*Aquaculture Reimagined: Modern Approaches to Sustainable Fish Farming*
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Chapter 8

# Aquaponics: Advanced System for Sustainable Aquaculture Production

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## Abstract

The increasing global population has placed immense pressure on the agriculture and allied sectors to meet the rising requirement for nutritious food. Aquaculture, as a key player in this arena, holds significant promise in providing high-quality nutrition while fostering entrepreneurship opportunities in rural and urban areas. However, the sector faces mounting challenges, including land scarcity, water pollution, urbanization and limited availability of freshwater resources. These pressures have necessitated a shift towards more intensified and integrated production systems, with the potential for more sustainable and cleaner methods of food production. Aquaponics has emerged as an innovative solution that integrates aquaculture with hydroponics to cultivate plants and aquatic animals combined in a symbiotic system. In this model, fish waste is used as a nutritional input for plants and the vegetation detoxify the water for the fish. The nitrogen cycle, facilitated by beneficial bacteria, is the driving force for the efficient functioning of this system. Technological advancements and ongoing innovations helped in developing various aquaponics models, such as the Nutrient Film Technique (NFT) and raft-based and media-based systems offering cost-effective solutions for food production. Despite these innovations, nutrient budgeting remains a significant challenge as plants often fail to absorb all available nutrients and minerals. To overcome this issue, supplementation through fish feed fortification or fertigation is required to enhance vegetation growth and improve the efficiency of the production system. Concept of hydraulic loading rates (HLR) was introduced to optimize water filtration and nutrient distribution within the system. Aquaponics presents a promising opportunity in response to the growing consumer demand for chemical-free and organic products. However, the efficiency of system hinges on the careful calibration of fish stocking density and fish-to-plant ratios. Further

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research is required to refine nutrient management and optimize species-specific HLR and component ratios to improve productivity and cost efficiency. Developing easy-to-operate, scalable systems and focusing on organic product development could unlock the full potential of aquaponics, opening new horizons for sustainable and integrated farming practices.

**Keywords** Aquaponics, Cost efficiency, Integrated system, Sustainable production, Water purification

## 1. Introduction

Rapid growth in human population resulted in numerous environmental challenges, including scarcity of water, arable land degradation, rapid change of climate and salinization of lands. These challenges have significantly impacted food production for human (Dijkgraaf *et al.,* 2019; Goddek *et al.,* 2019a; Yang and Kim, 2020). To nullify the difference within available resources and the growing demand for food, there is a need to shift from a growth dependant; cost effective model to one that prioritizes environment friendly food production systems in balanced way, ensuring nutritional security (Goddek *et al.,* 2019a). Pisciculture as a fast growing sector, is a viable solution for achieving food security and entrepreneurship development (Azra *et al.,* 2021). Though, traditional aquaculture practices such as ponds and open-water systems pose significant environmental risks, including eutrophication and habitat destruction (Joesting *et al.,* 2016). Therefore, adopting a more intensive, economical and environmentally friendly food production method is crucial for addressing these issues (Dijkgraaf *et al.,* 2019).

Aquaponics as a zero water exchange system delivers a potential remedy through enhancing nutrient and culture water recycling, thus minimizing harmful discharge from aquaculture sites. This system efficiently uses limited land and water resources, with a 95 to 99% water reuse rate. Additionally, it provides many economic benefits through the production of both fish and plants sustainably (Nuwansi *et al.,* 2016; Joyce *et al.,* 2019; Nuwansi *et al.,* 2019). Aquaponics operates as biologically-integrated model, improving food assurance while aligning as per United Nations Sustainable Development Goals (Goal 2: Zero Hunger and Goal 14: Life Below Water) and addressing the needs of a growing global populace (Goddek *et al.,* 2019a; Ani *et al.,* 2021; Baganz *et al.,* 2022). The system combines Recirculating Aquaculture Systems with hydroponics, where a plant's primary nutrient source is nutrient-rich culture water effluent supplied from fish tanks containing waste and uneaten feed. The filtered water is recirculated into the fish tanks (Roosta and Mohsenian, 2012; Thomas *et al.,* 2019). Baganz *et al.* (2022) emphasized that interdependence of aquaculture along with hydroponic components, previously called "coupled aquaponics," is fundamental. Hence, they proposed the term "permanently coupled" to describe these systems more precisely because their subsystems cannot function independently.

Aquaponics offers dual benefits by minimizing the requirement of nutrient supplementation in hydroponics, while enhancing waste-water purification in the RAS, resulting in excess nutrient exclusion with higher profitability through the concurrent production of two marketable crops (Hu *et al.,* 2015; Nuwansi *et al.,* 2019). This system is recognized as a cost-effective and advantageous method for phytoremediation, facilitating zero water exchange and enhancing vegetative growth (Nuwansi *et al.,* 2017; Nuwansi *et al.,* 2019). Despite its potential as an environment friendly way of food production through wastewater and nutrient recycling, aquaponics faces technical challenges like disparities in pH, nutrient budgeting for plants and temperature fluctuations in between the components (Goddek *et al.,* 2019a). Effective nutrient budgeting has become a key strategy for optimizing nutrient requirement to enhance vegetative growth (Roosta, 2014).

Current researches revealed that the rapid commercialization of aquaponics has led to a shift in the research focus. Initially, efforts were concentrated on optimizing the design and operational factors (*e.g.,* component ratios and hydraulic loading rates). However, recent studies have emphasized technical improvements to enhance production thus enhancing income for the farmers (Goddek *et al.,* 2019a; Greenfeld *et al.,* 2019). The concept of "decoupled aquaponics" gained prominence, wherein the hydroponic and aquaculture components are physically separated in what was previously referred to as a "permanently coupled" system (Goddek *et al.,* 2019a; Baganz *et al.,* 2022). Baganz *et al.* (2022) suggested that "on demand coupled" might better describe this approach, an idea explored further in this chapter. Additionally, recent trends point to the development of aquaponics in saline lands and coastal areas as the prospect of this agri-aqua system (Greenfeld *et al.,* 2019). Expanding aquaponics applications represents a valuable solution to reconcile the apparent conflict between sustainable and intensive food production.

This chapter provides a brief examination of the key research dimensions and expected directions in aquaponics, focusing on its potential to evolve into a more sustainable and efficient food production system.

## 2. History of Aquaponics

The history of aquaponics originates 1,500 years back, with early forms being practiced in Indonesia, South China and Thailand Farmers in these areas cultivated rice in paddy fields where fish were also raised and the fish waste acted as a natural fertilizer for rice plants. Approximately 500 years later, Aztecs in Central Mexico developed another version of aquaponics. As founders of a vast empire, the Aztecs established their capital, Tenochtitlán, along the shores of Lake Texcoco. Owing to the lack of fertile land in the wetlands, they constructed floating gardens known as "Chinampas". These islands, made of both mud and plant debris, allowed Aztecs to grow crops, such as maize, squash and tomatoes. The plants absorbed nitrogenous wastes from lake, which was enriched by aquatic animal waste.

Although aquaponics is an age old practice, modern science did not fully explore its potential until the 1970s. Aquaponics has evolved into a sophisticated and sustainable agricultural method that conserves natural resources. It uses less than 90% water in comparison to traditional farming methods (Graber and Junge, 2009), enables faster plant growth (Graber and Junge, 2009) and reduces environmental pollution by minimizing the need for tractors and chemical inputs (Monsees *et al.,* 2019).

## 3. Types of Aquaponics

Aquaponics system consists of various key components which include a growing bed where the plants are cultivated fish tanks that provide habitat for the aquatic organisms. Pumps which move water from the fish culture tank to the plant grow bed or substrate. Stand pipes or siphons connected with the substrate helps in draining water from the substrate back into the fish tank. Water pump circulates water throughout the system and assists in aeration. Grow media or floating rafts provide structural support for plants. The various designs of aquaponics are described below.

### *3.1. Media-based Aquaponics System (Goddeck et al., 2015)*

It is known as the flood and drain method, is widely used for small-scale setups and is favoured by DIY aquaponics enthusiasts for its simplicity and ease of operation. This design is space-efficient, has a low start up cost and is ideal for beginners in aquaponics.

#### *3.1.1. Working Principle of the System*

In this system, a plant growing bed or container filled with a growth medium *i.e.* gravel, lava rock, or pebbles is used to cultivate plants. The grow bed is flooded with nutrient-rich water from the fish culture tank intervally using a bell siphon, allowing the vegetation to absorb essential nutrients. Subsequently, the water recycled into the fish tank, initiating a new cycle. Organic waste is degraded within the substrate bed and insect larvae are sometimes added to the media to decompose the waste. Media-based systems require fewer components and do not require additional filtration, making them easy to manage. However, due to limited growing space, crop yields may be lower than in other aquaponics systems.

### *3.2. Nutrient Film Technique (NFT) Aquaponics Systems (Lennard, 2017)*

Nutrient Film Technique (NFT), a well known hydroponic method adapted as aquaponics system due to its simplicity and efficiency in specific environments. This system relies on gravity and consists of horizontal PVC pipes through which a thin film of nutrient-rich water flows. NFT systems are popular in commercial type aquaponics and useful in areas with limited land space.

#### *3.2.1. Principle of the System*

NFT systems merge the traditional hydroponic NFT principles with nutrient-laden water from fish tanks. A shallow layer of water flows continuously along various channels, supplying the plant roots with essential nutrients, water and oxygen. Similar to the floating raft system, the water from the fish culture tank is filtered before passing through the NFT channels, where the plants grow and return to the fish tank. Unlike other systems, NFT requires a separate biofilter because the system provides an insufficient surface area for the beneficial bacteria required for nutrient cycling.

### *3.3. Raft Aquaponics System (Graber and Junge, 2009)*

Deep Water Culture (DWC) system, raft aquaponics design is one of the most efficient for commercial operations. In this method, plants are floated, with the roots immersed in a nutrient enriched and oxygenated water solution, which promotes rapid nutrient uptake and robust plant growth.

#### *3.3.1. Principle of the System*

In the raft system, nutrient-dense water circulates through long channels, typically approximately 20 cm deep, with rafts (made of foam boards) floating on surface. Plants are attached in holes within rafts, supported by pots and their roots extend into nutrient-rich oxygenated water. This allows them to absorb nutrients and oxygen directly, thereby facilitating their rapid growth. The water spontaneously flows from the fish culture tank using a filtration system and into the raft tank, where the plants grow before being recirculated back into the fish tank. In major cases, the raft structure is separated from the fish culture tanks. Monitoring and management of major water quality parameters, such as pH, nutrient concentrations, ensure optimal performance and balance in raft aquaponics systems.

## 4. Mass Balance: The Fate of Nutrients in the Aquaponic System

Operation of aquaponic methods relies on the maintenance of a dynamic balance in nutrient cycles (Somerville *et al.,* 2014). To optimize system management, it is essential to understand these cycles. Plants grown in hydroponic environments have specific nutrient requirements that must be met during different growth stages (Resh, 2013). As a result, nutrient levels in various components of the system need to be carefully managed and supplements must be added to prevent shortcomings (Seawright *et al.,* 1998; Resh, 2013), either by adjusting the system water quality or through foliar application (Roosta and Hamidpour, 2011).

As mentioned by Delaide *et al.* (2016), supplementation of aquaponic solutions with minerals to achieve nutrient enhancement comparable to those of hydroponics may result in higher yields than hydroponic systems alone. The initial step towards establishing a balanced ecosystem is to understand the proper design of its components as per the requirement (Buzby and Lin, 2014). If the hydroponic component is disproportionately small relative to fish culture tanks, nutrient accumulation may occur, potentially reaching harmful levels. The feeding ration (*i.e.*, the amount of fish feed required to sustain the plant-growing area and plants variety) is typically used as a preliminary guideline for the understanding the system functioning (Rakocy *et al.,* 2006; Somerville *et al.,* 2014). However, Seawright *et al.* (1998) suggested that relying solely on fish feed as an input will not achieve an optimal plant-to-fish ratio that satisfies plant requirements.

Monitoring methods primarily focus on the nitrogen cycle to ensure that the system remains balanced and operates effectively (Somerville *et al.,* 2014; Cerozi and Fitzsimmons, 2017). Nevertheless, it is also essential to closely monitor the balance of macronutrients (N, P, K, Ca, Mg and S) and micronutrients (Fe, Zn, B, Mn, Mo and Cu) to ensure optimal system performance (Sonneveld and Voogt, 2009; Resh, 2013; Somerville *et al.,* 2014). Schmautz *et al.* (2015, 2016) investigated the effects of various hydroponic configurations *i.e.* nutrient film technique, floating raft system and drip irrigation system on the nutrient utilization of aquaponic-based tomato culture units. The findings indicate that the drip irrigation system yielded slightly better results for tomato production. Mineral content of the fruits (P, K, Ca and Mg) matched the conventional standards, although the iron and zinc levels were higher. However, the contained lower Mg, Fe, Cu, P, K, S, Zn and Cu concentrations than those from conventional agriculture systems. In the study of coupled aquaponic system, Delaide *et al.* (2016) assessed the utilization of macro- and micro-nutrients and found deficiencies in Cu, Zn, K, P, Fe, Mo and Mn, while Na, B, Ca and N accumulated quickly. For better absorption and utilization of micro-, macro- and trace-minerals, pH plays a crucial role in aquaponics systems. An optimal pH of approximately 7 is ideal for fish and bacteria to thrive, while a pH below 6.5 disrupts nitrification, an important step in water purification. However, plants highly absorb nutrients at a pH of 5.8 to 6.5 (Rakocy *et al.,* 2006). Macronutrients like nitrogen, potassium, sulphur, phosphorus, magnesium and calcium can be absorbed in vegetation at a varied pH range, which may be not be possible to maintain in aquaponics. As an example, micronutrients like iron (Fe) are best absorbed at a pH of 5.5 to 6.0, but absorption decreases at higher aquaponic pH levels (>7), which is primarily evident in aquapinics systems (Lennard and Goddek, 2019; Maucieri *et al.,* 2019b). To prevent nutrient deficiencies and better growth in plants, fertilizers or supplements need to be added through external means like foliar spray, water fertigation, or specially fortified fish feed (Roosta, 2014; Rono *et al.,* 2018; Siqwepu *et al.,* 2020a, 2020b). Details of nutrient supplementation for better plant growth are mentioned in table 1.

So, the requirement of micro and macronutrients as per the need of cultured plants is essential to understand and precautionary steps need to be taken for better plant growth, which may provide higher yield.

## 5. Optimization of Stocking Density or Component Ratio for Aquaponics Systems

Optimization of stocking density and determining the ideal fish and plant ratio is essential for the profitability of aquaponics systems (Mamatha *et al.,*

Table 1: Status of nutrient supplementation in the aquaponics system

| Micronutrient supplemented | Plant Used | Dose of Nutrient Supplemented | Beneficial Effect | References |
|---|---|---|---|---|
| Potassium (K) | Parsley | 0.5 g $L^{-1}$ ($K_2SO_4$ foliar spray) | 60.70% increase in plant growth compared to control | Roosta (2014) |
| Potassium (K) | Tomato | 80 mg $L^{-1}$ (K fertigation) | Significant yield increase | Peter *et al.* (2021a) |
| Potassium (K) | Spinach | 150 mg $L^{-1}$ (K fertigation) | Increased plant yield and optimal fish production | Jhon *et al.* (2022a) |
| Potassium (K) | Okra | 5 g $L^{-1}$ ( K foliar Spray) and Iron | Increased plant yield and optimal fish production | Meena *et al.* (2022) |
| Potassium (K) | Holy Basil | Mica | Positive correlation | Angkha *et al.* (2020) |
| Potassium (K) | Spinach | 150 mg $L^{-1}$ | Positive effect on leaf nutrient concentration (K, Fe, Mn, Zn); decreased Ca, Mg with increased K supplementation | Jhon *et al.* (2022a) |
| Iron (Fe) | Pepper | 0.5 g $L^{-1}$ (FeSO4 foliar spray) | Better vegetative and reproductive growth compared to Fe-EDDHA and Fe-EDTA | Roosta and Mohsenian (2012) |
| Iron (Fe) | Not mentioned | 2 mg $L^{-1}$ (Fe chelates) | Improved plant growth, stable pH | Rakocy *et al.* (2006) |
| Iron (Fe) | Spinach | 1.5 mg $L^{-1}$ (Fe-EDDHA fertigation) | Enhanced yield and nutrient uptake (N, P, Zn, Cu) | Farooq *et al.* (2023) |
| Iron (Fe) | Spinach | 30 g $kg^{-1}$ (Fe chelate in fish diet) | Improved water quality, higher nutrient concentration for plants and better yield | Rono *et al.* (2018) |

| Micronutrient supplemented | Plant Used | Dose of Nutrient Supplemented | Beneficial Effect | References |
|---|---|---|---|---|
| Iron (Fe) and Fulvic Acid | Not mentioned | 690 mg $L^{-1}$ (Fulvic acid) | Increased iron bioavailability by 22 μM, improved plant growth | Cerozi (2020) |
| Potassium (K) and Iron (Fe) | Okra | 5 g $L^{-1}$ (K) and 1 g $L^{-1}$ (Fe) | Inflated okra production with optimal fish production | Meena *et al.* (2023) |
| Potassium (K) and Iron (Fe) | Rocket plant | Not available | No effect in fish tissues when iron and potassium supplemented; improved freshness and growth of plants | Stathopoulou *et al.* (2021) |

2020; Nuwansi *et al.,* 2021). Different fish varieties exhibit varying responses to varied stocking density (Maucieri *et al.,* 2019a). The optimized species specific biomass maintains a stability in between nutrient availability from fish waste and plant nutrient utilization (Mamatha *et al.,* 2020; Nuwansi *et al.,* 2021). Therefore, the optimization of biomass is essential for maximizing productivity (Shete *et al.,* 2013a; Nuwansi *et al.,* 2021). Stocking density affects various important factors like fish growth, water quality and plant growth in aquaponics (Ani *et al.,* 2021). Parameters like Dissolved Oxygen (DO), pH and nitrogenous toxicants (TAN, $NO_2$-N, $NO_3$-N) are directly influenced by stocking density. Higher densities may lead to reduced DO, lower pH and increased nitrogen compounds if nutrient budgeting is not done as priority (Ani *et al.,* 2021; Nuwansi *et al.,* 2021). Elevated stocking ratio also increases oxygen demand due to higher fish biomass and organic waste accumulation, resulting in poor water quality and reduced fish growth (Ani *et al.,* 2021).

Low DO and high Free $CO_2$ levels lead to stress in fish, impairing their oxygen uptake and overall health (Hargreaves and Brunson, 1996). High stocking densities also exacerbate nitrogenous waste, further degrading water quality and inhibiting fish growth (Trang *et al.,* 2010). Increased crowding can reduce fish growth rates and efficiency (Nuwansi *et al.,* 2021), with negative impacts on weight gain, specific growth rate and feed conversion ratio (Ani *et al.,* 2021).

In contrast, higher fish stocking densities tend to increase plant yield, as nutrient-rich water enhances plant growth (Maucieri *et al.,* 2019a; Nuwansi *et al.,* 2021). Greater plant mass also improves water filtration, benefiting overall system health and fish growth (Verma *et al.,* 2020). Thus, optimal stocking density in aquaponics requires balancing water quality, nutrient cycling and productivity of both fishes and plants (Nuwansi *et al.,* 2021). Different fish with plant species used in aquaponics have been depicted in table 2 and the optimized fish-to-plant ratios for various species are provided in table 3.

Table 2: Compatible plant and fish species for aquaponics

| Food fish | Plant | References |
|---|---|---|
| Tilapia (*Oreochromis niloticus*) | Romaine lettuce (*Lactuca sativa longifoliac* var. Jericho.), Basil (*Ocimum basilicum*), Okra (*Abelmoschus esculentus*), Toamto (*Lycopersicon esculentum*), Pak choi (*Brassica campestris* L. subsp. *chinensis*), Lettuce (*Lactuca sativa* L.), Chinese cabbage, Kale, Collards, Sorrel, Cantaloupe, Cucumber, Summer squash, Spinach (*Spinacia oleracea*), Holy basil (*Ocimum tenuiflorum*), Swiss chard (*Beta vulgaris* L. spp. *cicla*) | Seawright *et al.* (1998); Rakocy *et al.* (2004); Hu *et al.* (2015); Kloas *et al.* (2015); Cerozi and Fitzsimmons (2016a,b); Schmautz *et al.* (2016); Bailey and Ferrarezi (2017); Ru *et al.* (2017); Thomas *et al.* (2019, 2021); Angkha *et al.* (2020, 2021); Kaburagi *et al.* (2020); Ani *et al.* (2021) |
| Murray cod (*Macculloch ellapeeliipeelii*) | Green oak lettuce (*Lactuca sativa*) | Lennard and leonard (2004); Lennard and leonard (2006) |
| African catfish (*Clarius gariepinus*) | Water spinach (*Ipomoea aquatica*), Mustard green (*Brassica juncea*), Basil (*Ocimum basilicum*) | Endut *et al.* (2009); Endut *et al.* (2011); Pasch *et al.* (2021) |
| Pangasius (*Pangasianodon hypophthalmus*) | Lettuce (*Lactuca sativa* L) and Red chicory (*Cichorium intybus* L.), Marigold (*Tagetes erecta*), Spinach (*Spinacia oleracea* L.), Basil (*Ocimum basilicum*) | Maucieri *et al.* (2017); Mohapatra *et al.* (2020); John *et al.* (2022a, 2022b); Farooq *et al.* (2023a, 2023b); Harika *et al.* (2023, 2024) |
| Comon carp (*Cyprinus carpio*) | Tomato (*Lycopersicon esculentum*), Pepper (*Capsicum annum* L.), Mint (*Mentha arvensis*) | Roosta and Hamidpour (2011); Roosta and Mohsenian (2012), Shete *et al.* (2016, 2017) |

| Food fish | Plant | References |
|---|---|---|
| Rainbow trout (*Oncorhynchus mykiss*) | Lettuce (*Lactuca sativa* L.) | Johnson *et al.* (2016); Forchino *et al.* (2017); Birolo *et al.* (2020) |
| Pearlspot | Tomato (*Lycopersicon esculentum*) | Peter et al. (2019, 2021a, 2021b) |
| Rohu (*Labeo rohita*) | Lemon Grass (*Cymbopogon citratus*), Spinach (*Spinacia oleracea*) | Mamatha *et al.* (2020); Verma *et al.* (2020) |
| Ornamental fish | Plant | References |
| Goldfish (*Carassius auratus*) | Spinach (*Spinacia oleracea*) | Shete *et al.* (2013a, b) |
| Koi carp (*Cyprinus carpio* var. *koi*) | Spinach (*Beta vulgaris* var. *bengalensis*), Gotukola (*Centella asiatica*) | Hussain *et al.* (2014, 2015); Nuwansi *et al.* (2021) |
| Platy fish (*Xiphophorus* sp.) | *Sesuvium portulacastrum* and *Batis maritima* | Boxman *et al.* (2017) |
| Shellfish | Plant | References |
| Crayfish (*Cherax quadricarinatus*) | Spinach (*Ipomoea aquatica*) | Effendi *et al.* (2015) |
| White leg shrimp (*Litopenaeus vannamei*) | *Sarcocornia ambigua, Batis maritima, Sarcocornia neei, Sporobolus virginicus,* Basil (*Ocimum basilicum*) | Pinheiro *et al.* (2020), Schardong *et al.* (2020), Alarcon-Silvas *et al.* (2021) |

Table 3: Component ratio in aquaponic system

| Plant and Fish species | Component ratio Plant no. m$^{-2}$: lb fish m$^{-3}$ | References |
|---|---|---|
| Spinach and Gold fish | 28:0.40 | Shete *et al.* (2013a) |
| Spinach and Koi carp | 28:3.09 | Hussain *et al.* (2014) |
| Water spinach, Koi and Gold fish | 28:0.57,1.19 | Nuwansi *et al.* (2017) |
| Leafy vegetables (chicory, lettuce and swiss chard) and European carp | 9,12,10:5.51 | Maucieri *et al.* (2019a) |
| Basil and Gold fish | 23:5.07 | Patil *et al.* (2019) |
| Tomato and Pearlspot | 4:1.89 | Peter *et al.* (2019) |
| Lemon garss and Rohu | 28:0.35 | Mamatha *et al.* (2020) |
| Gotukola and Koi carp | 35:4.63 | Nuwansi *et al.* (2021) |
| Lettuce and Tilapia | 16:5.95 | Ani *et al.* (2021) |

## 6. Hydraulic Loading Rate (HLR) in Aquaponics and Optimization of Water Flow

These crucial factors are essential for optimization of the efficiency of aquaponic systems (Yang and Kim, 2020). Maintaining required rate of water flow ensures suitable water quality, improving system performance and productivity (Nuwansi *et al.,* 2016; Peter *et al.,* 2021b). Flow of water can be managed through draining and intermittent flooding (Maucieri *et al.,* 2018). Intermittent flow enhances nutrient distribution and system aeration (McMurtry *et al.,* 1997), while continuous flow increases water retention, promoting longer contact between microbes and plant roots, leading to higher yields and improved water quality (Lennard and Leonard, 2004; Maucieri *et al.,* 2018). Plant growth in response to water circulation conditions (drained, half-drained, flooded) varies with respect to species variety (Trang *et al.,* 2010). For economic efficiency, water circulation in goldfish-spinach aquaponics can be optimized to 12 hours per day (Shete *et al.,* 2013b).

HLR in aquaponics is calculated using the formulae mentioned below (Endut *et al.,* 2010):

HLR (m $\text{day}^{-1}$) = Q (Flow rate of water in $m^3$ $\text{day}^{-1}$) × (surface area of the hydroponic trough or system in $m^3$)$^{-1}$.

HLR affects nutrient retention, water quality and yield (Peter *et al.,* 2021b). Maintaining optimal HLR ensures adequate nutrient supply for plants while minimizing toxicity risks for fish (Nuwansi *et al.,* 2020). HLR influences fish and plant growth, with higher HLR linked to better water circulation, improved oxygen levels and enhanced aerobic conditions (Shete *et al.,* 2016; Endut *et al.,* 2009). Higher water flow rates increase dissolved oxygen (DO) while lowering pH, temperature, Total Ammoniacal Nitrogen (TAN) and Nitrite-N levels (Endut *et al.,* 2009; Yang and Kim, 2020). However, improved aerobic conditions can inhibit denitrification, which is necessary for reducing nitrate concentrations.

## 7. Haloponics or Inland Saline Groundwater-based Aquaponics

The scarcity of freshwater resources significantly impacts food production inarid and semi-arid regions (Thomas *et al.,* 2019). Farmers often overuse groundwater and fertilizers to boost production, leading to increased accumulation of salt and reduced crop yield (Kaburagi *et al.,* 2020). One potential proposition to this challenge is to utilize the saline groundwater of inland saline area through aquaponics for environment friendly food production (Thomas *et al.,* 2019; Kaburagi *et al.,* 2020; Thomas *et al.,* 2021). Thomas *et al.* (2019) demonstrated the viability of integrating Nile tilapia and spinach in a 1:1.3 ratio using low saline (3 g $L^{-1}$) groundwater without adverse effects on fish or plant growth. Kaburagi *et al.* (2020) highlighted that saline tolerant plants like Swiss chard thrive in saline conditions, especially when supplemented with 50% of the microelements used in standard hydroponics, enhancing yield over time. Thomas *et al.* (2021) stated that moderate halophilic plants adapted to salinity levels and produced higher yields than freshwater aquaponic systems. Notably, spinach grew better at a higher salinity level (9 g $L^{-1}$) than non-saline water. Thus, aquaponics is an efficient way to utilize inland saline groundwater, helping conserve freshwater resources, particularly in arid areas (Thomas *et al.,* 2019; Kaburagi *et al.,* 2020; Thomas *et al.,* 2021). However, further research is needed to determine optimal fish-to-plant ratios in saline environments.

## 8. Maraponic or Marine Water-based Aquaponics

The rising global demand of seafood has necessitated the intensified production of marine fishes (Buhmann *et al.,* 2015; Boxman *et al.,* 2018). In response, marine water aquaponics commonly known as maraponics, has been conceptualized to enhance economical and diversified recirculating aquaculture systems (RAS) for high-value marine and brackish water fish production (Fronte *et al.,* 2016; Kotzen *et al.,* 2019). This system is well known for its capability to improve marine production while addressing the limitations of freshwater and soil salinity (Fronte *et al.,* 2016). The growth of marine aquatic species, the commercial potential of halophytes and their biofiltration efficiency in reducing inorganic compounds from RAS wastewater have driven marine aquaponics development (Beyer *et al.,* 2021).

Euryhaline species like Seabass (Waller *et al.,* 2015) and Gilthead seabream (Vlahos *et al.,* 2019) have been cultured effectively along with halophytes in aquaponics. Research has primarily focused on the compatibility of brackish water or marine finfish and shellfish with high-demand halophyte plants (Kotzen *et al.,* 2019). Though halophytes tolerate salinity, increased salinity levels can reduce their growth and biofilter performance (Buhmann *et al.,* 2015; Chu and Brown, 2021). Using brackish water has benefited plants and fish, optimizing system performance (Beyer *et al.,* 2021).

Studies have also revealed the importance of planting media and flow rates in marine aquaponics, with lower flow rates improving the growth of salt-tolerant plants and reducing operational costs (Boxman *et al.,* 2017). Specialized filtration units like sand filters and high-porosity substrates, enhance nitrate removal and water quality in marine systems (Gunning *et al.,* 2016). Moving Bed Bioreactors (MBBR) and sand filters support higher fish stocking densities and nutrient removal, producing organic solids useful as fertilizers (Boxman *et al.,* 2018).

Moreover, integrating polychaete-assisted sand filters has shown significant reductions in particulate organic matter and dissolved inorganic nitrogen, contributing to biomitigation (Marques *et al.,* 2017). Optimal salinity levels for species like *Litopenaeus vannamei* and halophytes such as *Sarcocornia ambigu* have been identified, with lower salinities supporting better growth and nutrient removal (Pinheiro *et al.,* 2020; Chu and Brown, 2021). However, micronutrient additions yield species-specific responses, highlighting the need for careful nutrient management in marine aquaponics (Doncato and Costa, 2021). Further research into marine aquaponics could provide sustainable alternatives to declining marine resources.

## 9. Decoupled Aquaponic System (DAPS)

The primary hinderance in traditional aquaponics is optimizing conditions for both fish and plants (Goddek and Keesman, 2018; Goddek *et al.,* 2019b). To address the challenge, the Decoupled Aquaponic System (DAPS) was conceptualized, which isolates the aquaculture and hydroponic components, allowing independent control of conditions like pH, temperature and nutrient levels. This system improves growth performance by minimizing trade-offs between the requirements of fish and plants (Goddek and Keesman, 2018).

Kloas *et al.* (2015) introduced the initial DAPS model, where RAS and hydroponics operate in separate loops. Water loss in hydroponics due to evapotranspiration is compensated by nutrient-rich RAS water, while RAS is refilled with tap water. However, this model had limitations due to nutrient enrichment in RAS, requiring frequent water discharge (Goddek *et al.,* 2019b). Modern DAPS incorporated additional loops to overcome these issues, such as a mineralization loop for nutrient recovery and a distillation or demineralization loop for separating nutrients and salts, allowing better system control (Goddek and Keesman, 2018).

While Baganz *et al.* (2022) suggested renaming DAPS to "on-demand coupled" aquaponics, the term "decoupled" is still widely used. DAPS subsystems are loosely connected, with water quality maintained through remineralization, ensuring optimal conditions for fish and plants. The system enhances nutrient use efficiency, increasing hydroponics yields and improving aquaculture water quality (Kloas *et al.,* 2015). For example, tomato yield increased by 36% in DAPS compared to traditional aquaponics due to better pH and nutrient budgeting while using less mineral nutrients and freshwater (Monsees *et al.,* 2019).

Although DAPS offers superior production and management, it is more complex and requires higher initial investment, making it suitable for large-scale operations or regions with geothermal energy resources (Goddek *et al.,* 2019b). While traditional aquaponics is still viable for small-scale, low-nutrient crops, DAPS is recommended for large-scale, nutrient-intensive production (Monsees *et al.,* 2017). Commercial viability of the system should be prioritized for popularization of the system.

## 10. Socio-Economic and Environmental Prospect of Aquaponics System

In recent years aquaponics has gained increasing recognition from governments, scientists and rural and urban communities as a viable solution for environment friendly food production. It addresses critical global issues, including climate change, land and water degradation and rising costs of fertilizers and energy (Goddek *et al.,* 2019a; Joyce *et al.,* 2019). Aquaponics is especially suited for arid or urban environments because it condenses food production in unconventional spaces such as terraces, underutilized building spaces, or food deserts (Konig *et al.,* 2016). Its minimal use of chemicals, antibiotics and its efficient resource utilization make it environmentally friendly, contributing to reduced greenhouse gas emissions and lowering food transportation costs, thereby promoting expansion in high population areas (Goddek *et al.,* 2019a; Krastanova *et al.,* 2022).

Milliken and Stander (2019) highlight aquaponics as a technique to fulfil the nutritional demand and earning among landless rural households. Homestead aquaponics, as suggested by Fernandez-Cabanas *et al.* (2023), can lead to significant cost savings for self-consumption. Moreover, aquaponics is increasingly used as an educational tool, fostering skill acquisition in schools and aiding socio-economic growth in developed countries like Switzerland and Sweden (Junge *et al.,* 2019). It also serves as a valuable way for income generation in developing countries (Somerville *et al.,* 2014).

The commercial systems of aquaponics which is nascent stages, faces challenges related to profitability. Research shows varied results regarding its financial viability, with some studies indicating marginal profits or losses, particularly in fish production (Tokunaga *et al.,* 2015). Factors such as location, chosen fish-plant combinations, market prices and energy consumption significantly affect the economic feasibility of aquaponics systems whereas high initial investment, complex regulations and challenges with organic certification are additional barriers for the system (Turnšek *et al.,* 2019; Greenfeld *et al.,* 2021). Also organic aquaponics has the potential to unlock new market opportunities, boosting the economic viability of this sustainable system (Kledal *et al.,* 2019; Fruscella *et al.,* 2021).

Aquaponics saves over 90% of water in comparison to traditional aquaculture (Lennard and Goddek, 2019) and reduces environmental impacts like eutrophication and global warming (Cohen *et al.,* 2018). A life cycle assessment (LCA) reveals that aquaponics has substantially lower environmental costs than standalone hydroponics or aquaculture systems (Chen *et al.,* 2020). Ongoing research, such as the development of species-specific diets and alternative protein sources like insect meal, aims to further enhance the sustainability of aquaponics by reducing reliance on fishmeal and minimizing environmental footprints (Robaina *et al.,* 2019).

Aquaponics holds great promise for addressing the global food crisis and environmental degradation. Its capacity for resource efficiency, nutrient recycling and climate-smart farming practices makes it a potential key player in sustainable agriculture. However, further technological advancements, regulatory frameworks and public policy support are required to overcome existing challenges and fully realize their potential (Vasdravanidis *et al.,* 2022).

## 11. Prospective of Aquponics

Aquaponics as an advanced technology ensures significant possibilities for addressing difficulties in both pisciculture and agriculture. Several future research areas have been identified which can contribute highly to shaping the future of this innovative technology:

- *Component Ratio and Hydraulic Loading Rate (HLR)*: Current studies mainly focus on freshwater species like carp. Future research should explore optimal fish and plant ratios and HLR for various species, including high-value brackish water and coldwater species.

- *Inland Saline Water*: Growing interest is in using inland saline water in aquaponics. Research should identify suitable fish and plant species, examine salinity tolerance and assess edible crops like broccoli and bell pepper for saline conditions.

- *Marine Aquaponics*: The increasing demand for seafood and halophytes has driven the development of marine aquaponics. Further studies are needed to optimize species combinations, stocking densities, HLR and nutrient removal efficiency in brackish water and marine systems.

- *Nutrient Limitation in Horticulture*: Studies have explored addressing nutrient deficiencies (*e.g.*, K, Fe, Ca) through foliar applications, fertigation, or fish diets. Research should standardize nutrient management across freshwater, marine and saline systems, ensuring economic viability and species-specific optimization.

- *Organic Fertiliser Use*: Future research should focus on using liquid organic fertilizers in aquaponics, assessing different types and application rates to enhance nutrient supply and yield in climate-resilient systems.

- *Decoupled Aquaponic Systems (DAPS)*: Developed to resolve challenges of conventional aquaponics, DAPS allow better control over conditions for fish and plants. Research should compare DAPS with traditional systems, analyzing economic efficiency, stocking density, nutrient removal and horticultural outcomes.

- *Organic Regulations in Aquaponics*: Addressing the regulatory challenges of organic certification requires further research, including the safety of organic fish feed, fish manure's impact on crops and the perception of intensive aquaponic systems within organic farming sector.

- *Alternative Protein Sources and Aquafeed*: Research should focus on reducing the carbon footprint of aquatic animal based ingredient in aquafeed through alternative proteins and genetic engineering. Lifecycle assessments of tailored diets can offer insights into environmental impact, safety and regulatory concerns.

These areas focus the requirement for continued study to optimize aquaponics systems and grow its commercial viability while addressing ecological, economic and regulatory challenges.

## 12. Conclusion

The aquaponic system demonstrates significant potential within circular economy as it is efficient in resource utilization, waste reduction and nutrient cycling, all while minimising environmental impact. This compilation of existing research offers a succinct summary of strategies for effectively selecting and implementing aquaponics at research, educational and practical levels to optimise production. This article provides a systematic overview of recent advancements and identifies future research priorities for the large-scale commercialisation of aquaponics. Such insights may guide researchers and entrepreneurs in developing practical and effective plans.

## 13. References

Alarcon-Silvas, S.G., Leon-Ca´nedo, J.A., Fierro-Sanudo, J.F., Ramírez-Rochín, J., Fregoso-Lopez, M.G., Frías-Espericueta, M.G., Osuna-Martínez, C.C., Paez-Osuna, F., 2021. Water quality, water usage, nutrient use efficiency and growth of shrimp *Litopenaeus vannamei* in an integrated aquaponic system with basil *Ocimum basilicum. Aquaculture* 543, 737023. DOI: https://doi.org/10.1016/j.aquaculture.2021.737023.

Angkha, B., Verma, A.K., Kumar, S.H., Prakash, C., Thomas, R.M., 2020. Mobilisation of mica by Bacillus sp. and its effect on Nile tilapia (*Oreochromis niloticus*) cum holy basil (*Ocimum tenuiflorum*)-based aquaponic system. *Aquaculture International* 28(5), 2045-2058. https://doi.org/10.1007/s10499-020-00575-4.

Ani, J.S., Manyala, J.O., Masese, F.O., Fitzsimmons, K., 2021. Effect of stocking density on growth performance of monosex nile tlapia (*Oreochromis niloticus*) in the aquaponic system integrated with lettuce (*Lactuca sativa*). *Aquaculture and Fisheries* 7(3), 328-335. DOI: https://doi.org/10.1016/j.aaf.2021.03.002.

Azra, M.N., Okomoda, V.T., Tabatabaei, M., Hassan, M., Ikhwanuddin, M., 2021. The contributions of shellfish aquaculture to global food security: Assessing its characteristics from a future food perspective. *Frontiers in Marine Science* 8, 654897. DOI: https://doi.org/10.3389/fmars.2021.654897.

Baganz, G.F.M., Junge, R., Portella, M.C., Goddek, S., Keesman, K.J., Baganz, D., Staaks, G., Shaw, C., Lohrberg, F., Kloas, W., 2022. The aquaponic principle - it is all about coupling. *Reviews in Aquaculture* 14(1), 252-264. DOI: https://doi.org/10.1111/raq.12596.

Bailey, D.S., Ferrarezi, R.S., 2017. Valuation of vegetable crops produced in the UVI Commercial Aquaponic System. *Aquaculture Reports* 7, 77-82. DOI: https://doi.org/10.1016/j.aqrep.2017.06.002.

Beyer, C.P., Gomez, S., Lara, G., Monsalve, J.P., Orellana, J., Hurtado, C.F., 2021. *Sarcocornia neei*: A novel halophyte species for bioremediation of marine aquaculture wastewater and production diversification in integrated systems. *Aquaculture* 543, 736971. DOI: https://doi.org/10.1016/j.aquaculture.2021.736971.

Birolo, M., Bordignon, F., Trocino, A., Fasolato, L., Pascual, A., Godoy, S., Nicoletto, C., Maucieri, C., Xiccato, G., 2020. Effects of stocking density on the growth and flesh quality of rainbow trout (*Oncorhynchus mykiss*) reared in a low-tech aquaponic system. *Aquaculture* 529, 735653. DOI: https://doi.org/10.1016/j.aquaculture.2020.735653.

Boxman, S.E., Nystrom, M., Capodice, J.C., Ergas, S.J., Main, K.L., Trotz, M.A., 2017. Effect of support medium, hydraulic loading rate and plant density on water quality and growth of halophytes in marine aquaponic systems. *Aquaculture Research* 48(5), 2463-2477. DOI: https://doi.org/10.1111/are.13083.

Boxman, S.E., Nystrom, M., Ergas, S.J., Main, K.L., Trotz, M.A., 2018. Evaluation of water treatment capacity, nutrient cycling and biomass production in a marine aquaponic system. *Ecological Engineering* 120, 299-310. DOI: https://doi.org/10.1016/j.ecoleng.2018.06.003.

Buhmann, A.K., Waller, U., Wecker, B., Papenbrock, J., 2015. Optimisation of culturing conditions and selection of species for the use of halophytes as biofilter for nutrient rich saline water. *Agricultural Water Management* 149, 102-114. DOI: https://doi.org/10.1016/j.agwat.2014.11.001.

Buzby, K.M., Lin, L.S., 2014. Scaling aquaponic systems: Balancing plant uptake with fish output. *Aquacultural Engineering* 63, 39-44. DOI: https://doi.org/10.1016/j.aquaeng.2014.09.002.

Calone, R., Orsini, F., 2022. Aquaponics: A Promising tool for environmentally friendly farming. *Frontiers for Young Minds* 10, 1-7. DOI: https://dx.doi.org/10.3389/frym.2022.707801.

Cerozi, B. da S., 2020. Fulvic acid increases iron bioavailability in aquaponic systems: Theoretical designs and practical considerations to prevent iron deficiency in plants. *Aquacultural Engineering* 90, 102091. DOI: https://doi.org/10.1016/j.aquaeng.2020.102091.

Cerozi, B. da S., Fitzsimmons, K., 2016a. Use of Bacillus spp. to enhance phosphorus availability and serve as a plant growth promoter in aquaponics systems. *Horticulturae* 211, 277-282. DOI: https://doi.org/10.1016/j.scienta.2016.09.005.

Cerozi, B. da S., Fitzsimmons, K., 2016b. The effect of pH on phosphorus availability and speciation in an aquaponics nutrient solution. *Bioresource Technology* 219, 778-781. DOI: https://doi.org/10.1016/j.biortech.2016.08.079.

Chu, Y.T., Brown, P.B., 2021. Evaluation of pacific whiteleg shrimp and three halophytic plants in marine aquaponic systems under three salinities. *Sustainability* 13(1), 269. DOI: https://doi.org/10.3390/su13010269.

Cohen, A., Malone, S., Morris, Z., Weissburg, M., Bras, B., 2018. Combined fish and lettuce cultivation: an aquaponics life cycle assessment. *Procedia Cirp* 69, 551-556. DOI: https://doi.org/10.1016/j.procir.2017.11.029.

Delaide, B., Goddek, S., Gott, J., Soyeurt, H., Jijakli, M.H., 2016. Lettuce (*Lactuca sativa* L. var. Sucrine) growth performance in complemented aquaponic solution outperforms hydroponics. *Water* 8(10), 467. DOI: https://doi.org/10.3390/w8100467.

Dijkgraaf, K.H., Goddek, S., Keesman, K.J., 2019. Modeling innovative aquaponics farming in Kenya. *Aquaculture International* 27, 1395-1422. DOI: https://doi.org/10.1007/s10499-019-00397-z.

Doncato, K.B., Costa, C.S.B., 2021. Micronutrient supplementation needs for halophytes in saline aquaponics with BFT system water. *Aquaculture* 531, 735815. DOI: https://doi.org/10.1016/j.aquaculture.2020.735815.

Effendi, H., Utomo, B.A., Darmawangsa, G.M., 2015. Phytoremediation of freshwater crayfish (*Cherax quadricarinatus*) culture wastewater with spinach (*Ipomoea aquatica*) in aquaponic system. *AACL Bioflux* 8(3), 421-430.

Endut, A., Jusoh, A., Ali, N., Wan Nik, W.N.S., Hassan, A., 2009. Effect of flow rate on water quality parameters and plant growth of water spinach (*Ipomoea aquatica*) in an aquaponic recirculating system. *Desalination and Water Treatment* 5(1-3), 19-28. DOI: https://doi.org/10.5004/dwt.2009.559.

Endut, A., Jusoh, A., Ali, N., Wan Nik, W.B., Hassan, A., 2010. A study on the optimal hydraulic loading rate and plant ratios in recirculation aquaponic system. *Bioresource Technology* 101(5), 1511-1517. DOI: https://doi.org/10.1016/j.biortech.2009.09.040.

Endut, A., Jusoh, A., Ali, N., Nik, W.B.W., 2011. Nutrient removal from aquaculture wastewater by vegetable production in aquaponics recirculation system. *Desalination and Water Treatment* 32(1-3), 422-430. DOI: https://doi.org/10.5004/dwt.2011.2761.

Farooq, A., Verma, A.K., Hittinahalli, C.M., Harika, N., Pai, M., 2023a. Iron supplementation in aquaculture wastewater and its effect on the growth of spinach and pangasius in nutrient film technique based aquaponics. *Agricultural Water Management* 277, 108126. DOI: https://doi.org/10.1016/j.agwat.2022.108126.

Farooq, A., Verma, A.K., Hittinahalli, C.M., Varghese, T., Pathak, M.S., 2023b. Iron supplementation in aquaculture wastewater and its impact on osmoregulatory, haematological, blood biochemical and stress responses of pangasius with spinach in nutrient film technique based aquaponics. *Aquaculture* 567, 739250. DOI: https://doi.org/10.1016/j.aquaculture.2023.739250.

Fern´andez-Cabanas, V.M., Suarez-C´aceres, G.P., P´erez-Urrestarazu, L., Lobillo Eguíbar, J., Gross, J.A., 2023. Contribution of household aquaponic production to a low price healthy Mediterranean diet in an economically depressed community. *Agronomy* 13, 498. DOI: https://doi.org/10.3390/agronomy13020498.

Forchino, A.A., Lourguioui, H., Brigolin, D., Pastres, R., 2017. Aquaponics and sustainability: The comparison of two different aquaponic techniques using the life cycle assessment (LCA). *Aquacultural Engineering* 77, 80-88. DOI: https://doi.org/10.1016/j.aquaeng.2017.03.002.

Fronte, B., Galliano, G., Bibbiani, C., 2016. From freshwater to marine aquaponic: New opportunities for marine fish species production. In: *Conference VIVUS-on Agriculture, Environmentalism, Horticulture and Floristics, Food Production and Processing and Nutrition*. Biotechnical Centre Naklo. pp. 514-521. URL: https://hdl.handle.net/11568/844495.

Fruscella, L., Kotzen, B., Milliken, S., 2021. Organic aquaponics in the European Union: Towards sustainable farming practices in the framework of the new EU regulation. *Reviews in Aquaculture* 13(3), 1661-1682. DOI: https://doi.org/10.1111/raq.12539.

Goddek, S., Delaide, B., Mankasingh, U., Ragnarsdottir, K.V., Jijakli, H., Thorarinsdottir, R., 2015. Challenges of sustainable and commercial aquaponics. *Sustainability* 7(4), 4199-4224. DOI: https://doi.org/10.3390/su7044199.

Goddek, S., Keesman, K.J., 2018. The necessity of desalination technology for designing and sizing multi-loop aquaponics systems. *Desalination* 428, 76-85. DOI: https://doi.org/10.1016/j.desal.2017.11.024.

Goddek, S., Joyce, A., Wuertz, S., Körner, O., Bläser, I., Reuter, M., Keesman, K.J., 2019. Decoupled aquaponics systems. *Aquaponics Food Production Systems* 10, 978-983. DOI: https://doi.org/10.1007/978-3-030-15943-6_8.

Goddek, S., Joyce, A., Kotzen, B., Dos-Santos, M., 2019a. Aquaponics and global food challenges. In: *Aquaponics Food Production Systems*. (Eds.) Goddek, S., Joyce, A., Kotzen, B. and Burnell, G.M. Springer International Publishing, Germany. pp. 3-17. DOI: https://doi.org/10.1007/978-3-030-15943-6_1.

Goddek, S., Joyce, A., Wuertz, S., Körner, O., Bläser, I., Reuter, M., Keesman, K.J., 2019b. Decoupled aquaponics systems. *Aquaponics Food Production Systems* 10, 201-209.

Graber, A., Junge, R., 2009. Aquaponic systems: Nutrient recycling from fish wastewater by vegetable production. *Desalination* 246(1-3), 147-156. DOI: https://doi.org/10.1016/j.desal.2008.03.048.

Greenfeld, A., Becker, N., McIlwain, J., Fotedar, R., Bornman, J.F., 2019. Economically viable aquaponics? Identifying the gap between potential and current uncertainties. *Reviews in Aquaculture* 11(3), 848-862. DOI: https://doi.org/10.1111/raq.12269.

Greenfeld, A., Becker, N., Bornman, J.F., Spatari, S., Angel, D.L., 2021. Monetizing environmental impact of integrated aquaponic farming compared to separate systems. *Science of the Total Environment* 792, 148459. DOI: https://doi.org/10.1016/j.scitotenv.2021.148459.

Gunning, D., Maguire, J., Burnell, G., 2016. The development of sustainable saltwater based food production systems: A review of established and novel concepts. *Water* 8(12), 598. DOI: https://doi.org/10.3390/w8120598.

Harika, N., Verma, A.K., Krishnani, K.K., Hittinahalli, C.M., Varghese, T., Bharti, V.S., Singh, A.L., Farooq, A., 2023. Stocking density optimisation of pangasius (*Pangasianodon hypophthalmus*) fingerlings with basil (*Ocimum basilicum* L.) in nutrient film technique (NFT) based aquaponics: Stocking density optimisation in nutrient film technique (NFT) based aquaponics. *Indian Journal of Fisheries* 70(3). DOI: https://doi.org/10.21077/ijf.2023.70.3.136073-09.

Harika, N., Verma, A.K., Krishnani, K.K., Hittinahalli, C.M., Reddy, R., Pai, M., 2024. Supplementation of potassium in aquaculture wastewater and its effect on growth performance of basil (*Ocimum basilicumin* L) and pangasius (*Pangasianodon hypophthalmus*) in NFT-based aquaponics. *Scientia Horticulturae* 323, 112521. DOI: https://doi.org/10.1016/j.scienta.2023.112521.

Hu, Z., Lee, J.W., Chandran, K., Kim, S., Brotto, A.C., Khanal, S.K., 2015. Effect of plant species on nitrogen recovery in aquaponics. *Bioresource Technology* 188, 92-98.

Hussain, T., Verma, A.K., Tiwari, V.K., Prakash, C., Rathore, G., Shete, A.P., Nuwansi, K. K.T., 2014. Optimising koi carp, *Cyprinus carpio* var. Koi (Linnaeus, 1758), stocking density and nutrient recycling with spinach in an aquaponic system. *J. World Aquaculture Society* 45, 652-661. DOI: https://doi.org/10.1111/jwas.12159.

Hussain, T., Verma, A.K., Tiwari, V.K., Prakash, C., Rathore, G., Shete, A.P., Saharan, N., 2015. Effect of water flow rates on growth of *Cyprinus carpio* var. koi (*Cyprinus carpio* L., 1758) and spinach plant in aquaponic system. *Aquaculture International* 23, 369-384. DOI: https://doi.org/10.1007/s10499-014-9821-3.

Joesting, H.M., Blaylock, R., Biber, P., Ray, A., 2016. The use of marine aquaculture solid waste for nursery production of the salt marsh plants *Spartina alterniflora* and *Juncus roemerianus*. *Aquaculture Reports* 3, 108-114. DOI: https://doi.org/10.1016/j.aqrep.2016.01.004.

John, V.C., Verma, A.K., Krishnani, K.K., Chandrakant, M.H., Bharti, V.S., Varghese, T., 2022a. Optimization of potassium ($K^+$) supplementation for growth enhancement of *Spinacia oleracea* L. and *Pangasianodon hypophthalmus* (Sauvage, 1878) in an aquaponic system. *Agricultural Water Management* 261, 107339. DOI: https://doi.org/10.1016/j.agwat.2021.107339.

John, V.C., Verma, A.K., Krishnani, K.K., Chandrakant, M.H., Varghese, T., Pathak, M.S., 2022b. Effect of potassium supplementation on osmoregulatory and stress response of *Pangasianodon hypophthalmus* (Sauvage, 1878) with *Spinacia oleracea* L. in aquaponics. *Journal of Fish Bioloy* 101(1), 249-261. DOI: https://doi.org/10.1111/jfb.15104.

Johnson, G.E., Buzby, K.M., Semmens, K.J., Waterland, N.L., 2016. Comparison of two harvest methods for lettuce production in an aquaponic system. *Journal of Agricultural Science* 9(1), 64-74.

Joyce, A., Goddek, S., Kotzen, B., Wuertz, S., 2019. Aquaponics: Closing the cycle on limited water, land and nutrient resources. *Aquaponics Food Production Systems*, 19. DOI: https://doi.org/10.1007/978-3-030-15943-6_2.

Junge, R., Bulc, T.G., Anseeuw, D., Yildiz, H.Y., Milliken, S., 2019. Aquaponics as an educational tool. In: *Aquaponics Food Production Systems*. (Eds.) Goddek, S., Joyce, A., Kotzen, B. and Burnell, G.M. Springer, Cham. pp. 561-595. DOI: https://doi.org/10.1007/978-3-030-15943-6_22.

Kaburagi, E., Yamada, M., Baba, T., Fujiyama, H., Murillo-Amador, B., Yamada, S., 2020. Aquaponics using saline groundwater: Effect of adding microelements to fish wastewater on the growth of Swiss chard (*Beta vulgaris* L. spp. cicla). *Agricultural Water Management* 227, 105851. DOI: https://doi.org/10.1016/j.agwat.2019.105851.

Kledal, P.R., König, B., Matulić, D., 2019. Aquaponics: The ugly duckling in organic regulation. In: *Aquaponics Food Production Systems*. (Eds.) Goddek, S., Joyce, A., Kotzen, B. and Burnell, G.M. Springer, Cham. pp. 487-500. DOI: https://doi.org/10.1007/978-3-030-15943-6_19.

Kloas, W., Groß, R., Baganz, D., Graupner, J., Monsees, H., Schmidt, U., Staaks, G., Suhl, J., Tschirner, M., Wittstock, B., Wuertz, S., Zikova, A., Rennert, B., 2015. A new concept for aquaponic systems to improve sustainability, increase productivity and reduce environmental impacts. *Aquaculture Environment Interactions* 7(2), 179-192. DOI: https://doi.org/10.3354/aei00146.

Konig, B., Junge, R., Bittsanszky, A., Villarroel, M., Komives, T., 2016. On the sustainability of aquaponics. *Ecocycles* 2, 26-32. DOI: https://doi.org/10.19040/ecocycles.v2i1.50.

Kotzen, B., Emerenciano, M.G.C., Moheimani, N., Burnell, G.M., 2019. Aquaponics: alternative types and approaches. In: *Aquaponics Food Production Systems*. (Eds.) Goddek, S., Joyce, A., Kotzen, B. and Burnell, G.M. Springer, Cham. pp. 301-330. DOI: https://doi.org/10.1007/978-3-030-15943-6_12.

Krastanova, M., Sirakov, I., Ivanova-Kirilova, S., Yarkov, D., Orozova, P., 2022. Aquaponic systems: biological and technological parameters. *Biotechnology and Biotechnological Equipment* 36, 305-316. DOI: https://doi.org/10.1080/13102818.2022.2074892.

Lennard, W.A., Leonard, B.V., 2004. A comparison of reciprocating flow versus constant flow in an integrated, gravel bed, aquaponic test system. *Aquaculture International* 12(6), 539-553. DOI: https://doi.org/10.1007/s10499-004-8528-2.

Lennard, W.A., Leonard, B.V., 2006. A comparison of three different hydroponic sub systems (gravel bed, floating and nutrient film technique) in an aquaponic test system. *Aquaculture International* 14, 539-550. DOI: https://doi.org/10.1007/s10499-006-9053-2.

Lennard, W., Ward, J., 2019. A comparison of plant growth rates between an NFT hydroponic system and an NFT aquaponic system. *Horticulturae* 5(2), 27. DOI: https://doi.org/10.3390/horticulturae5020027.

Lennard, W., Goddek, S., 2019. Aquaponics: The basics. In: *Aquaponics Food Production Systems*. (Eds.) Goddek, S., Joyce, A., Kotzen, B. and Burnell, G.M. Springer, Cham. pp. 113-143. DOI: https://doi.org/10.1007/978-3-030-15943-6_5.

Mamatha, D., Verma, A.K., Tiwari, V.K., Chandrakant, M.H., Nayak, S.K., Javed, H., 2020. Biointegration of rohu (*Labeo rohita*) fry and lemon grass (*Cymbopogon citratus*) in a recirculating aquaponic system. *Journal of the Indian Society of Coastal Agricultural Research* 38(2), 132-139.

Marques, B., Calado, R., Lillebø, A.I., 2017. New species for the biomitigation of a super intensive marine fish farm effluent: combined use of polychaete-assisted sand filters and halophyte aquaponics. *Science of* *the Total Environment* 599-600, 1922-1928.

Maucieri, C., Nicoletto, C., Schmautz, Z., Sambo, P., Komives, T., Borin, M., Junge, R., 2017. Vegetable intercropping in a small-scale aquaponic system. *Agronomy* 7(4), 63. DOI: https://doi.org/10.3390/agronomy7040063.

Maucieri, C., Nicoletto, C., Junge, R., Schmautz, Z., Sambo, P., Borin, M., 2018. Hydroponic systems and water management in aquaponics: A review. *Italian Journal of Agronomy* 13(1), 1-11.

Maucieri, C., Nicoletto, C., Van Os, E., Anseeuw, D., Van Havermaet, R., Junge R., 2019. Hydroponic technologies. *Aquaponics Food Production Systems* 10, 978-983. DOI: https://doi.org/10.1007/978-3-030-15943-6_4.

McMurtry, M.R., Sanders, D.C., Cure, J.D., Hodson, R.G., 1997. Effects of biofilter/ culture tank volume ratios on productivity of a recirculating fish/vegetable coculture system. *Journal of Applied Aquaculture* 7(4), 33-51. DOI: https://doi.org/10.1300/J028v07n04_03.

Meena, L.L., Verma, A.K., Bharti, V.S., Nayak, S.K., Chandrakant, M.H., Haridas, H., Reang, D., Javed, H., John, V.C., 2022. Effect of foliar application of potassium with aquaculture wastewater on the growth of okra (*Abelmoschus esculentus*) and *Pangasianodon hypophthalmus* in recirculating aquaponic system. *Scientia Horticulturae* 302, 111161. DOI: https://doi.org/10.1016/j.scienta.2022.111161.

Meena, L.L., Verma, A.K., Krishnani, K.K., Hittinahalli, C.M., Haridas, H., John, V.C., 2023. Combined foliar application effect of iron and potassium on growth of okra and striped catfish using media bed based aquaponics. *Aquaculture* 569, 739398. DOI: https://doi.org/10.1016/j.aquaculture.2023.739398.

Milliken, S., Stander, H., 2019. Aquaponics and social enterprise. In: *Aquaponics Food Production Systems*. (Eds.) Goddek, S., Joyce, A., Kotzen, B. and Burnell, G.M. Springer, Cham. pp. 607-619. DOI: https://doi.org/10.1007/978-3-030-15943-6_24.

Mohapatra, B.C., Chandan, N.K., Panda, S.K., Majhi, D., Pillai, B.R., 2020. Design and development of a portable and streamlined nutrient film technique (NFT) aquaponic system. *Aquaculture Engineering* 90, 102100. DOI: https://doi.org/10.1016/j.aquaeng.2020.102100.

Monsees, H., Kloas, W., Wuertz, S., 2017. Decoupled systems on trial: Eliminating bottlenecks to improve aquaponic processes. *PLoS One* 12(9), e0183056. DOI: https://doi.org/10.1371/journal.pone.0183056.

Monsees, H., Suhl, J., Paul, M., Kloas, W., Dannehl, D., Würtz, S., 2019. Lettuce (*Lactuca sativa*, variety Salanova) production in decoupled aquaponic systems: Same yield and similar quality as in conventional hydroponic systems but drastically reduced greenhouse gas emissions by saving inorganic fertilizer. *PLoS One* 14(6), e0218368. DOI: https://doi.org/10.1371/journal.pone.0218368.

Nuwansi, K.K.T., Verma, A.K., Prakash, C., Tiwari, V.K., Chandrakant, M.H., Shete, A.P., Prabhath, G.P.W.A., 2016. Effect of water flow rate on polyculture of koi carp (*Cyprinus carpio* var. koi) and goldfish (*Carassius auratus*) with water spinach (*Ipomoea aquatica*) in recirculating aquaponic system. *Aquaculture International* 24, 385-393. DOI: https://doi.org/10.1007/s10499-015-9932-5.

Nuwansi, K.K.T., Verma, A.K., Tiwari, V.K., Prakash, C., Chandrakant, M.H., 2017. Standardisation of the stocking density ratios of koi carp (*Cyprinus carpio* var. koi): Goldfish (*Carassius auratus*) in polyculture aquaponic recirculating system. *Turkish Journal of Fisheries and Aquatic Sciences* 17, 1271-1278. DOI: https://doi.org/10.4194/1303-2712-v17_6_20.

Nuwansi, K.K.T., Verma, A.K., Rathore, G., Prakash, C., Chandrakant, M.H., Prabhath, G.P.W.A., 2019. Utilisation of phytoremediated aquaculture wastewater for production of koi carp (*Cyprinus carpio* var. koi) and gotukola (*Centella asiatica*) in an aquaponics. *Aquaculture* 507, 361-369. DOI: https://doi.org/10.1007/s10499-019-00485-0.

Nuwansi, K.K.T., Verma, A.K., Chandrakant, M.H., Prabhath, G.P.W.A., Peter, R.M., 2021. Optimisation of stocking density of koi carp (*Cyprinus carpio* var. koi) with gotukola (*Centella asiatica*) in an aquaponic system using phytoremediated aquaculture wastewater. *Aquaculture* 532, 735993. DOI: https://doi.org/10.1016/j.aquaculture.2020.735993.

Pasch, J., Ratajczak, B., Appelbaum, S., Palm, H.W., Knaus, U., 2021. Growth of basil (*Ocimum basilicum*) in DRF, raft and grow pipes with effluents of African catfish (*Clarias gariepinus*) in decoupled aquaponics. *AgriEngineering* 3(1), 92-109. DOI: https://doi.org/10.3390/agriengineering3010006.

Patil, P.A., Dube, K., Verma, A.K., Chadha, N.K., Sundaray, J.K., Jayasankar, P., 2019. Growth performance of goldfish, *Carassius auratus* and basil, *Ocimum basilicum* in media bed aquaponics. *Indian Journal of Fisheries* 66(1), 112-118. URL: http://eprints.cmfri.org.in/id/eprint/13612.

Peter, R.M., Verma, A.K., Saharan, N., Tiwari, V.K., Thomas, R.M., 2019. Optimising pearlspot, *Etroplus suratensis* (Bloch, 1790) stocking density with tomato (*Solanum lycopersicum*) in recirculating aquaponic system. *Journal of Experimental Zoology India* 22(2), 1109-1113.

Peter, R.M., Verma, A.K., Chandrakant, M.H., Mamatha, D., 2021a. Effect of different potassium ($K^+$) doses on growth of tomato (*Solanum lycopersicum*) with pearlspot (*Etroplus suratensis*) in a recirculating aquaponic system. *Journal of Experimental Zoology India* 24(2), 951-959.

Peter, R.M., Verma, A.K., Saharan, N., Tiwari, V.K., Chandrakant, M.H., Thomas, R.M., 2021b. Effect of hydraulic loading rate on production of tomato (*Solanum lycopersicum*) with pearlspot (*Etroplus suratensis*) in recirculating aquaponic system. *Journal of Agricultural Engineering* 58(3), 300-308. DOI: https://doi.org/10.52151/jae2021581.1753.

Pinheiro, I., Carneiro, R.F.S., Vieira, F. do N., Gonzaga, L.V., Fett, R., Costa, A.C. de O., Magallon-Barajas, F.J., Seiffert, W.Q., 2020. Aquaponic production of *Sarcocornia ambigua* and Pacific white shrimp in biofloc system at different salinities. *Aquaculture* 519, 734918. DOI: https://

doi.org/10.1016/j.aquaculture.2019.734918.

Rakocy, J.E., 2012. Aquaponics - Integrating fish and plant culture. In: *Aquaculture Production Systems*. (Ed.) Tidwell, J.H. John Wiley & Sons, Inc. pp. 344-386. DOI: https://doi.org/10.1002/9781118250105.

Rakocy, J.E., Bailey, D.S., Shultz, R.C., Thoman, E.S., 2004. Update on Tilapia and vegetable production in the UVI aquaponic system. *ResearchGate*.

Resh, H.M., 2022. *Hydroponic Food Production: A Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower*. CRC Press. p. 642.

Robaina, L., Pirhonen, J., Mente, E., Sánchez, J., Goosen, N., 2019. Fish diets in aquaponics. In: *Aquaponics Food Production Systems*. (Eds.) Goddek, S., Joyce, A., Kotzen, B. and Burnell, G.M. Springer, Cham. pp. 333-352. DOI: https://doi.org/10.1007/978-3-030-15943-6_13.

Rono, K., Manyala, J.O., Lusega, D., Sabwa, J.A., Yongo, E., Ngugi, C., Fitzsimmons, K., Egna, H., 2018. Growth Performance of spinach (*Spinacia Oleracea*) on diets supplemented with iron-amino acid complex in an aquaponic. *International Journal of Research Science and Management* 5(7), 117-127.

Roosta, H.R., Hamidpour, M., 2011. Effects of foliar application of some macro- and micro-nutrients on tomato plants in aquaponic and hydroponic systems. *Scientia Horticulturae* 129(3), 396-402. DOI: https://doi.org/10.1016/j.scienta.2011.04.006.

Roosta, H.R., Mohsenian, Y., 2012. Effects of foliar spray of different Fe sources on pepper (*Capsicum annum L.*) plants in aquaponic system. *Scientia Horticulturae* 146, 182-191. DOI: https://doi.org/10.1016/j.scienta.2012.08.018.

Roosta, H.R., Hamidpour, M., 2013. Mineral nutrient content of tomato plants in aquaponic and hydroponic systems: Effect of foliar application of some macro-and micro-nutrients. *Journal of Plant Nutrition* 36(13), 2070-2083. DOI: https://doi.org/10.1080/01904167.2013.821707.

Roosta, H.R., 2014. Effects of foliar spray of K on mint, radish, parsley and coriander plants in aquaponic system. *Journal of plant Nutrition* 37(14), 2236-2254. DOI: https://doi.org/10.1080/01904167.2014.920385.

Ru, D., Liu, J., Hu, Z., Zou, Y., Jiang, L., Cheng, X., Lv, Z., 2017. Improvement of aquaponic performance through micro- and macro-nutrient addition. *Environmental Science and Pollution Research* 24(19), 16328-16335. DOI: https://doi.org/10.1007/s11356-017-9273-1.

Schardong, R.M.F., Moro, M.F., Bonilla, O.H., 2020. Aquaponic system with white shrimp *Litopenaeus vannamei* rearing and production of the plants *Batis maritima*, *Sarcocornia neei* and *Sporobolus virginicus*. *Brazilian Archives of Biology and Technology* 63, e20190118. DOI: https://doi.org/10.1590/1678-4324-2020190118.

Schmautz, Z., Loeu, F., Liebisch, F., Graber, A., Mathis, A., Bulc, T.G., Junge, R., 2016. Tomato productivity and quality in aquaponics: comparison of three hydroponic methods. *Water* 8(11), 533. DOI: https://doi.

org/10.3390/w8110533.

Seawright, D.E., Stickney, R.R., Walker, R.B., 1998. Nutrient dynamics in integrated aquaculture-hydroponics systems. *Aquaculture* 160(3-4), 215-237. DOI: https://doi.org/10.1016/S0044-8486(97)00168-3.

Shete, A.P., Verma, A.K., Tandel, R.S., Prakash, C., Tiwari, V.K., Hussain, T., 2013. Optimization of water circulation period for the culture of goldfish with spinach in aquaponic system. *Journal of Agricultural Science* 5(4), 26. DOI: https://doi.org/10.5539/jas.v5n4p26.

Shete, Amruta P., Verma, A.K., Kohli, M.P.S., Dash, A., Tandel, R., 2013a. Optimum stocking density for growth of goldfish, *Carassius auratus* (Linnaeus, 1758), in an Aquaponic system. *Israeli Journal of Aquaculture-Bamidgeh,* 65.

Shete, A.P., Verma, A.K., Chadha, N.K., Prakash, C., Peter, R.M., Ahmad, I., Nuwansi, K.K.T., 2016. Optimization of hydraulic loading rate in aquaponic system with Common carp (*Cyprinus carpio*) and Mint (*Mentha arvensis*). *Aquacultural Engineering* 72, 53-57. DOI: https://doi.org/10.1016/j.aquaeng.2016.04.004.

Shete, A.P., Verma, A.K., Chadha, N.K., Prakash, C., Chandrakant, M.H., Nuwansi, K.K.T., 2017. Evaluation of different hydroponic media for mint (*Mentha arvensis*) with common carp (*Cyprinus carpio*) juveniles in an aquaponic system. *Aquaculture International* 25, 1291-1301. DOI: https://doi.org/10.1007/s10499-017-0114-5.

Somerville, C., Cohen, M., Pantanella, E., Stankus, A., Lovatelli, A., 2014. Small-scale aquaponic food production: Integrated fish and plant farming. *FAO Fisheries and Aquaculture Technical Paper* (589), I.

Sonneveld, C., Voogt, W., Sonneveld, C., Voogt, W., 2009. *Plant Nutrition in Future Greenhouse Production.* Springer, Netherlands. pp. 393-403. DOI: https://doi.org/10.1007/978-90-481-2532-6_17.

Stathopoulou, P., Tsoumalakou, E., Levizou, E., Vanikiotis, T., Zaoutsos, S., Berillis, P., 2021. Iron and potassium fertilization improve rocket growth without affecting tilapia growth and histomorphology characteristics in aquaponics. *Applied Sciences* 11(12), 5681. DOI: https://doi.org/10.3390/app11125681.

Thomas, R.M., Verma, A.K., Prakash, C., Krishna, H., Prakash, S., Kumar, A., 2019. Utilisation of inland saline underground water for bio-integration of nile tilapia (*Oreochromis niloticus*) and spinach (*Spinacia oleracea*). *Agricultural Water Management* 222, 154-160. DOI: https://doi.org/10.1016/j.agwat.2019.06.001.

Thomas, R.M., Verma, A.K., Krishna, H., Prakash, S., Kumar, A., Peter, R.M., 2021. Effect of salinity on growth of nile tilapia (*Oreochromis niloticus*) and spinach (*Spinacia oleracea*) in aquaponic system using inland saline groundwater. *Aquaculture Research* 52, 6288-6298. DOI: https://doi.org/10.1111/are.15492.

Tokunaga, K., Tamaru, C., Ako, H., Leung, P., 2015. Economics of small-scale commercial aquaponics in Hawaii. *Journal of World Aquaculture Society* 46, 20-32. DOI: https://doi.org/10.1111/jwas.12173.

Trang, N.T.D., Schierup, H.H., Brix, H., 2010. Leaf vegetables for use in integrated hydroponics and aquaculture systems: effects of root flooding on growth, mineral composition and nutrient uptake. *African Journal of Biotechnology* 9(27), 4186-4196.

Treftz, C., 2015. *Comparison of Nutritional and Sensory Qualities between Hydroponic and Soil-Grown Strawberries and Raspberries*. University of Nevada, Reno.

Turnˇsek, M., Morgenstern, R., Schroter, I., Mergenthaler, M., Hüttel, S., Leyer, M., 2019. Commercial aquaponics: a long road ahead. In: *Aquaponics Food Production Systems*. (Eds.) Goddek, S., Joyce, A., Kotzen, B. and Burnell, G.M. Springer, Cham. pp. 453-485. DOI: https://doi.org/10.1007/978-3-030-15943-6_18.

Vasdravanidis, C., Alvanou, M.V., Lattos, A., Papadopoulos, D.K., Chatzigeorgiou, L., Ravani, M., Liantas, G., Georgoulis, L., Feidantsis, K., Ntinas, G.K., Giantsis, L.A., 2022. Aquaponics as a promising strategy to mitigate impacts of climate change on rainbow trout culture. *Animals* 12, 2523. DOI: https://doi.org/10.3390/ani12192523.

Verma, A.K., Nayak, S.K., Chandrakant, M.H., Reang, D.S., Javed, H., Peter, R.M., 2020. Production of spinach (*Spinacia oleracea*) plant and seed of rohu (*Labeo rohita*) in a recirculating aquaponic system. *Journal of Water Engineering and Management* 1(2), 35-42.

Vlahos, N., Levizou, E., Stathopoulou, P., Berillis, P., Antonopoulou, E., Bekiari, V., Krigas, N., Kormas, K., Mente, E., 2019. An experimental brackish aquaponic system using juvenile gilthead sea bream (*Sparus aurata*) and rock samphire (*Crithmum maritimum). Sustainability* 11(18), 4820. DOI: https://doi.org/10.3390/su11184820.

Waller, U., Buhmann, A.K., Ernst, A., Hanke, V., Kulakowski, A., Wecker, B., Orellana, J., Papenbrock, J., 2015. Integrated multi-trophic aquaculture in a zero-exchange recirculation aquaculture system for marine fish and hydroponic halophyte production. *Aquaculture International* 23(6), 1473-1489. DOI: https://doi.org/10.1007/s10499-015-9898-3.

Yang, T., Kim, H.J., 2020. Effects of hydraulic loading rate on spatial and temporal water quality characteristics and crop growth and yield in aquaponic systems. *Horticulturae* 6(1), 9.