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REVIEW ARTICLE

INTEGRATING AQUACULTURE AND HYDROPONICS: A REVIEW OF AQUAPONICS SYSTEMS AND THEIR SUSTAINABILITY

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ABSTRACT

Integrating hydroponics and aquaculture into a single system, aquaponics can be an effective strategy that fight against regional and global issues like food scarcity, soil erosion, climate change, and population growth. This review focuses on how aquaponics can enhance food production and resource utilization based on the subject's theoretical principles, the type of systems, and sustainability aspects. Hydroponics or aquaculture, which is the production of plants without soil and the farming of water animals respectively are examined in respect of their enhancing benefits in aquaponic systems. The benefits and drawbacks of each important system design are analyzed: Nutrient film technique (NFT), deep-water culture (DWC), and media-based grow beds (MGB). Thus, though NFT systems provided the lowest nitrate removal efficiency and overall lettuce yields, these systems were preferred by the users because of their cheap and rather simplistic construction. At the same time, MGB systems offered stability and were adequate for relatively small-scale projects, but required constant care and attention. Aquaponics Systems required large structures, but were extremely water conserving and low-profile. Each system has been estimated in terms of performance, easy to use, and maintenance. Nitrifying bacteria, plants, and fish share mutual interactions that help in water purifying the nutrient cycling process. Nutrients are used by plants to grow, which cleans the water. The purified water is immediately cycled again into the fish tank, ensuring that the scientific basis of aquaponics is followed to in all systems. This review also looks at the economic feasibility of aquaponics and limitation before concluding that it is a sustainable means of carrying out agriculture and it highlights the opportunity of using aquaponics for sustainable food production and environment preservation.

KEYWORDS

Aquaculture, Aquaponics, Hydroponics, Resource efficiency, Sustainability

1. INTRODUCTION

Aquaculture, which is also the main source of aquatic animal food used for human consumption, is the sector of the global animal feed business that is expanding the fastest (Ottinger et al., 2016). It continues to grow, advance, and increase across almost all regions of the world. The demand for both fish and other aquatic products is therefore increasing with the world's population (Subasinghe et al., 2009). Aquaculture is defined as a method in which commercial fish are cultured in tanks, or even ponds (Blidariu and Grozea, 2011). The systems that include crustaceans (shrimp, prawn, crabs, freshwater crayfish), mollusks (e.g. mussels, oysters, and clams), and finfish (e.g. catfish, trout, carp, tilapia, salmon) produce over 600 distinct animal species (Troell et al., 2014). A recirculating aquaculture system (RAS) is an aquaculture system that integrates water treatment and reuse, with less than 10% of total water volume replenished every day (Blidariu and Grozea, 2011). Aquaculture has the potential to improve resilience by increasing the diversity of farmed species, production locations, and feeding practices, as well as by increasing resource use efficiency (Troell et al., 2014). Future advancements in aquaculture will be crucial for the world's protein supply, trade, and food security from the perspective of human health (Beveridge et al., 2013). Sustainable aquaculture development must be achieved in an environmentally sustainable way that protects the quality of the environment for other users, while it is equally necessary for society to protect the quality of the environment for aquaculture (Frankic and Hershner, 2003).

On the other hand, Hydroponics is easier to explain as a way of growing plants without necessarily having to use the soil (Jan et al., 2020). It is a technique of growing plants without using the soil for growing them, their roots are placed in a nutritive solution (Maharana and Koul, 2011). Growers frequently respond that hydroponics always allows them to have higher productivities and yields without any constraints from climate and weather circumstances (Sarah, 2017). Again Growers frequently claim that hydroponic productions are easier, and since they do not require cultural activities such as plowing, weeding, soil fertilization, and crop rotation, they are light and clean (Nguyen et al., 2016). likewise, hydroponics is not dependent on seasonality, thus its productivities are higher and more consistent throughout the year (Okemwa, 2015). A variety of plants, including vegetables, fruits, flowers, and medicinal crops, can be cultivated utilizing soilless or hydroponic culture (Sardare and Admane, n.d.). It has a huge possibility in many countries, together with high space research, to satisfy an absence of arable land when adequate cultivable land is not accessible (Jan et al., 2020). Although hydroponics and aquaculture both have drawbacks, hydroponics is more costly due to the need for costly fertilizers and frequent system flushing, which can cause problems with waste disposal (Blidariu and Grozea, 2011).

Overpopulation, global warming, desertification, water scarcity, famine,

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increased diseases, and other alarming characteristics are some of the big challenges facing the world nowadays. Since aquaponics is a closed-loop system that has both hydroponics and aquaculture systems, it may provide solutions to such challenges (Goddek et al., 2015a). Aquaponics is an ecologically friendly aquaculture and planting method that has gained interest in a number of industries, including agriculture, ecology, and fisheries (Hao et al., 2020).The aquaponics production system combines hydroponics with recirculating aquaculture to produce plants and fish simultaneously (Okomoda et al., 2023a). The researchers from the New Alchemy Institute at North Carolina State University initially implemented this technology in the late 1970s and early 1980s. This technology was implemented by the University of the Virgin Islands (UVI) in 1980 (Love et al., 2015).The scientific literature has seen a significant increase in the number of publications on aquaponics in recent years, from approximately 5 in 2010 to approximately 35 in 2014 (Junge et al., 2017). In the broader sense, aquaponics is a term that refers to indoor and outdoor substrate aquaponics. This term surround horticulture techniques for the cultivation of herbs or gardening plants, as well as crop production in agriculture, all of which are conducted using conventional soil cultivation techniques (Palm et al., 2018). The nitrifying bacteria in the biofilter convert the nitrogen form from ammonia to nitrate, which is absorbed by the plants (Wongkiew et al., 2017).

Modern aquaponics is primarily categorized based on the hydroponic form and the degree of closure of the water cycle. Deep Water Culture (DWC), Media-Based Growing Bed (MBGB), and Nutrient Film Technique (NFT) are prevalent methods (Goddek et al., 2015a). This kind of cultivation is considered one of the most effective and environmentally friendly animal protein production systems. Overall, fish necessitate less feed per kilogram of added growth than all other agricultural animal products, including beef, mutton, and goat (Tilman and Clark, 2014). In aquaponics, feed loss and fish refuse can be recycled and converted into valuable plant biomass. Effective nutrient recycling is supported by mineral transfers from aquaculture to hydroponics, and water recirculation lowers water consumption (Turcios and Papenbrock, 2014).

The aim of this review is to assess how aquaponics, involves the integration of hydroponics and aquaculture that can address some of the world's most serious problems like environmental conservation and food shortage. This paper explores the different types of aquaponics system, strengths, weakness, and opportunities in the ability to increase food production, conserve resources, and integrate sustainable agriculture. This review aims to prove that aquaponics is feasible, sustainable and economical in terms of putting into practice the concepts of conserving the environment and producing food.

2. PRINCIPAL OF AQUAPONICS

Aquaponics embodies the ideas of reusing fertilizers and water, making it a sustainable alternative to recirculating aquaculture and hydroponics. Its primary ideas include converting waste from one system into nutrients for another, creating several goods at the same time by combining fish and plant culture, recycling water via biological filtration, and boosting local economies through healthier food access (Gosh and Chowdhury, 2019). When choosing plants, it's best to stick with herbs and specialist greens (such watercress, spinach, chives, and basil) since they have low to medium nutritional needs and work well in an aquaponics system (Gosh and Chowdhury, 2019). Aquaponics is a freshwater ecosystem in which live organisms such as fish, plants, and bacteria interact with non-living elements such as water, air, and growing medium. Fish are fed in a tank, and their waste, which is high in ammonia from the diet, is converted by bacteria and other microorganisms into nutrient-rich fertilizer containing nitrate and ammonium. Plants use these nutrients to flourish, thereby cleaning the water. The cleansed water is then recirculated back into the fish tank, ensuring that the scientific principle of aquaponics is followed across all systems (Adhikari et al., 2020).

3. AQUAPONICS SYSTEM DESIGN

The three most popular forms of hydroponic beds are the gutter-shaped Nutrient Film Technique (NFT) bed, the media-based grow bed, and the Deep-Water Culture (DWC) bed (Goddek et al., 2015a). According to an analysis of hydroponic systems in aquaponic publications, 43% of the systems employed were media-based, 33% were DWC, 15% were NFT, and 9% were other, less popular hydroponic systems, and less common hydroponic systems include: drip irrigation, ebb and flow , and vertical towers/walls (Maucieri et al., 2018; Schmautz et al., 2016; Knaus and Palm, 2017; Khandaker and Kotzen, 2018). The user group influences how aquaponics systems are designed to be effective. Due to the significant technological and knowledge input (loggers, aerators, and pumps) and yield requirements, soilless, high-yield cultivation is best suited for commercial operations. Urban Farmers' recently opened rooftop farm in Den Haag is a prime example of this (Junge et al., 2017).

It is possible to build aquaponic systems for both large commercial organizations and tiny household setups. Even though there are a lot of aquaponic systems in use worldwide , there are still many unknowns or hazy issues about the social, economic, environmental, operational, and ecological fundamentals, and more research and development is still required for the technology to advance (Love et al., 2015). If the water cycle is closed, aquaponics can be classified as a connected or decoupled system. A linked system allows water to flow from the hydroponic subsystem directly back into the aquaculture subsystem; a decoupled system breaks this loop and permits water to leave the system. With more control over water quality and higher water requirements than the connected system, the decoupled system produces higher vegetable yields (Gibbons, 2020). Different types of design are given below:

3.1 Deep-Water Culture (Dwc)

Net plant pots are placed into huge troughs with perforated floating rafts as part of the DWC system. The roots of the plants in these pots are supported with media, such as rockwool, coco, or pumice, which is added to the DWC system and kept immersed in the water tank (Goddek et al., 2015a). Commercial farmers love DWC for its minimal maintenance requirements, maximum root-to-water contact, and capacity to support a high number of plants with few resources (Moldovan and Băla, 2015). Since generalized aquaponics systems are frequently advocated for water use efficiencies comparable to DWC, it is significant that no other hydroponic component has been found to have such a high water use efficiency (Yep and Zheng, 2019). (Camposeco-Negrete, 2013) created a revolutionary hydroponic system in which the roots of the plants were exposed to air between the water and the suspended raft, with the plants being half submerged in DWC. The name of this technique was Dynamic Root Floating Technique. The increased bug population is one drawback of DWC (Yep and Zheng, 2019). And other are A separate biofilter must be added (Lennard and Leonard, 2006). A significant amount of water is needed, a substantial hydroponic infrastructure is required, and a device for root aeration is required (Hao et al., 2020; Nicola et al., 2006).

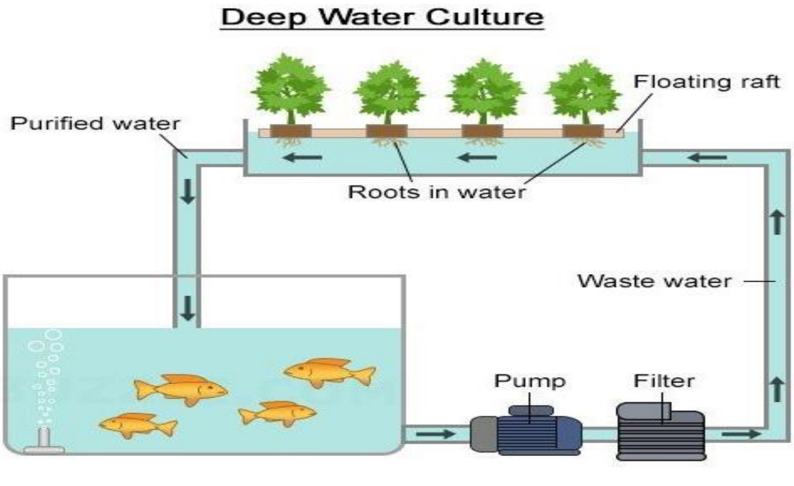

Figure 1: Schematic Diagram of a Deep-Water Culture (DWC) Aquaponics System (*The Surprising Benefits and Types of Aquaponic Systems | Akuarium, Ikan Akuarium, Ikan*, n.d.)

3.2 Nutrient film techniques

A small, perforated square pipe channel with partially submerged roots in a thin film of flowing water (Lennard and Leonard, 2006). NFT has a lower yield but a higher water use efficiency (Goddek et al., 2015a). Nutrient uptake is lower because smaller root-water contact area (Goddek et al., 2015a). Researchers conducted a study to compare the efficacy of an NFT system to a media culture and DWC system (Lennard and Leonard, 2006). The results of the study indicated that the NFT system had the lowest lettuce yields and, as a result, successfully removed the least amount of nitrate (20% less efficient at nitrate removal). In NFT systems, the limited space in the trough causes roots to collapse on top of each other, which is caused by the root mats (Cooper, 1979). This may restrict the amount of time that roots are in contact with the nutrient water (Maucieri et al., 2018). Also, Maucieri et al., recently conducted a review of 122 articles and concluded that NFT was the least successful hydroponic component in aquaponic systems (Maucieri et al., 2018). This conclusion was substantiated by their findings. In spite of these disadvantages, NFT remains a popular choice for commercial systems due to its straightforward design, minimal initial costs, and overall ease of operation (Goada et al., 2015; Lennard and Leonard, 2006).

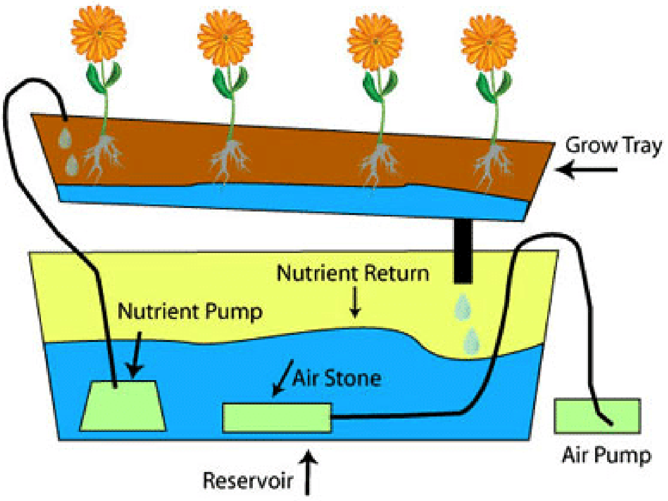

Figure 2: Nutrient film technique in Aquaponic system (İncemehmetoğlu et al., 2012**)**

3.3 Media-Based Grow Bed (MGB)

Media culture is the most frequently employed hydroponic system in aquaponic research publications, as it is a viable alternative for small-scale research systems and can be applied to an extensive range of plant species (Maucieri et al., 2018; Schmautz et al., 2017). Additionally, media bed offers increased stability for root development, which may render larger plants more suitable for these systems (Moldovan and Băla, 2015). One of the advantages of media-based hydroponics is that the substrates provide an adequate amount of surface area for the growth of nitrifying bacteria and physical filtration, eliminating the necessity for a biofilter (Maucieri et al., 2018). Media bed systems with a variety of substrates (but primarily gravels) are still frequently employed in small-scale aquaponics for the purpose of plant cultivation. One issue is the management of the substrate, which is cumbersome and heavy, which restricts the optimum area for plant production. This is due to the difficulty of transport and cleaning (Rakocy, 2012a). The disadvantages of media bed system are maintenance and cleaning difficult, clogging leads to inefficient biofiltrations, heavy hydroponics infrastructure (Lennard and Leonard, 2006; Nicola et al., 2006).

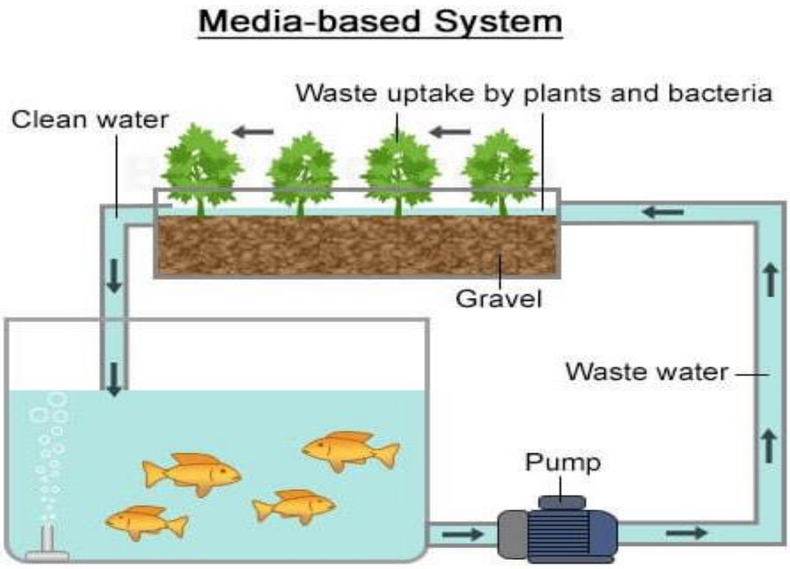

Figure 3: Schematic layout of recirculating simple media based system (*The Surprising Benefits and Types of Aquaponic Systems | Akuarium, Ikan Akuarium, Ikan*, n.d.)

3.4 Vertical towers/walls, ebb and flow, drip irrigation

Vertical towers or walls are the latest hydroponic system advancement for aquaponic systems. Systems with a vertical hydroponic component have been developed because aquaponics has the potential to be a type of urban agriculture (Khandaker and Kotzen, 2018).The hydroponic components utilized in aquaponic systems that are less commonly recorded (9%) include drip irrigation, vertical towers/walls, and Ebb and Flow, also known as flood and drain tables. These systems can work well in some situations, although being less prevalent in aquaponic publications (Schmautz et al., 2016). DWC, drip irrigation, or NFT in many layers are further extensions of vertical hydroponics. explains, however, that towers and other vertical systems are vulnerable to clogging and biofouling (Pattillo, 2017). The accumulation of solid particles in the drip lines is another possible issue when utilizing drip irrigation with aquaponics (Palm et al., 2018). Ebb and flow has several benefits, such as enhanced aeration with reduced energy consumption, enhanced adaptability during dry and wet seasons, reduced infrastructure requirements, and more surface area available for microbial development (Palm et al., 2018; Pattillo, 2017).

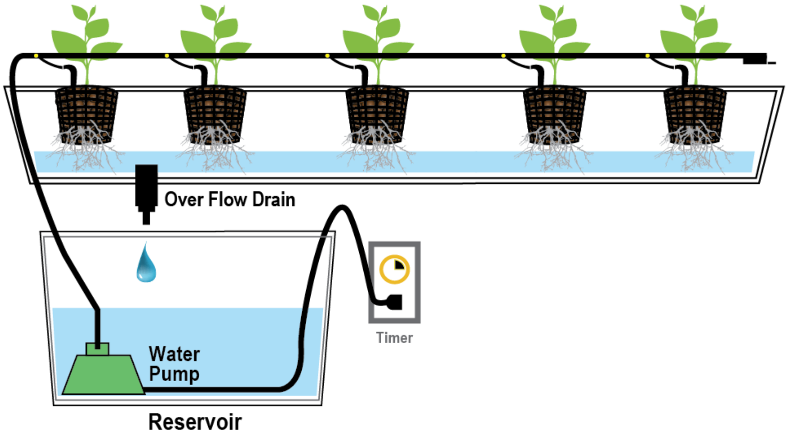

Figure 4: Drip irrigation in Aquaponics system (*Hydroponic Drip Systems*, n.d.)

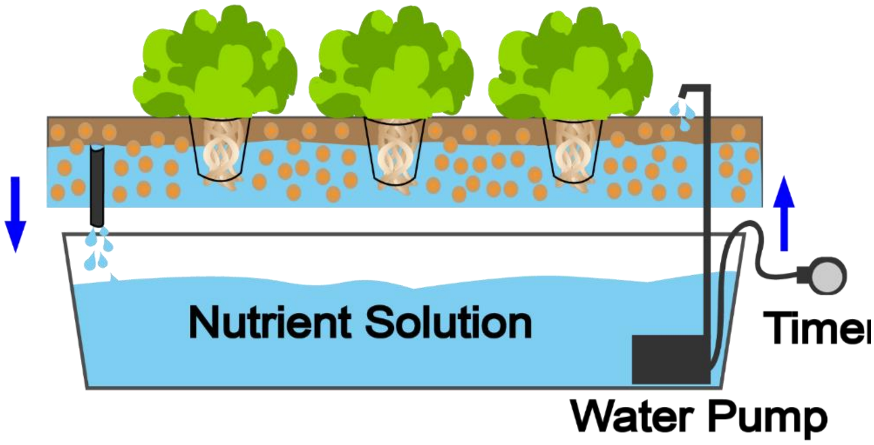

Figure 5: Ebb and Flow system of Aquaponics (NoSoilSolutions, 2014)

4. Biological And Ecological Interaction

4.1 Symbiotic relationship between fish, plant and bacteria

This makes the choice of plant and fish species extremely important in terms of their suitability for aquaponics production. The primary fish species produced under the current conditions are tilapia, koi, goldfish, carp, catfish, barramundi, and various ornamental fish species; the primary plant species produced under the current conditions are lettuce, Pak choi, kale, basil, mint, water cress, tomatoes, peppers, cucumbers, beans, peas, squash, broccoli, cauliflower, and cabbage (Yavuzcan Yildiz et al., 2017). A unique ecosystem known as aquaponics is created when beneficial bacteria, hydroponics, and aquaculture are all combined in a symbiotic connection (Krastanova et al., 2022). Fish, microbes, and plants all develop symbiotic relationships as a result of the system, which also promotes the recycling of nutrients and water (figure 6)

4.1.1 Fish species

Researchers performed an international survey which revealed that of the 257 respondents who were aquaponic farmers, 69% utilized *Oreochromis niloticus* (tilapia), 43% used ornamental fish, and 25% used Siluriform (catfish) in their commercial operations (Love et al., 2015). Tilapia is among the most widely used species in aquaponics. Its voracious nature, quick reproduction, and quick development are the reasons behind this (Rakocy et al., 2003). This type of fish is highly capable of adapting to a broad variety of water conditions, including a broad temperature range (15 – 30°C) and a concentration of free ammonia (NH3) (0.2 – 3.0 mg/L (El-Sayed, 2006; Popma and Masser, 1999) as well as tilapia have rapid growth, illness resistance, environmental tolerance, and the capacity to consume food at low trophic levels. Tilapia are low trophic omnivores by nature, and as microphages, they eat both small organic particles and tiny creatures like phytoplankton and Due to their low dissolved oxygen requirement (they can survive at 0.5–1.0 mg/L), may be stocked at a higher rate, which is perfect for meeting the nutrient requirements of plants in aquaponics. As a result, they don't require a large amount of growing area (Endut et al., 2010; Rakocy et al., 2003). Choosing the plants that will be produced is a crucial initial step in selecting the appropriate aquaculture type for a new aquaponic system. The species' symbiosis is directly related to the process optimization (Krastanova et al., 2022).

4.1.2 Plant species

Aquaponics is a growing medium for several plant species. Due to their low to medium nutritional requirements, the most popular ones include medicinal plants, watercress, calendula, zinnia, Pak choi, Chinese cabbage, basil, coriander, chives, parsley, and mint; they are also popular as culinary herbs and spices. Due to their higher nutritional needs, plants like tomatoes, peppers, and cucumbers grow more successfully in well-stocked, well-established aquaponic systems (Licamele, 2009). Since leafy vegetables grow well in nitrogen-concentrated water, have a short growing season, require little in the way of nutrients, and are generally in great demand worldwide, they beneficial have traditionally been the crop grown in aquaponic systems (Bailey and Ferrarezi, 2017). There aren't many research on the development of blooming crops using aquaponics (Hao et al., 2020). *Salicornia persica* is an important species of plant that may be produced in brackish or saline water aquaponics (Carter and Ungar, 2003) and it is a halophyte that can absorb large amounts of phosphate and nitrate and can withstand severe salinity. In addition, salicornia shoots, which are becoming more and more well-liked in the European market, are a nutrient-dense vegetable rich in lipids, omega-3s, and minerals (Turcios and Papenbrock, 2014).

4.1.3 Nitrifying bacteria

In aquaponics, bacteria are crucial to a species' ability to grow and thrive (Alderman, 2015). The nitrifying bacteria are probably amongst the most significant organisms in any aquaponic system. The main process by which nitrifying bacteria transform Total Ammonia Nitrogen (TAN) into nitrate (NO3), a type of nitrogen that plants may easily absorb (Canfield et al., 2010). Bacterial action takes place in two steps to convert nitrogen. It is necessary to first make TAN available in the water before the bacterial process. Fish can expel TAN through their gills as ammonia or as urine (urea), of which nitrogen comprises up 10–40% of the excrement. After entering the water, TAN can be used by bacteria that oxidize ammonia as a source of energy, and plants can absorb NH4þ (Wongkiew et al., 2017). Through biological nitrification, Ammonia Oxidizing Bacteria (AOB) such as Nitrosomonas, Nitrosococcus, and Nitrosospira convert total ammonium nitrogen (TAN) to nitrite (NO2). The poisonous nitrite is then converted to the relatively safe nitrate (NO3) by nitrite-oxidizing bacteria (NOB), which include Nitrobacter, Nitrospira, Nitrococcus, and Nitrospina. AOB and NOB growth cause nitrification to start as soon as a new aquaponic system is turned on, but it happens slowly (Rakocy et al., 2003; Silva et al., 2017). (Goddek et al., 2015b) concluded that Nitrobacter, Nitrosomonas, and Nitrospira are the three main nitrifying bacteria in aquaponic systems, based on earlier research. But the idea that Nitrobacter is the main ammonia-oxidizing bacteria and Nitrosomonas is the main nitrite-oxidizing bacteria is rapidly shifting. Furthermore, because Nitrospira have a lower half-saturation constant (Ks), they are more prevalent than Nitrobacter in settings with lower nitrite and ammonium concentrations (Blackburne et al., 2007) Representatives from the genera Flavobacterium and Sphingobacterium can contribute to the breakdown of organic materials (Rakocy et al., 2003).

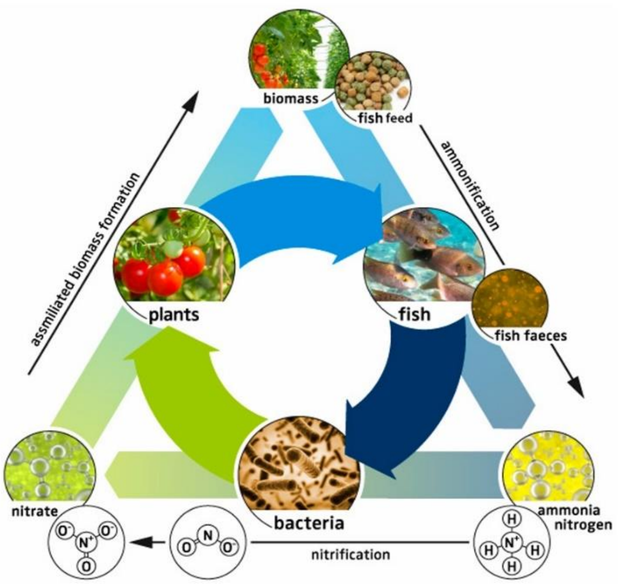

Figure 6: symbiotic Aquaponics cycle (Goddek et al., 2015b)

4.2 Nutrient cycling and waste conversion process

By fertigating nutrient-rich fish tank effluent onto hydroponic growing beds, aquaponics achieves symbiosis between fish and plants. This method not only treats fish waste by removing ammonia, nitrate, and other micronutrients necessary for plant growth but also fosters a sustainable link between aquaculture and hydroponics. The hydroponic beds serve dual roles as bio-filters, effectively purifying water by removing gases, acids, and chemicals such as ammonia, nitrates, and phosphates. Additionally, the gravel beds provide habitats for nitrifying bacteria, which further enhance nutrient cycling and water filtration. This integrated approach allows for the recirculation of freshly cleansed water back into the fish tanks, completing a closed-loop system. In experimental aquaponic projects featuring wetland pools with perch and tilapia, their waste provided essential nutrients for cultivating lettuce, herbs, and specialty greens like watercress, spinach, chives, and basil. This innovative system resolves key challenges in both hydroponics and aquaculture, demonstrating its potential for sustainable food production (Diver, n.d.). Overproduction of solid waste raises the need for oxygen, which causes hypoxia in the rhizosphere and can result in dangerously high levels of nitrite and ammonia. Thus, to maintain the oxygen gradient surrounding plant roots, which permits Pant Growth-Promoting Microorganism colonization and inhibits phytopathogen growth, effective solids management is required. To provide the plant with micro- and macronutrients, however, a suitable degree of solid waste re-mineralization is required in the hydroponic subsystem's roots (J. E. Rakocy, 2012b).

4.3 Role of microorganism

In an aquaponic system, microflora or plant growth-promoting microorganisms (PGPM) may be crucial to the plant's capacity to absorb nutrients. Due to the sterility and lack of need for PGPM in hydroponics, few studies have been published on PGPM in soilless environments, despite the fact that PGPM has been extensively studied in soil environments. Thus, there is a plethora of potential to research PGPM in aquaponics (Bartelme et al., 2018). Although there is little research on PGPMs in soilless environments, what is known about them indicates that they are important for plant development and health (Gravel et al., 2006; Villarroel et al., 2011). According to (Bartelme et al., 2018), Pseudomonas, Bacillus, Enterobacter, Streptomyces, Gliocladium, and Trichoderma species have the ability to enhance the availability of nutrients for plants. Rhizobiales and Actinobacteria were discovered to be highly prevalent in the biofilter, whereas Burkholder ales, Flavobacteria, and Pseudomonadales were found to be highly prevalent in the roots. Pseudomonas species are important microorganisms because they may produce antibacterial qualities as a means of growth, which also shields the surface area they occupy from disease, including Pythium-caused root rot (Avis et al., 2008). Considering lower nutrient levels, PGPM in aquaponics is often mentioned as the reason plants are able to fight off illness and produce yields that are comparable to hydroponics and Their findings showed that weekly additions of B103 (BIOZYM, USA), a blend of nitrobacteria, denitrifying bacteria, bacillus, lactobacillus, and actinomycetes, improved lettuce yields by 15% and increased NUE by 4.4% (Yep and Zheng, 2019).

5. SUSTAINABILITY AND ENVIRONMENT IMPACT

5.1 Resource use efficiency

Studies have indicated that the water used by aquaponic systems usually ranges from 0.3 to 5.0% of the total system water per day. This further increases the water use efficiency of RAS since plants use the water that is normally lost for waste filtration (Maucieri et al., 2018; Rakocy, 2012b). By definition, aquaponics uses at least 50% of the nutrients that are initially obtained from fish feed as fertilizer for the plants. As a result, it requires far less fertilizer than hydroponics, and in certain situations, it requires no fertilizer at all. Reducing fertilizer consumption in agriculture has a significant effect because, according to estimates, 57% of the energy used in agriculture is used in the creation of synthetic nitrogen fertilizer (Mudahar and Hignett, 1985). Following the analysis of the literature, it was clear that there are four primary areas of aquaponics where constraints have been identified for maximizing plant output and minimizing resource use. They are listed in the following order: solid accumulation in the system water, pH restrictions, nutrient limitations, and nitrogen use efficiency (NUE) (Yep and Zheng, 2019). This gives farmers more opportunity to focus on this expanding market in the future, especially in metropolitan regions where area is limited but population concentrations are high (McGuire and Popken, 2015). According to some writers, aquaponics uses 90% less water than traditional commercial fish and crop production systems (Love et al., 2015). The fact that an aquaponic system for growing vegetables makes optimum use of available space is another benefit (Okomoda et al., 2023a).

5.2 Comparison traditional agriculture and aquaponics

Conventional farming has traditionally been defined as cultivating crops in soil, outdoors, with irrigation, and with the active application of nutrients (AlShrouf, 2017). Conventional agriculture has several detrimental effects, such as excessive and inefficient water usage, high land needs, high nutrient consumption concentrations, and soil deterioration (Killebrew and Wolff, 2010). Conventional agricultural systems use large quantities of irrigation fresh water and fertilizers, with relatively marginal returns (Pfeiffer, 2003). Modern agricultural techniques such as hydroponics, aeroponics, and aquaponics use nutrient-rich water instead of soil to nourish plants (Bridgewood, 2003). Scientists have developed novel and inventive techniques for cultivating food in recent decades, which taken together could provide the means to efficiently and sustainably feed the world's growing population (Gosh and Chowdhury, 2019). Unlike traditional versions, which were fake and fixed, modern aquaponic structures are made to fit any size, from tabletop to enormous commercial ones (Endut et al., 2010). The new, current agricultural systems have many advantages. When used in a controlled setting, those new, contemporary technologies can be made to support year-round production in addition to improved yields and water efficiency (Brechner et al., 1996). In comparison to conventional agriculture, hydroponic, aquaponic, and aeroponic systems increase water use efficiency and decrease water loss (AlShrouf, 2017). Some of the most significant resource inefficiencies found in conventional agriculture may be avoided with aquaponic systems; nevertheless, the achievement of the aforementioned resource efficiency has not been adequately measured in scientific studies (Yep and Zheng, 2019). When compared to traditional aquaculture, aquaponics may offer greater sustainability, lower resource use, and less environmental effects (Lennard, 2004).

5.3 Promoting sustainable practices

An effective green farming and environmentally beneficial substitute for sustained agricultural output is the aquaponics system (Okomoda et al., 2023a). To "maintain the economic viability of farm operations" and "improve the standard of living for farmers...and society at large," food must be produced using environmentally bio-rational practices, sustainable agricultural methods, and waste-free environmental discharge (Tyson, 2007). Aquaponics is an environmentally friendly aquaculture and planting technique that has garnered interest in a number of sectors, including ecology, agriculture, and fisheries (Hao et al., 2020). Globally and regionally, aquaponics has showed promise as a sustainable method of food production. While numerous research has demonstrated the viability of aquaponics food production, only a small number of studies have examined the total technical and financial viability of the aquaponics system (Gosh and Chowdhury, 2019). It functions as a bio-integrated model for producing food in a sustainable manner (Diver, n.d.). Using an aquaponics system helps the farmer make more money by eliminating nitrate from the system and transforming nitrogenous waste that would otherwise be poisonous into forms that plants can consume and sell (Pantanella et al., 2010). In contrast to traditional farming methods, the aquaponics production system relies on long-term nitrogen cycling procedures and consistent nutrient-rich wastewater (fish-produced nitrate that plants absorb) to irrigate the plants (Okomoda et al., 2023a).

The environmental friendliness of aquaponics production systems sets them apart from more traditional conventional food systems. This is so that the aquaponics system can quickly and effectively remove the degradation of soil structure and the associated pollution since it does not require the employment of large earth-moving machinery or equipment to till the soil (Oladimeji et al., 2020). Integrated production systems, enhanced productivity with less ecological effect, and less chemical use are just a few of the fundamental ideas that more sustainable fish production must adhere to (Pantanella et al., 2010). The farming of the new century is sustainable farming. Many individuals think it makes sense to carry out sustainable practices, whether they are in the construction of homes or the management of farming businesses (Lennard, 2004). As aquaculture releases contaminated water into the environment in an effort to enhance water quality, it is therefore considered a highly polluting system. Nonetheless, a number of methods have been developed over time to lessen pollution, and the AQUAPONIC system is one of them (Blidariu & Grozea, 2011) and Among the fundamental ideas that more sustainable fish production must adhere to are increased productivity with less of an ecological impact, system integration, and decreased chemical use (Pantanella et al., 2010).

6. ECONOMIC VIABILITY AND MARKET POTENTIAL

From an economic perspective , integrating the two productive systems into an aquaponic system necessitates a large advance expenditure (Tokunaga et al., 2015). Lower management expenses and combined returns follow from the sales of fish and vegetables, whose profitability gains from the interaction of these expenses and returns (Rakocy, 1999; Rupasinghe and Kennedy, 2010). Many investigations have evaluated the economic viability by calculating a number of factors, including net income, the break-even price, the modified internal rate of investment, net present value, and the discounted cost benefit rate (Rupasinghe and Kennedy, 2010; Tokunaga et al., 2015). Commercial aquaponics systems of greater size yield higher profits than smaller ones (Bailey et al., 1997). Even though small-scale aquaponics has gained popularity throughout the world for many years and is well-known (Junge et al., 2017).

Consequently, in order to determine the possibility of selling vegetables and fish at a profit while keeping in mind their freshness and pesticide-free nature, a complete analysis of the demand side of the consumer market is required (Asciuto et al., 2019). Aquaponics is eight times more water-efficient than field-grown vegetables in addition to being more land-efficient (Van Ginkel et al., 2017). Between the early 1950s and 2005, the production of aquaculture worldwide increased dramatically from less than one million tons to 48.1 million tones (Subasinghe et al., 2009).

By sharing certain infrastructure, administration, and labor expenses and utilizing resources (mostly water and nutrients) in different ways, the unit achieves economic efficiency (Bailey et al., 1997). For putting more emphasis on three underappreciated factors that have the potential to revolutionize commercial aquaponics. Among them are the following: Consumer perception of aquaponic products, including willingness to pay more for added value; (ii) grower considerations such as risk management and financial planning that impact potential growers' initial engagement in aquaponics; and (iii) the economic value of the environmental benefits of aquaponic systems and ways to internalize them for professional (Greenfeld et al., 2019).

Numerous energy-saving techniques have been shown to be cost-effective in full-scale plants. Innovations that save money and energy in Western Europe or North America might not always save the same amount in developing nations (Mudahar & Hignett, 1985). Consumer awareness of the health advantages of locally and organically produced goods is growing these days (Falguera et al., 2012). Because of this, it will be impossible to sustain fish supplies from catch fisheries to meet the increasing demand for aquatic food worldwide. In most parts of the world, aquaponics is seen as a potential solution to close the gap between the supply and demand of aquatic food (Subasinghe et al., 2009).

7. CHALLENGES OF AQUAPONICS

Although aquaponics has numerous advantages, it also faces challenges that may prevent it from attaining its full potential in terms of food security and environmental conservation. These challenges include high energy demands, large initial costs, the impact on present manufacturing and marketing processes, and public perception (Okomoda et al., 2023b). Stable pH levels are crucial for the optimal growth of fish, plants, and helpful microbes in aquaponics systems. While tilapia (Oreochromis) grows best at pH 7.0–9.0 and can tolerate pH changes from 3.7 to 11, plants thrive best at pH 6.0–6.5 (McAndrew and Beveridge, 2000). Maintaining system-wide pH levels can be challenging due to this complexity (Goddek et al., 2015c). Continuous monitoring and management are required for environmental elements such as hydraulic loading rate (HLR), dissolved oxygen (DO), temperature, water hardness, and ammonia concentration. Furthermore, the nutritional composition of fish tank effluent alone may not be sufficient for achieving ideal plant development. Hence, it is imperative to provide frequent supplementation of essential minerals such as potassium (K), calcium (Ca), and iron (Fe) to facilitate plant growth. The efficacy of organically generated nutrients in comparison to readily soluble mineral fertilizers continue to be a subject of contention

Pest and management is another area of improvement in aquaponics in spite of lower incidence of disease and pest attack (Wilson, 2005). Controlling antibiotic resistance for disease prevention in aquaponics is difficult. Conventional pesticides are used rarely because of the risk to fish and important species such as nitrifying bacteria and nutrient solubilizers (Gichana et al., 2018). Apart from technical challenges, developing nations like Nepal confront social, economic, and educational barriers in using aquaponics. The concept is still uncommon, and without local feasibility studies and tests, scaling up commercial aquaponics could be challenging. Skilled staff is important for operation, requiring significant training for local farming communities to adopt aquaponics properly. Subsistence agricultural methods in Nepal may hamper adoption of novel aquaculture technology. Additionally, weak marketing tactics leave farmers concerned about production circumstances and market security (Karki, 2016). Understanding and operating aquaponics requires a broad range of expertise across various disciplines. The issue lies in merging hydroponics and aquaculture successfully, which are generally taught separately in universities. There's a need for better education networks to stimulate interdisciplinary collaboration among stakeholders for practical and scientific improvements in aquaponics (Goddek et al., 2015c).

8. Conclusion

Aquaponics represents a promising integration of aquaculture and hydroponics, offering sustainable solutions to some of the world's pressing challenges, including population growth, climate change, land degradation, water shortages, and food security. By combining the cultivation of fish and plants in a symbiotic system, aquaponics efficiently recycles nutrients and conserves water, making it an environmentally friendly alternative to traditional farming practices. The various types of aquaponics systems, such as Deep-Water Culture (DWC), Nutrient Film Technique (NFT), and Media-Based Growing Beds (MGB), each offer unique advantages and challenges, serve to different scales of production from small household setups to large commercial operations.

The complex biological and ecological interactions between fish, plants, and bacteria are essential to the success of aquaponics, highlighting the significance of choosing suitable species and preserving ideal conditions for water quality and nutrient cycling. Although the potential advantages, there are a number of obstacles that must be overcome before aquaponics is widely used. These include high startup costs, the requirement for technical know-how, and continuous research to fill in knowledge gaps and boost system effectiveness. In addition to improving environmental sustainability, aquaponics also improves social and economic aspects. It may be applied in urban areas, bringing agriculture closer to customers, and it encourages the production of food locally while reducing reliance on chemical pesticides and fertilizers. Aquaponics-related educational programs can help encourage future generations to adopt ecologically friendly technologies by increasing awareness of sustainable practices.

Finally, aquaponics shows great potential as a sustainable farming method. It provides a comprehensive strategy for tackling issues related to socioeconomic development, environmental preservation, and global food security. Aquaponics has the potential to significantly influence how agriculture develops in the future and provide a more robust and sustainable food supply for future generations if innovation, research, and policies are sustained.

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