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REVIEW

Decarbonizing Aquatic Food Production Through Circular Bioeconomy of Aquaponic Systems

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Abstract

Aquaponics is rapidly emerging as a sustainable aquatic food production system that addresses the many concerns associated with aquaculture, especially those related to environmental footprint. Depending on certain factors aquaponics can be graded as low-carbon, carbon neutral or carbon negative method. In aquaponics, water discharged from the fish production chamber feeds the plants and plants absorb the waste and filter the water which returns to the fish tank. This characterizes the circular bioeconomy of the system. Nitrifying bacteria play a vital role in biological filtration by way of transforming toxic waste into a form usable by plants. Grow-bed media filters are central in the nitrogen cycle in a closed-loop system. That is highly biodynamic, with the variables that tend to change the balance among the various components of the whole system. Optimization of biological processes allows the system-level changes within a specified range but because of self-renewal inherent in the operations, the system shows no overall change. Modulating the grow-bed media is the essential feature of this balancing mechanism. It includes selection of media filters according to their physical attributes. This paper seeks to advance the current understanding of the most critical aspects of aquaponics that could help in developing system designs for a truly aquatic carbon farming.

Introduction

The emerging scientific evidence is good enough to put the food systems in the context of their impact on the environment and the sustainability dimensions. In a straight-forward way, Laganda (2021) elaborates the gravity of the situation caused by prevailing food systems and addresses the implications arising from more of the same practices in terms of environmental degradation as well as food security. Emissions from food systems in 2015 accounted for 18 Gigatonnes of CO_2 equivalent globally, representing 34% of total Greenhouse Gas (GHG) emissions (Crippa et al., 2021). Out of this amount, agriculture and land-use activities shared 71% of the total. It is being recognized that aquaculture can make a significant contribution to global food security by environmentally compatible methods. There are concerns about the ecological footprint of highly diversified aquaculture systems. Granada et al. (2015) have reviewed this problem in the context of metabolic waste products and uneaten feeds released by fish farms as among the most important factors causing loading of nutrients. These authors expressed concern particularly about nitrogen and phosphors, in the surrounding environment. Some technological solutions have been proposed by Saufie et al. (2021) for mitigating the wastewater impacts. However, aquaponics and integrated multi-trophic aquaculture systems are gaining importance due to waste recycling inherent in their operations and the lower environmental impacts.

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Aquaponics combines fish and vegetables in a closed loop system. It represents a hybrid technology for blending aquaculture (growing fish) and raising plant crop in a soil-free medium (hydroponics) in a controlled system (FAO, 2014). In its simple form, this sort of integrated culture of aquatic animals and plants has been practiced for centuries but application of technologies has transformed it into a modern form of aquaponics modules. Farming of fish produces harmful wastes, but these are held in the closed-loop system and transformed into biomass. A captive fish or other fed species produces waste containing ammonia that must be removed to prevent toxicity to the fish but plants in the hydroponic section live off this waste, using the nitrogenous elements for building biomass. At the same time the nitrifying bacteria degrade the toxic substances to ensure a healthy growing environment for the plant and mitigating the water quality to a level that it can be recycled back to the aquaculture segment of the loop. The technologies of water recirculation help in ensuring a symbiotic environment across the aquaponics system (Anson, 2009). Although the aquaponics concept was developed in 1980s but witnessed a surge of interest in research and developments in this area much later (Somerville et al. 2014; Hu et al. 2015; Skar et al. 2015; Frincu and Dumitrache 2016; Flett 2017; Arroyo 2018; Estim et al. 2019; Fickerton 2018; Lenard and Goddek 2019). Aquaponics is widely perceived as a method of more sustainable food production, but it has many challenges that open enormous opportunities for solution-oriented innovations (Konig et al. 2018).

Harmonizing production and technology that is sought to be achieved in aquaculture essentially rests on the three dimensions of sustainability which remains a work in progress towards perfection in terms of balancing the variables that are hallmarks of a self-sustaining renewal system aimed at reducing or eliminating the resource inputs. Being a mainly closed-loop integrated production system, the aquaponics has several variables, especially those associated with the different species, waste recycling processes, and the nitrogen cycle. Each of these offer scope for improvement through creative design modifications and approaches.

Several models of aquaponics have been documented, and there are many suggestions for different fish-to-plant ratios and other components suitable for the various types of systems. The focus of attention in developing aquaponics remains on recycling of water and nutrients for growth of biomass that would constitute human food while meeting the criteria of sustainable development. A survey of published information reveals different production efficiencies related to diversity in the methods of aquaponics, requirements and performance of integrated species and the quality of the recirculating water. Obviously, there are knowledge gaps and a glaring lack of knowledge management constraining the development of commercial-scale aquaponics. It is, therefore, important to address this problem by synthesis of knowledge and to provide solution options for successfully implementing the environment-friendly low-carbon aquaculture systems represented by aquaponics. For this purpose, a clear understanding of the structural components of aquaponics systems and their functions is necessary to highlight the pertinent issues. This paper focuses on the role of grow-bed media which is the most biodynamic component in aquaponics. Grow-bed media plays a crucial role in ecologically engineering the aquaponics for functional homoeostasis required for sustainability of the production cycle. It is a key factor in nitrification and water quality renewal. Synthesis of knowledge generated by more than a decade of experimental trials that we carried out and findings of several other relevant investigations was done to produce this review. The main motivation for undertaking this effort was to advance the current understanding of nitrogen cycle in aquaponics and to provide a foundation for future research that could lead to improved models of the system for efficient use of resources for organic food production. This study presents the practical relevance of adopting nature's designs in aquatic food production and an outstanding example of understanding how biomimicry works in a real-world design. The way aquaponic functions leaves no doubt about its ability to lessen or obliterate the adverse impact of aquaculture on nature in tune with the global goals of sustainable food security.

Low Carbon, Carbon-neutral or Carbon-negative Farming

Aquaculture releases approximately 0.49% of anthropogenic GHG emissions based on species that support 93% of the global aquaculture (MacLeod et al., 2020). These authors opined that if the remaining 7% of aquaculture produces similar level of emissions, the total emissions will amount to 263 metric tons of carbon dioxide equivalent (MtCO2e). Evidently, emissions from aquaculture form a significantly small amount compared to cattle meat production where emissions are as high as 3000 MtCO2e (MacLeod et al., 2020). Currently, livestock contribute 14.5% of the 30% GHG emissions arising from agriculture (Vermeulean et al., 2012; Gerber et al.2013; FAO, 2014; Grossi et al., 2019). While reviewing the problem of agricultural emissions, Mustafa & Hill (2021) cited data indicating that a single ruminant releases 250-500 litre of CH_4 into the air in one day (Watts, 2019).

Aquaponic models generally represent low-carbon aquatic food production systems. They release far less greenhouse gas emissions to produce the same amount of food due to high feed efficiency and inbuilt energy-saving processes unlike land-based systems that cover larger areas and need more energy expenditure (FAO, 2021). In specific terms, aquaponics can be graded into carbon-neutral (or net zero) or even carbon-negative system of farming, depending on design of the production unit and species that are selected. Providing metrics to justify grading is not easy since it requires the ability of integrated species of plants to remove as much carbon dioxide from the atmosphere during photosynthesis as what is emitted by the aquaponic system so that the net amount added is zero. This is an ideal situation to happen but 'net zero' does not imply zero emissions, rather balancing out the measured emissions by appropriate actions.

For aquaponics to be considered carbon-negative the plant species in the unit should be able to remove more carbon dioxide from the atmosphere than it emits at a given time (FAO, 2022). Much depends on the source of energy (renewable or non-renewable) used in aquaponics, whether in preparing inputs (feed) or operations involved throughout the production cycle. These operations have carbon footprint that is practically difficult to measure since aquaponic enterprises get feed supplies from commercial-scale manufacturers and do not measure emissions such as from aeration. Use of renewable energy in running the entire system will undoubtedly quality it for carbon-negative farming. Attaining carbon neutrality is the essential first step towards achieving carbon negativity consistent with the concepts elaborated by Edengreen (2021). The dual benefits of producing food and removing more CO_2 that it produces makes carbon negativity so much important in a changing climate. The challenge posed by climate change requires this sort of carbon reversal processes. While land-based farming can help in carbon negativity by compositing that increases the carbon storage in the soil but tilling it for routine agricultural practices releases much of the stored carbon into the atmosphere. West et al. (2004) have estimated that as much as 30% of carbon is released over a 20-year period of continued tilling and cropping. There is no such risk of carbon emission in a soilless culture system of aquaponics. Aquaponics can be done in rural as well urban areas, and even in houses with a limited space which saves water use and eliminates emissions that are associated from transporting food. Vertical aquaponic systems can sequester more carbon per unit area than any of the traditional farming system. Design innovations are necessary for further reducing the carbon footprint. A widely used crop in aquaponics is tomato and depending on farming system the annual carbon footprint values have been reported to vary between 0.1 and 10.1 CO2-eq/kg tomato (Ntinas et al., 2017). More investigations and experimental trials are needed on stocking rates of the integrated species and their nutrient requirements for a healthy growth and production. Any research should be based on an understanding that plants and animals used in aquaponics release carbon dioxide through respiration, but plants capture CO_2 through photosynthesis and chemically reduce the carbon for stored chemical energy in the plant, and in developing and maintaining the carbon structure (skeleton) of the organic molecules that make the plant structure (Taub, 2010). The carbon, together with hydrogen and oxygen, assimilated into organic molecules by photosynthesis constitutes up almost 96% of the total dry mass of a typical plant (Marschner 1995).

Environmental compatibility of aquaponics indicates the potential of integrated agriculture in positively interacting with the environment. Food demand is expected to increase about 70% by 2050 and climate-friendly investment in this area towards an integrated systems-level approach will yield significant outcomes (Bell & Horvath, 2020). Traditional agriculture requires a substantial input of natural resources while releasing large quantities of pollutants, and accounts for at least one quarter of global greenhouse gas (GHG) emissions (IPCC, 2014; UNESCO, 2014; Roser & Ritchie, 2017). Expanding food production systems such as aquaponics and integrated multi-trophic aquaculture is vitally important for environment, society and economy.

A problem encountered in obtaining accurate data on carbon footprint of different aquatic species is that aquaculture is practiced in highly diversified ways according to species selected and compatibility of farming systems from technical and economic considerations. Same species raised through different farming systems will produce different carbon footprints. Species used in aquaculture differ in feeding habits and water quality requirements such as dissolved oxygen, salinity, and pH. These and other factors influence energy inputs and emissions from the system. While it appears simple if expressed as the total amount (kg) of carbon dioxide (CO_2) or relative amounts of other GHGs released per kg of food produced, the carbon footprint assessment entails a series of activities involved in production, including supplies such as feed, processing, maintenance of water quality, especially dissolved oxygen through aeration, and waste degradation or its recycling. This is the reason for a wide range of carbon footprint values for aquaculture. Carbon footprint is higher for some species of finfish (for example, groupers and seabass), varying in the range of 4-6/ kg carcass weight at the farm gate compared to cultured bivalves (Lutz, 2021). This has been attributed to variability in feed composition, energy source and consumption, type of fuel used, storage, transport, form of the marketed product and distribution. Emissions associated with the fish meal and oil production account for a significant share in the carbon footprint. Emissions have been reported to correlate with the production pattern and contribution of different geographical regions, but this cannot be generalized. Investigations conducted by MacLeod et al. (2020) produced interesting results (Figure 1) that showed that in the region of Asia, cyprinids shared 31% of production and accounted for 31% of emissions. On the other hand, shrimp shared 10% of production but released 21% of emissions whereas bivalves contributed 21% of production and only 7% of emissions.

Key Components of Aquaponic Systems

Aquaponics system comprises mainly the fed species, fish tank, grow bed, plant, aeration and pump. Fish tank provides holding space for the captive fish or other selected fed species. The Grow bed is the chamber with several sub-components collectively constituting an ecosystem where some activities that happen are not so visible but understandable and verifiable. This unique ecosystem functions according to the principles of biodynamics where a combination of biological and dynamic processes tends to make the production unit sustainable. Success of this production system depends on harmonizing the multiple factors and variables. This is necessary for completion of the farming cycle with minimal dependence on external inputs and for maintaining the capacity of the biomass production system for self-renewal. Undoubtedly, grow-bed is central in this complexity of processes. It is in this chamber that aquaculture effluents entering with water from the fish tank have to be cleaned so that the water could be returned to the fish tank to repeat the cycle in the closed loop system. These steps are shown in Figure 2.

Grow-bed has the facilities and mechanisms for transforming fish effluents into useable nutrients by having a) substrates for proliferation of nitrifying bacteria and, b) plants for uptake of the products of bacterial activity and other nutrients, particularly phosphate and minerals. Functional efficiency of these processes contributes to restoring the quality of wastewater to the recyclable state. The substrates placed in the grow-bed primarily for aggregating nitrifying bacteria constitute the 'Grow-Bed Media' (or in short, Grow Media). The nitrifying bacteria colonizing the grow media convert fish waste (ammonia) into nitrites and then nitrates that can be used by plants as nutrition. In addition to this microbial biofiltration, the

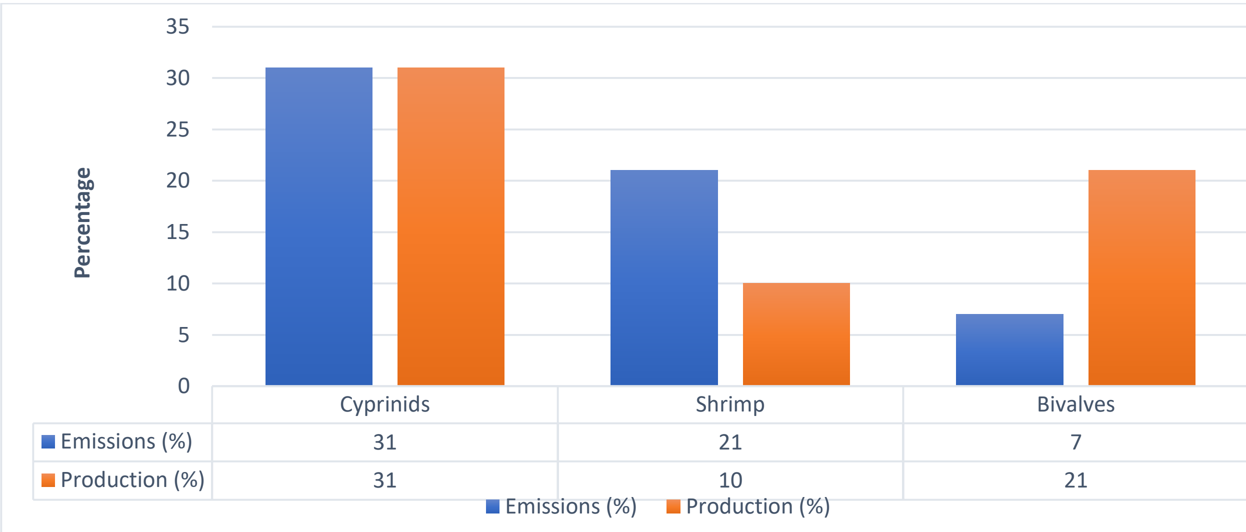

Figure 1. Percentage production and GHG emissions in aquaculture of three main groups of animals (Source: MacLeod et al., 2020).

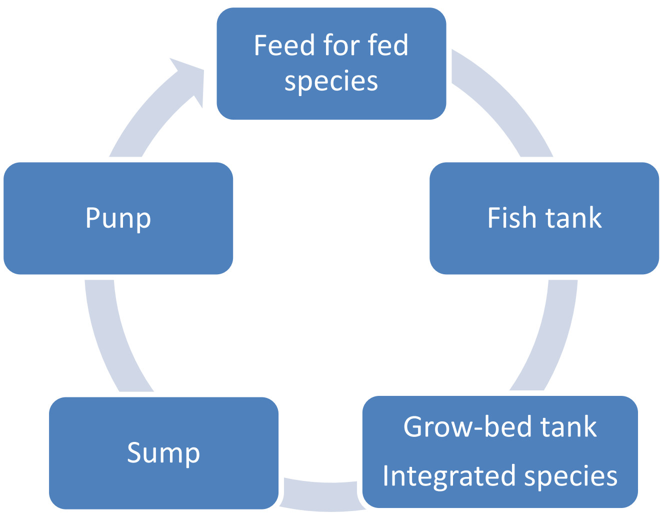

Figure 2. Fate of feed provided to fed species and its transformation pathways in a recirculated aquaponic system.

grow media is also selected for its other functional attributes that include:

a) Anchoring support to roots of plants dangling in water to allow the plant to grow in a soilless condition and upright posture for supporting its weight in a normal orientation while effectively absorbing nutrients.
b) Moderating the temperature and mechanical activity of the flowing water.

Products not suitable for making grow media are those that leach chemicals which impair the water chemistry and pH, and overall water quality, or those that impede the water drainage, causing water logging, stagnation and oxygen deficiency anywhere in the grow-bed area. There is no dearth of materials that can serve as grow media, and a survey of literature reveals an array of choices for different types of aquaponics systems (Table 1). For a start-up enterprise, there could be some difficulty in selection. It will be helpful to understand the suitability of materials for adapting to the needs of the system or where it will be operated.

Besides the above widely used media filters that are of general use in most of the aquaponic systems, there are also specially designed biofilter media. Performance of some of these media has been reviewed by Fickerton (2018) and Wahap et al. (2010). Their unique features are summarized in Table 2.

Out of these products that are available in the market, only two (Crystal Bio and AquaMat), have been subjected to thorough experimental trials in aquaponics systems conducted by Wahap et al. (2010) and Estim and Mustafa (2014). Both were reported to be good substrates for biofiltration mainly due to their surface features.

A significant problem that constrains the comparative assessment of the functional efficiency of grow media is that there are also factors other than simply the size, weight and volume of the media. These include variations in the difficult-to-measure surface features and surface areas of complex structures that determine the capacity to concentrate the nitrifying bacteria. For example, coral rubble and gravel of equal weight or volume will hold different densities of bacteria, and this makes a marked difference in the biofiltration efficiency of the grow media. These is still no accurate method for directly measuring the differences in their biofiltration capacities but physical attributes that influence this process have been identified in an earlier work (Estim and Mustafa, 2011).

Nitrogen Cycle in the Grow-bed

Perhaps the most important issue in aquaponics is nitrogen transformations that determine the recovery of resources and production output. Grow-bed is the central component where key steps in these transformations take place. While nitrogen is abundant in the atmosphere in the form of N_2, it occurs as ammonia, nitrite, and nitrate in the aquatic ecosystems. The sequence of nitrogen conversion follows a cycle. In aquaponics systems, the nitrogen cycle is a controlled process, unlike in nature where it has many variables that exert their effects. Nitrogen enters the system through the feed for the fish which then excretes it as ammonia that undergoes transformation first into nitrite and subsequently into nitrate. This pathway has 3 steps:

Ammonification –Excretion of ammonia (NH_3) in the metabolic waste of the fish in water in the fish tank.

Nitrification –Two-step aerobic process of oxidation of ammonia to nitrite (NO_2^-), and oxidation of nitrite to nitrate (NO_3^-). The former is catalyzed by

Table 1. Common types of grow-bed media

Types of grow-bed media	Advantages	Disadvantages	References
Gravel	Easily available, long-life, easy to wash for reuse.	Heavy, lower surface area for bacterial activity, gets hot upon long exposure to sun	Oladimeji et al. (2018); Rinehart (2019)
Igneous rock (pumice)	Cheap, easily available, light, composed of highly tubular microvesicles with very thin, translucent bubble walls that provide a large surface area for the nitrifying bacteria. Contains numerous air pockets due to which it does not become hot.	Not easy to clean.	Somerville et al. (2014); Arroyo (2018)
Clay pebbles or Lightweight Expanded Clay Aggregate (LECA), or Hydroton	Smooth for delicate new roots. Easy with draining of water without mechanical disturbance to facilitate oxygenation. Less blockages and anaerobic areas due to large but less pore spaces. Loose form makes it easy to transplant in quantities required and detach plant roots.	Due to smooth surface the biological surface area is less than other substrates such as pumice. Reusable over long periods.	Skar et al. (2015); Flett (2017)
Coral rubble	Easily available and free of cost in coastal areas. Surface has cavities, crevices and holes that provide enormous substrate for nitrifying bacteria. Does not hinder water circulation.	Vulnerable to bioerosion due to removal of rock substrate by dissolution of organic matrix and $CaCO_3$ and mechanical abrasion. Requires renewal.	Estim (2015); Wahap et al. (2010); Estim and Mustafa (2011)

Ammonia-Oxidizing Bacteria of the *Nitrosomonas* group while the latter by the Nitrite-Oxidizing Bacteria represented by *Nitrobacter* group. Both are chemolithotropic organisms that get their energy by oxidation of inorganic nitrogen compounds mentioned above.

Assimilation – Absorption of nitrate as a nutrient by plants. This also takes place in the grow-bed

In a properly functioning aquaponics system ammonia and nitrite are immediately neutralized before they reach levels that breach the tolerance limits of the stocked species. Biofiltration, if effective, should keep their level close to zero, or no more than 0.25 mg/liter for just a short period of time. Only a healthy bacterial population can do it and prevent accumulation of any of these toxic nitrogenous products. Nitrification in the grow- bed is totally reliant on the bacteria, and in the event these bacteria are not present, or their count is low, or they are not actively involved then the ammonia concentration increases to a level that is fatal for the fish and can also undermine the biofiltration process. Somerville et al. (2014) have characterized it as an exponentially deteriorating condition that develops when the undersized biofilter cannot cope with high ammonia load. The ammonia level rises further when the bacteria begin to die, leading to collapse of the aquaponics production cycle. This is evident from the findings established earlier (Song, 2016).

Ammonia toxicity depends on temperature and pH. It is more toxic when values of these parameters increase. At lower pH in the acidic range, ammonia becomes ionized (NH_4^+) by binding with the excess hydrogen ions (H^+) and becomes less toxic. On the contrary, when there are not enough hydrogen ions (higher pH in the alkaline range) the ammonia remains in the more toxic, un-ionized (NH_3) state. Ammonia toxicity is exacerbated in warmer water. Details of these chemical profiles in integrated aquaculture have been the subject of thorough research published earlier (Mustafa et al., 2019). The nitrate can reach up to 150 mg/liter, depending on the species, number of fish and volume of the waste produced (ISB 2019). Above this level, the plant roots could get the so-called 'nutrient burn' that impairs their functional roles, and the nitrate-rich recycled water will also put stress on the captive fish. This is in consonance with the concept presented by Stone (2020).

Nitrifying bacteria are naturally present in the water. They occur in a wide variety of environments such as sand, water, and air (Somerville et al., 2014) and can easily gain access into the culture system. In aquaponics, once ammonia appears in the tank, then it is just a matter of time before the nitrifying bacteria infiltrate it and colonize the grow bed by settling on the tank walls and the plant roots. However, their population should proliferate on the grow media to handle the scale of nitrification required, depending on the stocking density of the fish in the fish tank. Constraints in managing a healthy level of nitrifying bacteria results in accumulation of toxic ammonia and nitrite, and at the same time shortage of nutrients (mainly the nitrate) for the plants. A regular monitoring of conditions in the grow-bed is thus necessary for remedial action when the parameters exceed the levels that undermine the activities of nitrifying bacteria. Optimum values suggested by Somerville et al. (2014)

Table 2. Types of biofilter media

Biofilter media	Features and performance
Fluval BioMax BioRings	Made up of silica and aluminum oxide structured in the form of porous rings with thick walls. The internal pores provide surface for nitrifying and denitrifying bacteria to colonize. Hole in the center of each ring allows easy water flow.
Fluval Bio Foam	Prepared from a dense, porous foam substance. Provides considerable area for nitrifying bacteria. Effective in capturing particulate matter. Requires frequent cleaning to prevent clogging which will reduce water flow rate through the filter. Cleaning is easy but removes nitrifying bacteria.
Sachem Matrix	It is a solid pumice bimedia processed to form pebbles of 10 mm. Rough surface of this product is good for bacterial attachment. Provides external and internal macroporous surface area. The macropores are large enough for nitrifying and denitrifying bacteria to settle inside. This media can be used loose or in a filter bag. Does not require replacement. Can be rinsed without disturbing the bacteria and reused.
Eheim Substrate Pro	This inert product is in the form of fine glass particles compressed (sintered) into porous beads. Can be rinsed and reused. Comparatively expensive.
CerMedia MarinePure	Porous ceramic material developed at high temperature in kilns. It has numerous pores and rough surface. The chemical composition includes aluminum oxide and silicone dioxide in a stable form. Chemicals do not leach out of this ceramic. Water flows freely. It is expensive to use.
Biofilter Balls	Non-porous plastic 'bio-balls'. No pores at the surface to trap particulate matter. Water flows smoothly. Helps in removing ammonia and nitrite (nitrification). Inexpensive.
CrystalBio	Porous structure of light-weight ceramic, manufactured by heating a mixture of glass substance particles with a foaming agent at 900°C. Provides a large surface area to aerobic bacteria due to its porous structure. The product is light and available in many sizes, and a little alkaline that can buffer the culture medium. Recyclable and inexpensive.
AquaMat	Made up of ultrafine yarn shaped into ribbons that can be suspended in an aquaculture system. They have a large surface area that can be easily colonized by nitrifying bacteria and does not impair the water flow condition and aeration. Can be washed and reused multiple times with no change in the texture and properties. Long-term use of AquaMat makes then commercially viable.

for bacterial growth and activity are: Temperature (7–34ºC), pH (6–8.5) and dissolved oxygen (4–8 mg/liter). The authors have pointed out that while the optimum pH range is 7.2–7.8 for the *Nitrosomonas* and 7.2–8.2 for *Nitrobacter* but for aquaponics where other species of different tolerance limits are integrated in one system the permissible pH range could be 6–7. Plants have been reported to grow well when pH is 5-6 and fish prefer pH in the range 6-7. This information is presented in Table 3.

Any setback to the bacterial growth on account of the pH maintained for aquaponics (6 – 8.5) can be offset by increasing the biofiltration through the surface area of the grow media in the grow bed. Ammonia build-up beyond the threshold level established for the aquaponics system should warrant urgent attention on the possible conditions that cause impairment of the mechanism of nitrification. Any sort of treatment that eliminates the nitrifying bacteria from the system or reduces their population or creates conditions under which a bacterial colony is unequal to the task threatens the sustainability of the aquaponic system. Recovery takes time as is evident from the evidence provided by Frincu and Dumitrache (2016) who noticed a relatively slow rate of reproduction in nitrifying bacteria and formation of colonies. For this purpose, a sump (reservoir) generally connected to grow-bed for receiving water flowing from there requires chemical monitoring for determining its suitability for recycling to the fish tank. EC (2017) has suggested a neutral pH (7.0) as a compromise between the tolerance ranges for fish, plants and the bacteria in the aquaponic systems. This is based on the experimental data that showed an optimum pH for fish in the range of 6.5 – 8.0, for plants 5.0 – 7.0 and for nitrification 7.5 – 8.0. This report warns about ammonia and nitrite to be maintained less than 0.25 ppm. Tilapia is an exceptionally tolerant species that has been reported to survive even when unionized ammonia concentration was as high as 2.4 ppm (D'Amato et al., 2007). However, this is not an optimum condition for survival of this species.

Source of water is an important consideration in aquaponics. The reason is that the quality of water significantly influences the biofiltration, nutrient management and ability to manipulate the chemical profile for mitigating the adverse conditions. Water drawn from a natural source contains a variety of chemicals and microorganisms that pose management problems. Rainwater and municipal water are suitable. The latter should be free of chlorinating substances. Initially, these sources of water might not show the biofiltration activity until a colony of nitrifying bacteria establishes in the grow bed. The bacterial colonization starts with the appearance of ammonia in the grow bed due to excrement from the fish tank. However, biofiltration can also be activated before the aquaponics operations by releasing a small fish in the fish tank to generate ammonia. In a matter of days there will be enough ammonia for the generation of nitrogen cycle.

Dynamic Equilibrium and Homoeostasis

Aquaponics is a biodynamic system because of the biological activities of different organisms in the integrated production unit. Conditions constantly change but the system shows no overall change. This sort of dynamic equilibrium defines the unique homeostasis of aquaponics where alterations and restoration mechanisms occur simultaneously. Balancing in such a system is not easy but vital for success. It implies a balance between the three components: a) biomass of fish, b) biomass of plants, and c) biofiltration area. There is no universally applicable standard metrics that can guide in this balancing act due to diversity of species and the farming systems. As rightly pointed out by Lennard and Goddek (2019) 'rules of thumb' and predictive models based on experience apply in this matter even if this is an approximate approach.

Modulating the biofiltration capacity can help in striking the balance between fish and plant but within reasonable limits. The widely used combination are tilapia and carp (fish) and lettuce, beans, basil, tomato and mint (plants). The priority, of course, is optimization of the ratio of fish waste output and nutrient uptake by the plants (Gaddek et al. 2015). Preliminary trials can help provide what should be the rational stocking biomass ratios, and size and type of biofilters for balancing the system. This approach has helped in successfully managing the water quality profiles within the tolerance levels of the fish in experiments carried out by Estim and Mustafa (2010, 2014) and Estim et al. 2019). Estim and Mustafa (2010) used Asian seabass (*Lates calcarifer*) as the fed species in two culture modules operated with similar biomass ratio and environmental conditions (temperature, salinity, pH, dissolved oxygen and aeration). The only difference was in the grow media, with one in the form of coral rubble

Table 3. Optimum water quality values for aquaponics systems

Organisms	Temperature, ºC	pH	Dissolved oxygen, mg/liter	References
Finfish	27 - 29	6 - 7	>5	Sallenave (2016)
Nitrosomonas	7 - 34	7.2 – 7.8	4 - 8	Somerville et al. (2014); Frincu and Dumitrache (2016)
Nitrobacter	7 - 34	7.2 – 8.2	4 - 8	Somerville et al. (2014); Frincu and Dumitrache (2016)
Plant	17 - 30	5-6	>3	Sommerville et al. (2014)

and other a combination of coral rubble + Aquamat. Analysis of the results of the quantitative profiles of NH_3-N, NO_2-N and NO_3-N revealed that while nitrification occurred in both the sets, its rate was significantly higher ($P<0.05$) in the unit containing the grow media combination. The efficiency of Aquamat in biofiltration was earlier demonstrated by Estim and Mustafa (2014) who carried out the microbiological examination of grow bed. The authors identified 12 bacterial types and noticed that the grow-bed tank with Aquamat biofilter media contained $8.11 \times 10^6 \pm 4.95$CFU/ml against the grow-bed without it where the bacterial count was significantly lower ($1.77 \times 10^6 \pm 0.56$ CFU/ml). This produced marked differences in ammonia profile.

Different species of plants require different amounts of nutrients. The nutrient requirements of leafy and fruit vegetables are also different. After reviewing many aquaponics systems, Skar et al. (2015) reported the differences in several species of plants in their nitrogen uptake and utilization efficiencies primarily due to differences in the root surface area (Skar et al., 2015). These are among the main reasons that make it difficult to develop a 'generic' design for the fish-plant ratio (Lennard and Goddek 2019). This sort of practical understanding seems to have evolved considering the complexities associated with the aquaponics. For example, Lennard (2017) outlined the efforts made for matching the rates of production of individual fish waste based on feed composition and its conversion and utilization, with specific nutrient uptake by the plants. This method provides ideas on determining the suitable fish-plant ratio and designing a specific management approach. However, it involves a great deal of experimental trials on nutrient analysis in fish feed and assimilation by plants to calculate if all are utilized, and to identify those that are needed by plants but not available in the fish waste, for possible supplementation from outside the system. This poses difficulties in a commercial-level aquaponics comprising multiple species. Yet, testing concentrations of ammonia, nitrite, and nitrate is critical in making informed decision in modulating the nitrogen cycle for homoeostasis in aquaponics. If the aquaponic module can achieve a balance in biomass ratios and biofilter size, the system will efficiently transform ammonia into nitrate and the yield will be high and sustainable.

Neutralizing ammonia and nitrite is an essential requirement and this problem has received due attention but an issue that is often ignored is the nitrate level. Appropriate nitrate level is also important for nourishment of plants integrated in the aquaponic system. Plants increase the output of the farming system and are effective in uptake of nitrate as well as other nutrients in the fish waste. Through monitoring of water quality dynamics, it is possible to attain homoeostasis. This will enhance the output of organic food from the same production unit. If this can be achieved, then the system will become fully recirculating, obviating the need for water renewal. Considering the prime importance of nitrification in aquaponics, this topic has received a great deal of interest (Eck et al., 2019). A review on this aspect helps in explaining two distinct conditions pertaining to the nitrate turnover together with remedial intervention are described below:

Nitrate-deficiency condition:

1. Increasing the stocking rate of fish to generate nitrogenous waste that will produce the amount of nitrate required for the plant nourishment.
2. Increasing the density of nitrifying bacteria (*Nitrosomonas* group) when there is excess ammonia and adequate number of fish to enhance its transformation to nitrate through the usual pathways. In this case there is no need to change the stocking density of fish.
3. Enhancing the count of *Nitrobacter* bacteria if the grow-bed is nitrate-deficient but contains excess of nitrite. This will generate more nitrate at the expense of nitrite, without the need for changing the stocking density of fish.
4. If the system shows excess of ammonia as well as nitrite, then this problem can be fixed by introducing both the types of nitrifying bacteria, relying on a commercially available product.

Nitrate excess condition:

1. Reducing the stocking density of fish to curtail release of ammonia, leading to decline in the nitrite as well as nitrate levels.
2. Increasing the plant biomass.
3. Enhancing the grow-bed media.
4. Renewal of certain volume of water to lower the nitrate concentration by dilution. The percentage of water replacement will depend on attainment of the required level of nitrate in the medium. If the water is to be replaced by tap water, it is necessary to examine if it contains chlorine or chloramine that could have been added during the water treatment process. The easiest way is to store the tap water in a tank and expose it to air for about 48 hours to drive off chlorine before transferring to the aquaponic tank. Water replacement should be considered as a means of urgently fixing the problem, not a long-term solution of nitrate build-up.

Synthesis of information emerging from the experimental trials carried out at this institute by Estim and Mustafa (2014), Estim (2015), Sumbing et al. (2016) and Estim et al. (2019) makes it abundantly clear that: a) When biomass of fish and plant is imbalanced and in favor of the latter, the metabolic waste originating from the fish tank is inadequate to generate sufficient quantities of nutrients for the plants, and, as a result, the plant health and yield decline; b) When the fish component is oversized, the nutrient uptake in the grow-bed will decrease and the recycled water will contain the nitrogenous substances that will impair the water quality for fish. This might slow down fish growth and condition. Although, it might not adversely affect the plants initially but reflects the imbalance in the system that needs mitigation intervention before the production suffers.

It deserves mention that in aquaponics the different species of plants also differ in their nutrient uptake, and even if their stocking biomass is the same, the results could be different for this reason. Moreover, the nitrate uptake by the same plant species varies with the growth stage. Literature reviewed in the NZAP (2013) report reveals that leafy vegetables need more nitrate during vegetative growth but relatively less amount when fruiting. Working on aquaponics with tilapia and green beans integrated in the system Saufi (2020) noticed, perhaps for the first time, that fish waste supported growth of green bean only up to the fruiting stage. Failure of pod formation was linked to nutrient deficiency. This is an issue that draws attention to the need for intervention in the nutrient management in aquaponics. Generally, fish feed is the only nutrient input in the system. Feeds are formulated to meet the nutritional requirements of the fish, not that of plants. Plants have different nutrient requirements. Metabolic waste produced from the digested fish feed does not contain the nutrients necessary for fruiting (pod formation). It has nothing to do with the fish-plant ratio which could be exactly matched. Mitigation should be in the form of providing supplements in graded doses directly to the grow bed to nourish the green bean plant. In this case, and possibly aquaponic systems where plant is also high-value crop, the objective is to optimize production of fish as well as plant through all its stages for maximizing the overall output of the farming system. Nutrients that fish feeds do not contain in rich amounts are calcium, iron, and potassium (Rackocy et al., 2006). These need to be supplemented. The likely effects of additional nutrients on the chemical quality of culture water and the nitrification process require monitoring, and possibly buffering if that disturbs the system homoeostasis.

The above discussion leaves no doubt that aquaponic systems have several variables that should be monitored and balanced when required through knowledge-based interventions to achieve homoeostasis for sustainability of the food production cycle. Approaches and streategies for successful aquaponics have been documented by EC (2017), Hager et al. (2021) and GGA (2021). Main considerations contained in these documents are listed below:

1. Selection of species and stocking rates of the integrated species.
2. System maintenance to check water flow, aeration, pumping and connecting pines.
3. Temperature and sunlight.
4. Water quality balance- dissolved oxygen, pH, nityrogen, phosphorus,
5. Algal growth prevention.
6. Cleaning of filters and substrate for nitrifying bacteria.
7. Stress prevention in fish (surfacing activity, swimming activity, alertness and general vigour, and any other sign of health impairement).

Scope for Disruptive Innovations

Aquaponics combines traditional knowledge and various levels of technology. Many of the problems constraining the growth of aquatic farming require breakthrough in green technologies to ensure that food systems remain harmonized with the sustainability perspectives. There are several tools of the Fourth Industrial Revolution (or IR4.0) that are feasible for application in aquaponics, especially in urban areas. Limited space and resources, and urban lifestyles require a greater automation, accuracy, and risk management. This can lead to development of digital or smart aquaponic modules, the success of which will be determined by the practical operation of the technological tools designed to integrate with the biodynamic of biological processes of the aquaponics. Before bringing such modules into real-world farming, simulations will have to be performed to determine their effectiveness and sustainability. Aquaponics has always been adjustable, and with new technologies it will be even more adaptable, depending on how technological innovations are designed to be compatible with the biological and other requirements of the aquaponic systems. Perhaps, the most important technological intervention will be in the sensors that can anticipate the potential problems and trigger actions through the artificial intelligence system and machine learning tools to mitigate the risk. In a comprehensive review, Shaleh et al. (2021) and Yue and Shen (2021) have presented the scope and application of IR4.0 technologies in the domain of digital aquaculture, and many of the suggested applications are relevant to aquaponics. The chemical turnovers that take place and sensitivities of stocked species to chemicals such as ammonia, behavioral response of fed species, or stress factors for integrated plants need accuracy of detection and promptness of response systems that are much easier through automation and machine learning. Generally, any of the animal and plant species selected that have vastly different requirements, there will be trade-offs, but the digital technologies can reduce it through a rapid response system based on the biological data of fundamental importance that is available for the selected species. Of particular attention are the feeding systems for fed species, water quality dynamics, efficiency of biological filtration, and physicochemical and nutrient conditions take drive in the aquaponics modules. Efficiency of biomass production can improve further by applying the outcomes of targeted research on more pertinent topics such as optimizing feeding rate of the fed species of fish based on feed conversion ratio as well as specific growth rate (Ebrahimi and Mani, 2022). Working on sturgeon (*Huso Huso*) these authors have demonstrated changes in optimum feeding rate in relation to environmental conditions and the need for optimizing multiple independent and response variables. Such an approach has produced more appropriate feed formulations and rationing system in aquaculture for improving the gains from sustainability perspectives (Ebrahimi and Mani, 2022). Input costs in aquaponics may be higher compared to some traditional farming systems, and in some cases about 30-fold higher, but can still be considered economical due to space efficiency and additional income it generates (El-Essawy et al., 2019). Dalsgaard et al. (2013) and El-Essawy et al. (2019) have determined that aquaponics can save 90% of the water that generally goes waste in conventional farming methods. Inputs of digital technologies will further optimize the aquaculture production systems and resource conservation.

Conclusions

Aquaponics offers a new method of sustainable aquatic food production. It yields fed species (fish, lobster, shrimp) as well as vegetables (the extractive component) generally using a single nutrient source in the form of fish feed. The system design ensures water use efficiency, nutrient utilization, product quality and food security with biofiltration playing a key role. The complex nutrient solutions generated by biological pathways possess probiotic properties that bolster the nutrient uptake and resilience of the stocked species. Grow media have a central role in the success of aquaponics no matter what the species combination and overall system design. There are challenges in each of the components of aquaponics, requiring knowledge application and innovative solutions to ecologically engineer the system for meeting the environmental, economic, and societal criteria of sustainable development of this food production sub-sector. Dependence of the production cycle on market demand, resource availability, and access to knowledge and technology will constrain generalizations vis-à-vis systems' operations and outcomes. Validation of a selected approach and optimization coupled with a local feasibility study should precede any commercial-scale investment in aquaponics or upscaling the systems over larger production areas in a business perspective. Experiential and experimental knowledge management and mobilization will contribute significantly to success of aquaponics and its growth as a commercially viable and environment-friendly method of food production. With further research it will be possible to emulate more of problem-solving designs of nature and present diverse types of aquaponic systems. These systems will reflect potential significance of applying biomimicry and circular economy concepts and exploring the adaptive opportunities of such designs in a real-world food production. In view of the seriousness of the problem caused by GHG emissions, researchers and all those involved in the entire food system should consider not just the production aspect but also farming operations, care of stocked species, harvesting, processing and transportation and other energy consuming activities.

Ethical Statement

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Funding Information

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Author Contribution

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Conflict of Interest

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