in aquaponic systems when compared to culture in RAS system. Tilapia also showed higher weight gains and higher Specific Growth Rates (SGR) with lower Feed Conversion Ratio (FCR) compared with *empurau* and *jelawat* fish (*Laptobarbus hoevenii*) (Colin *et al*., 2024).

Rakocy *et al*. (2004) cultured tilapia fish with basil and identified that the basil production is sustainable in the aquaponic system where the waste nutrients from the fish culture was used to fertilise the plant crops.

Other types of plants that can be cultivated in aquaponic systems include Chinese cabbage (*Brassica rapa*), basil (*Ocimum basilicum*), Swiss chard (*Beta vulgaris*), and lettuce (*Lactuca sativa*) (Yang & Kim, 2020).

The culture of Nile tilapia (*Oreochromis niloticus*) with romaine lettuce (*Lactuca sativa* L. var. *longifolia*) was identified as growing well in the aquaponic system without the need of water exchange and could maintain a good water quality for the fish compared with conventional cultivation methods (Effendi *et al*., 2017).

Meanwhile, the culture of carp (*Cyprinus carpio* var. *koi*) and goldfish (*Carassius auratus*) in combination with water spinach (*Ipomoea aquatica*) was conducted an aquaponic system by Nuwansi *et al*. (2015), who identified that plant growth is increased with modifications to the flow rate on the system. Table 1 shows the fish and vegetables cultured in the aquaponics systems.

Table 1: The fish and vegetables cultured in aquaponic systems

Name of Aquaponic Systems	Fish	Vegetables	Description	References
Aquaponics Recirculation System (ARS)	African catfish (*Clarias gariepinus*)	Water spinach (*Ipomoea aquatica*) and mustard green (*Brassica juncea*)	Improve survival rate of fish by 94%, reduce ammonia (78-85%), nitrite (82-92%), nitrate (79-87%), and orthophosphate (75-84%)	Enduta *et al*. (2011)
Recirculation Aquaponic System (RAS)	Nile tilapia (*Oreochromis niloticus*)	Lettuce (*Lactuca sativa* var. *crispa*)	Higher nutrients removal rates and higher Specific Growth Rate (SGR), fish weight gain increased from 63% to 81.7%, FCR was 1.05, 1.171.32, and 1.36 for 1.2,1.8, 2.4, respectively, and 3.0 $mday^{-1}$ hydraulic loading rate in the system	Khater *et al*. (2023)
Aquaponics Recirculation System (ARS)	African catfish (*Clarias gariepinus*)	Water spinach (*Ipomoea aquatica*)	Removal of total ammonia nitrogen (TAN), nitrite-nitrogen (NO_2^-N), nitrate-nitrogen (NO_3^-N), and orthophosphate (PO_4^3) were 89%, 93%, 94%, 81%, and 80%, respectively, the FCR was 1.08, and SGR was 3.56 kg/m^2	Endut *et al*. (2016)
Decoupled aquaponic with 3-hydro component (grow pipe, raft, gravel)	African catfish (*Clarias gariepinus*)	Basil (*Ocimum basilicum*)	Basil shows rapid growth in grow pipe system, the FCR was 0.74 in smaller fish, 0.84 medium size fish, and 0.91 in large fish, the SGR was 3.23%/day for small fish, 1.50%/day for medium fish, and 0.90%/day for large fish	Knaus *et al*. (2020)
Recirculation Aquaponic System (RAS)	Koi carp (*Cyprinus carpio* var. *koi*) and goldfish (*Carassius auratus*)	Water spinach (*Ipomoea aquatica*)	Plant growth and nutrient removal was increased with decrease in flow rate. Flow rate 0.8l min^{-1} showed highest growth in both fish species. 0.8l min^{-1} suggested as optimum water flow rate for polyculture of fish in aquaponic system	Nuwansi *et al*. (2016)

Recirculation Aquaponic System (RAS)	Nile tilapia (*Oreochromis niloticus*)	Romaine lettuce (*Lactuca sativa* L. var. *longifolia*)	Tilapia best growth performance was 3.96 g/day, FCR was 1.6, survival rate was 96.11%, and SGR was 12.10%/day	Effendi *et al*. (2016)
Raft Aquaponic System	Red tilapia (*Oreochromis* sp.)	Water spinach (*Ipomoea aquatica)*	Weight gain was 43.9%, no fish mortality, 24 hours light resulted in 2.4% increment of fish growth, and 12% higher for plants growth	Liang and Chien (2013)
Recirculation Aquaponic System (RAS)	African catfish (*Clarias gariepinus*)	Red and green-red amaranth (*Amaranthus* spp.) and water spinach (*Ipomoea aquatica*)	Highest length and weight of catfish obtained with the green-red amaranth (20.22 ± 0.19 cm/fish; 55.42 ± 1.34 g/fish)	Mamat *et al*. (2016)

Nitrogen Cycle in the Aquaponic System

In the aquaponic system, fish waste becomes the source of nutrients that acts as natural fertiliser for plant growth, meanwhile the plants become natural filters that help purify the water that circulates in the system (Ibrahim *et al*., 2023).

Fish waste becomes a source of ammonia nitrogen in the water, and it will be degraded by the nitrifying bacteria into nitrite and to nitrate. Nitrates will then be absorbed by the plants and crops for growth which become sources of natural fertiliser. The water also can be reused by the system as the ammonia nitrogen in the water will be purified by the plants which can save water and reduce water exchange (Wei *et al*., 2019).

Nitrifying bacteria usually found in the biological filter and in the substrates such as in the hydroponic media beds that allow colonisation of the bacteria in the aquaponic system as biological filtration (Somerville *et al*., 2014). Bacteria that conduct on the nitrification process to convert nitrites (NO_2^-) to nitrates (NO_3) such as Nitrobacter, Nitrococcus, and Nitrospira (Kasozi *et al*., 2021).

The plant in the aquaponic system serves as a bio-filter to convert the harmful nitrogenous wastes into beneficial product or fertiliser for plants growth. Nutrients taken by the plants will improve the water quality and boost fish production in the system (Khater *et al*., 2023).

In aquaponic systems, ammonia is converted by bacteria and absorbed by the aquaponic plants (Tokuyama *et al*., 2004). Usually, ammonia concentration is lower in aquaponic systems, which is below than 1 ppm, at about 0.3 ppm and 0.4 ppm which are within the safety limits for fish (Effendi *et al*., 2017).

Aquaponic provides a sustainable approach by converting the aquaculture effluents from fish wastes into beneficial nutrients sources for plant growth (Babatunde *et al*., 2021). The waste in the water that recirculates in the aquaponic system is a source of nutrients for hydroponic plants vegetables, where it provides basic nutrients such as N, P, K, Ca, Mg, and Na for the plants growth (Suhl *et al*., 2016). Figure 1 shows the nitrogen cycle in aquaponic system.

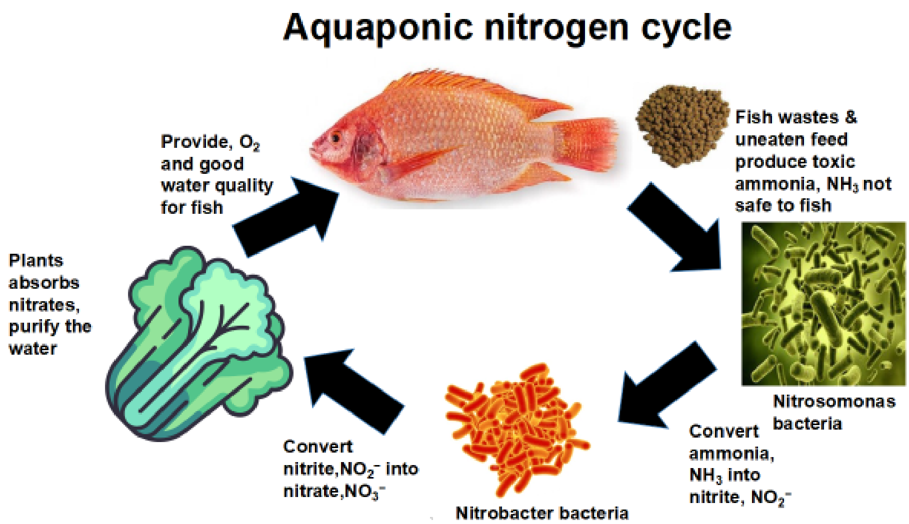

Figure 1: The details nitrogen cycle in aquaponics system

Benefits of Aquaponic Culture System

Aquaponic systems reduce the input from outside nutrients source and are an environmentally friendly means of cultivation due to the nutrient recycling by the system that via the RAS. Aquaponic systems are also a viable food security tool especially where water resources are limited (Goddek *et al*., 2016). The water used in aquaponic systems is also lower than traditional culture methods due to the use of RAS systems (Krastanova *et al*., 2022).

Aquaponic integrates culture of fish and plants in the recirculating aquaculture system, and it is considered an innovative, eco-friendly, and farming system (Khater *et al*., 2023). Aquaponic systems also produce higher yields and require smaller spaces which is an advantage especially in urban settings (Bailey *et al*., 1997). Aquaponic produced higher profit during first to third year of farming by using these system as compared to conventional agriculture method (Love *et al*., 2014).

Aquaponic has gained so much traction in the community. It has a solution and an innovative response to the issue of food security (Diver & Rinehart, 2010). Aquaponics is also important to members of the scientific and business communities where this green technology could have the potential to boost local food production (Endut *et al*., 2010).

In recent years, the interest in the commercialisation of aquaponic systems has grown significantly and it is predicted that this system will produce significant results in terms of food production and food security in the future (Junge *et al*., 2017).

Aquaponics is a green technology that is suitable for implementation in urban areas, where space is limited, and it is also suitable for use in rural areas (Specht *et al*., 2014). Aquaponic systems maximise the fish and plant productions by applying a sustainable farming method with minimal water use and small land area requirements (Joyce *et al*., 2019).

Aquaponic systems can help achieve SDG Goal 2, which is a zero-hunger target, enhance food production and food security, improve nutrition for all, and promote a sustainable agriculture farming practices (Flores-Aguilar *et al*., 2024). Aquaponic application also supported the SDG goals; SDG 14 (life below water), SDG 2 (zero hunger), and followed by SDG 13 (climate action), which aquaponic potential practice in supporting on the environmental sustainability, food security, and also for human public health (Nair *et al*., 2024).

Aquaponics reduces the use of chemical fertiliser, decrease the effluents from agricultural run-off, and also improves the water quality by using the bio-filter and plants that absorbs the nutrients from the fish waste as source of beneficial nutrients (Khater *et al*., 2023). Aquaponic systems are an effective practical solution for raising fish and growing vegetables in one system by using the water from the fish tank water for watering the plants in the system and successfully recycle the waste of aquaculture through application of the system (Mamat *et al*., 2016).

The application of aquaponic systems, helps reduce the use of chemical fertiliser and improves the water quality in the system where plant used the waste as sources of nutrients for growth (Roosta & Hamidpour, 2011). The aquaponic systems offer better solution for increasing intensive aquaculture and agriculture also support environmental sustainability efforts (Olanrwaju *et al*., 2022).

Conclusions

The use of aquaponics is in line with global Sustainable Development Goals (SDGs), in terms ending world hunger and poverty. This aquaponic technology is a promising means of obtaining high-quality fish protein and vegetables in very small spaces. Aquaponics can contribute to a more sustainable food production system, in terms of aquaculture and agriculture output. This system promotes sustainable environmental practices by recycling fish wastes into fertilisers for plants. Aquaponic systems also promote socioeconomic growth to local communities.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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