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SUSTAINABLE FOOD PRODUCTION USING WASTEWATER AQUAPONICS AS AN ENVIRONMENTALLY FRIENDLY SYSTEM

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ABSTRACT

The pressure to find effective strategies for the sustainable transformation of agricultural systems is higher than ever. Combining different production systems and using their respective wastes to produce more with fewer resources is the concept of aquaponics. Aquaponics is a biological process that involves recirculating aquaculture (RAC) and the production of vegetables, flowers, and herbs. Several scientific reports and observations by growers show that aquaponics can be considered as a very suitable model for food production in a sustainable way. Aquaponics can be used as an efficient method of food production by following several ecological principles such as waste generation by one biological system that may serve as a source of nutrients for another biological system by the activity of appropriate microbes and their coordinated activities. Integration of fish and growth of plants on fish waste is like a multitrophic ecosystem that leads to diversity and increases yield of multiple products. Wastewater generated in aquaculture is re-used through biological filtration and recirculation process. This results in localized food production throughout the year and provides healthy foods to the local community and boosts their economy.

This review aims to discuss the recent scientific technologies, trends in implementation, and ideas of aquaponic food production, role of microbes and algae in waste recycling and system operation and the beneficial effect on the environment.

Keywords: Aquaponics, Hydroponics, Aquaculture, Microbes, Algae

INTRODUCTION

Rapid population growth is currently a major crisis for the world and the trajectory indicates that there will be a need to build new cities and increase agriculture practices from now to 2030 with a population of one million every five days! The present world population is around 7.7 billion and will reach 8.6 billion by 2030 and 9.8 billion in 2050 and over 11 billion people by 2100 with more than 75 percent of population living in urban areas. Also due to the economic downfall triggered by the recent pandemic, there is a pressing need to enhance social protection for impoverished individuals (U Nations, 2017, 2020a, 2020b). Food security will be a matter of concern in this situation and an expected sharp rise in demand of animal protein (Alexandratos and Bruinsma 2012). This will lead to a 60% increase in demand of food compared to current demand by 2050 and cause heavy demands on water resources, land usage by deforestation and soil degradation of ecosystems (Tilman, et al., 2011). The aim of agriculture therefore is challenging aimed to produce more food to feed a continuously growing population with shrinking agricultural area, fluctuating energy and oil costs, changing climate, and decreasing of constrained freshwater supplies (Bindraban, et al., 2012). Therefore, more efficient and sustainable production methods need to be implemented that include choices of technologies adapting to climate change. Farmers in the past have evolved intensive farming methods using pesticides and agrochemicals, (Klinger and Naylor 2012; Mahmud, et al., 2012). However, overdoses of chemicals in agricultural cultivation cause significant contamination of terrestrial ecosystems and poisoning of human foods (Foss, 2013; Fernando, 2017). For farmers to produce more food conventional methods need to be changed to more appropriate methods. They simply can’t continue using the same conventional soil-based agricultural system while facing climate change, volatility, shifting nutrition needs, and the increasing scarcity of most of the physical factors of production. Farming has great impacts on the world’s most critical resources. Accordingly, farmers will have to produce while also ensuring the provision of various vital ecosystem services. If this weren’t to happen, people will not only degrade those resources but also exhaust the ability to produce enough food. Therefore, agriculture is at the threshold of a necessary paradigm shift.

Currently, the agricultural industry is the world's largest water user and consumes about 70% of the water in different processes. In this food and environmental crisis, the new methods for growing plants in the agricultural domain are various; aquaponics being one of the most attractive that is a sustainable agriculture system that combines two names: aquaculture, that is the farming of fish and hydroponic that is the cultivation of plants (no-soil) using the wastewater enriched with mineral and other organic material from fish growth. Aquaponics comes as a solution to enhance farming and agriculture productivity. Focus on aquaponics has heightened due to their high efficiency, nutrient availability, and less consumption of resources. However, much research and initiatives are required for intensive automation, biomonitoring, and control requirement for the generation of a smart aquaponics system (Nair et al 2025)

The need to produce large amounts of high-quality vegetables justifies the development of technologies which synchronize the water & nutrient solution demand and supply to greenhouse plants to achieve crop yield optimization. Detailed studies on water and nutrient uptake by plants is important for identifying control strategies to supply the required amounts of water and nutrients for maximum crop growth and development (Klaring, 2001, Pena 2025).

Conventional Agriculture versus Aquaponics

In the present agricultural practice’s huge quantities of fresh water for irrigation and fertilizers are used with relatively small returns (Pfeiffer 2003). Hydroponics and aquaponics utilize nutrient-rich wastewater rather than soil for plant nourishment (Bridgewood 2003). In the absence of fertile land availability, aquaponics plays an important role with regards to reduced water and space requirements. One more advantage of this technology is the ability to practice vertical farming production which increases the yield of the area unit (Marginson 2010). Higher yield and efficient use of water under control conditions in an aquaponic system can sustain continuous production over a long period of time (Savidov 2018). Other recent developments in aquaponic design and usage provide possibilities to control all the agricultural practices along the growing season through precise agricultural technologies in the greenhouse. Advanced technologies such as crop monitor technology and mobile apps to aid farmers in "when", "where", “how” or "what" to plant are other innovations offer farmers greater control over production, the ability to increase yields, operate more sustainably, and more flexibility as the weather changes.

Why aquaponics

Aquaponics is a technology that is a subset of a broader agricultural approach known as integrated agri-aquaculture systems (IAAS) (Gooley and Gavine 2003, Wang et al 2024). The rationale of using this recirculation system of wastewater use from fish cultivation to support plant growth, is to develop environmentally sustainable and economically viable primary production practices.

Aquaculture causes many environmental problems due to the release of nutrient rich water into aquatic surroundings resulting in severe pollution problems. Similar situations may be produced by hydroponic systems. Adapting aquaponics will result in coupling use of the nutrient rich wastewater for plant growth there by reducing the direct impact on the environmental pollution (Boyd and Tucker 2012).

Traditional Aquaponics

Use of fish culture with plant growth in ancient agricultural practices is the steppingstone of modern aquaponics. This was prevalent in southeast Asian countries where flooded paddy fields are common and south American Chinampa floating island agricultural practices (Komives and Junge 2015). Paddy cultivation was not associated with fish culture until the nineteenth century (Halwart and Gupta 2004). Eutrophic or semi-eutrophic lake sediments may have provided the nutrients for the Chinampas traditionally built on lakes in Mexico rather than from fish cultivation practices (Morehart 2016; Blidariu and Grozea 2011).

Modern Applied Aquaponics

To evolve more sustainable farming practices several institutions in the USA took interest in around 1970's. James Rakocy and his team at the University of the Virgin Islands (UVI) in early 1980's was the leader in all modern aquaponic systems although there were several other researchers working on this aspect (Lennard 2017, Lennard and Goddek 2019). Aquaponics now has emerged as a global agricultural practice with immense potential to increase the productivity of crops through an integrated wastewater recirculating system coupled with plant growth (Knaus and Palm 2017 Wang et al 2024).

Aquaponics as an integrated system helps to negotiate many of the agricultural problems existing across the globe. This system only uses a fraction of the water, about 10% of soil growing. There is no requirement for fertilizers, no soil-borne diseases, no tilling, and no weeds. It results in high fish stocking density, high crop yield. The principle of this integrated system is no waste, as waste from fish has been used by plants. In other words, waste from fish is used to feed the plants. Water is reused in the re-circulating system. No pesticides or herbicides are required rather continuous organic fertilizer is supplied naturally. This system aids food security as we can grow our own food within a defined space, year-round and equally potent in draught or places with poor soil quality which results in local food production, enhances the local economy, and reduces food transportation. Thus, aquaponics is considered as sustainable as it has lots of advantages with respect to hydroponics and aquaculture (Love et al 2014, Wang et al 2024).

Role of Microbes

Microorganisms are the important link between fish and plants growing in an aquaponic system. The presence of microbes in all parts of the aquaponic systems serves as an important channel for facilitating nutrient production by fish tanks and rapid uptake by the plants and increased metabolic growth. Hydroponic production beds are generally fertilized with wastewater from fish tanks, that is good for the fish as plant roots and rhizobacteria remove nutrients from the water. Fish manure, algae, and decomposing fish feed are contaminants that would otherwise build up to toxic levels in the fish tanks but serve as liquid fertilizer for the growth and support of plants. The Hydroponic bed strips off the nutrients such as ammonia, nitrates, nitrites, and phosphorus, thus acting as a biofilter producing clean water for the fish tanks. The presence of nitrifying bacteria found living in the gravel and around the plant roots plays a vital role in nutrient cycling; without these microorganisms the whole system would stop functioning.

In contrast to hydroponics, aquaponics is a natural process that acts as a no- waste sustainable food production system (Endut et al 2014)

Traditional Recirculation aquaculture

RAC requires that wastewater be treated to remove nutrients before discharge, usually into a local body of water. RAC is expensive given the cost of fish feed, the cost to treat the water, and the costs associated with permitting and discharge. It also produces a waste stream that must be managed (Love, et al. 2015, Ibrahim et al 2023). Aquaculture systems with a recirculating mode of operation benefit a lot from the presence of plants in it that act as a natural biofilter making it a closed loop system. After biofiltration the solid fish wastes are left behind and that is managed by field applications, anaerobic digestion and composting (Zaid et al., 2019). The disadvantages of such practices are nutrient loss, leaching and greenhouse gas emissions. If the solid waste could somehow be recycled to the aquaponic system then there would be no waste at all. The development of a two-looped aerobic bioreactor for liquid and solid waste could be an answer. Such bioreactors are known for their efficient nutrient breakdown capacity and loop them back into the system (Savidov, 2018). Another advantage of the two looped system over the conventional aquaponic system is the need for nutrient addition in the latter and non in the former. Liquid effluent nutrients complement solid waste nutrients resulting in no waste in the system. Aquaponics has complex technology and requires marketing and production of 2 different agricultural products together.

The attempt to integrate hydroponics and aquaculture together has met with little success historically. Recent innovative technologies applied to aquaponics have, however, transformed this process into a viable and sustainable process for food production. However, to make this modern system efficient and successful careful attention to business planning and marketing as well as intensive and careful management of the system together with monitoring for control of the system is required. Integration of aquaculture with field grown and aquatic plant production systems have several advantages that are summarized below Gooley and Gavine (2003):

1. There is no net increase in water consumption but increase in profit and productivity.
2. Increase in diversity of plants produced that include high value aquatic and crop species.
3. Farm resources that are otherwise wasted are recycled and used.
4. Intensive and semi-intensive farming practices with reduced environmental impact.
5. Counteract existing farm capital and operating expenses by net economic benefits.

Aquaponics: Key Elements and Considerations

There are some key elements and considerations besides special training, skill and management that are required for running a profitable aquaponic system. Some of these are listed below:

Vertical agriculturists and farmers are attracted to aquaponics for several reasons:

1. Fish manured wastewater is viewed as a rich source of nutrients and organics by hydroponic users.

2. Hydroponics is viewed as an efficient biofiltration process that supports recirculating aquaculture.
3. Agriculturists want to introduce plants in the marketplace as organic when produced by an aquaponic system because the only nutrient input is fish feed that is totally processed by an efficient biological system.
4. Aquaponics is a naturally appealing process in niche marketing and green labeling that produce fish and plants from the same cultivating unit.
5. This has far reached applications in arid regions and water limiting regions and farms for its capacity to reuse water.
6. Plant and animal agriculture and recycling of water via filtration and nutrients make aquaponics a sustainable model for food industry.
7. Aquaponics has gained popularity as a training aid in school and college biology classes (Rakocy 2007).

Basic Aquaponic System Operation

There are two production components (plants and fish) in basic aquaponics that combine feed and waste products in a closed system. A fish rearing tank where the fish consumes the feed leading to the start of the nitrogen cycle in which proteins are produced from the nitrogen taken up by fish and the waste is released into the water as waste. Feed and feces in the water then reaches the settling tank where solid particles are removed and can be used in compost. After this the ammonia produced by the fish converts into nitrite and nitrate by bacteria in the biofiltration tank. The nitrates then are pumped to the grow beds where these are integrated into the plants to produce plant metabolites and simultaneously removed from the water. The wastewater produced in the grow beds then moves to a degassing sump where oxygen is added and carbon dioxide is released. The oxygenated water is then cycled back to the fish rearing tank (Endut et al 2011).

COMPONENTS OF AQUAPONICS

Hydroponics

Growing plants without soil and in a liquid medium are termed as hydroponics, where all the nutrients supplied to the crop are in the form of a solution in water. Hydroponic systems may operate with nutrient film techniques (NFT), floating rafts and non-circulating water cultures. Inert materials, organic, and mixed media contained in bags, trough, trench, pipe, or bench setups are employed in aggregated hydroponics. Perlite, vermiculite, gravel, sand, expanded clay, peat, and sawdust are the media used in such processes. Plants are fertigated with fertilizers added to the water system in a regular cycle for the roots to retain moisture and receive the required nutrients in hydroponics. The nutrients used in this process are commercially available chemical fertilizers that are highly soluble in water. However, adding organic fertilizers like fish hydrolysate are being used in recent times. Recipes for this process are made from exact concentration of minerals to be used are a part of hydroponics. Use of the greenhouse and possible environmental parameter controls together with precise nutrient delivery and water contributes to the success of hydroponics (Damon et al 1998).

Nutrients in Aquaculture Effluent

In contrast to hydroponics, aquaponic nutrients are obtained from aquaculture wastewater. Enough ammonia, nitrate. Nitrite, phosphate, potassium and other nutrients and secondary metabolites are found in fish effluents, and this is sufficient for plant growth (Rakocy et al., 2006). Accurate nutrient profile is essential for plant growth in aquaponics. However, in different aquaponic designs like recirculating or decoupled without sterilization systems nutrient concentrations are not that rigid. The reason behind this is the involvement of microbes in the multitrophic nature of the system assist in nutrient availability to plants (Lennard 2017). In sterilized decoupled designs it is necessary to follow stringent nutrient concentrations for successful operations (Suhl et al. 2016; Karimanzira et al. 2016).

Plants Adapted to Aquaponics

Stocking density of fish tanks and subsequent nutrient concentration of aquacultural effluent is largely responsible for the selection of plant species that will grow best in hydroponic and aquaponic systems. Plants with low to medium nutritional requirements such as lettuce, herbs, special greens like spinach, chives, basil, and watercress are well adapted to aquaponic systems. Vegetables like tomatoes, bell peppers, and cucumbers have greater nutritional demand and are successfully grown in well-established aquaponic systems. Greenhouse grown tomatoes are adapted to low-light, high-humidity conditions than field varieties are well adapted to grow in aquaponic systems (Nichola et al 2007, Adler et al 2000).

Design Principles

Successful aquaponic designs should encourage judicious use of nutrients and water resources. Fish keeping in earthen ponds is discouraged as they can lower the nutrient and water utilizing capacity of the system. For hydroponic methods too use of excess media and therefore excess nutrients or water makes them unavailable to the plants (Lennard 2017). It’s important to check that no nutrients and water leak out to the waste stream because it will result in the fish and plants not receiving enough for their production and therefore nutrients are wasted. Also, a waste stream with nutrients is a major environmental threat so systems need to be designed to completely ward off any environmental impact from wastewater and nutrients that can leak into the surroundings.

The most important aim for aquaponics is the use of fish waste as a source of nutrients for plants so that the nutrients are not directly released into the surroundings (Tyson et al. 2011). Clean rooms and similar structures like fish rooms, green houses that are environmentally controlled should be used to house the aquaponic system. The capital cost of aquaponic designs is relatively high and so if the conditions of growth are enhanced by placing the system in an environmentally controlled place, then profit chances are increased that somehow can justify high production costs (Lennard 2017).

RAC versus decoupled systems

For the success of classic recirculating aquaponic design, one of the essential drivers is to use the fish feed efficiently as the main nutrient source so that the plants get most of the nutrients from fish feed rather than waste (Lennard 2017). In decoupled designs plant growth is dependent on nutrients and strengths used in standard hydroponic systems and there in these aquaponic systems plant growth is not dependent on fish feed nutrients (Delaide et al. 2016). The technical design approach is based on the origin of nutrients and supply to the aquaponic systems. Fish feed is the major plant nutrient for fully recirculating systems and nutrients for the decoupled designs are from external supplements (Lennard 2017).

TYPES OF AQUAPONIC SYSTEMS

Nutrient film technique (NFT)

In whatever the type of aquaponics the NFT allows the plant roots to absorb nutrients from a ½-inch film of water with high oxygen exposure. In this method wastewater slowly enters from one side of a channel and flows to the other end by gravity where it collects into a collection place. This allows a bigger plant productivity because of the larger surface area and use of less water (Goddek et al 2015, Zolia et al 2024).

Flood and drain model

A substrate using pea gravel, expanded clay and perlite are used as plant growth medium in this method. In this system a biofilter is not required as the nitrification of fish waste is accomplished by bacteria that colonize the internal structures and pipes of the system and provide the necessary nutrients to the plants. A 20- to 30-minute continuous water cycle provides the plant roots with necessary moisture and air. For heavy fruiting plants like peppers and tomato flood and drains systems are suitable (Goddek et al 2015).

Floating raft systems

In this system a Polystyrene platform gives support to the plants to help the roots reach the water underneath. A biofilter is generally not required in this system and large volumes of circulating water to the roots account for better water quality and maintain stable temperatures (Goddek et al 2015).

A MICROBIOLOGICAL APPROACH TO AQUAPONICS

The fully recirculating design of aquaponics has been popular until recently that shares the wastewater between the culture of fish and plant species (Rakocy et al. 2006; Lennard 2017). Aquatic sterilization is an important selective component that has not been included by aquaponic designers to standard RAS and hydroponic culture systems. High density of plant and fish culture attracts a lot of aquatic or pathogenic organisms that lower the overall production rates therefore sterilization process is universally applied to RAS and hydroponic systems (Van Os 1999; Timmons et al. 2002). Not applying any aquatic sterilization or disinfection allows the water to develop a complex aquatic ecosystem that consists of different microbes in the aquaponic industry presently (Goddek et al. 2016; Lennard 2017). This leads to an interesting biodiversity of microbes like natural ecosystems that interact within themselves as well as other lives forms within the systems (Plants and fish). These interesting microbial interactions between several types lead to a balance that does not allow a single species to dominate and therefore cannot cause any deleterious effects on plants or fish production. In coupled or fully recirculating systems this microbial diversity effect as a non-sterilized approach to aquaponics that has been followed historically (Rakocy et al. 2006), while for hydroponic systems a sterilized approach has been followed for some time (Monsees et al. 2016; Srivastava et al 2017; Goddek and Korner 2019). The decoupled designers in more recent times are adopting the principles of non-sterilized approach using microbial diversity in their systems (Goddek et al. 2016; Suhl et al. 2016; Karimanzira et al. 2016) which proves very clearly about the positive effects of the presence of microbial aqua flora in aquaponic systems (Goddek et al. 2016; Lennard 2017).

INNOVATIVE APPROACH OF USING ALGAE IN AQUAPONIC

Algae, naturally occurring microorganisms in water bodies and naturally developing in aquaponic system, are commonly considered a nuisance because they often plug the water pipes, consume oxygen, attract other microbial pathogens, and worsen the water quality. The decomposed algae lead to excessive consumption of dissolved oxygen and results in an increase in high levels of biological oxygen demand and very low dissolved oxygen (DO) that is dangerous to fish life. Many other water characteristics are also altered like diurnal pH swings and DO variation due to photoautotrophic growth under daytime light and respiration during the night that indicates algae have a great impact in an ecological system (Storey 2013). Recently studies have shown that the beneficial aspects of algae can be utilized in the aquaponics when algae are properly managed. Algae may further play an important role in removal of nutrients, maintain pH balance and increase the dissolved oxygen in the system, produce PUFA as a value-added fish feed, and add diversity and improve resilience to the system. In fish waste, ammonia nitrogen is the main form of nitrogen pollutant (90%) in the exit water (Wongkiew et al 2017)). In aquaponic systems nitrogen cycle the ammonia is firstly converted to nitrite (NO_2^-) by ammonia oxidizing bacteria like *Nitrosomonas* and then nitrite oxidizing bacteria like *Nitrobacter* convert nitrite further to nitrate (NO_3^-) (Godek et al 2015). Algae are found to utilize both ammonia and nitrates in contrast to aquaponically grown vegetables that can use only nitrates (Shi et al 2000, Xin et al 2010).

There are many reports in which algae have been used for aquaculture and wastewater treatment (Banerjee and Siemann 2015, Thom et al 2018, Sfez et al 2015, Kuo et al 2016). Algae prefer to take up ammonia in conditions when both ammonia and nitrate are present together. A low level of 0.018 mg/L ammonium in a system can reduce nitrate use and therefore can be very beneficial for reduction of ammonium in aquaponic systems (Raven et al 1992, Syrett and Morris 1963).

Nitrification process is pH sensitive, optimum at 7-8 but algae exhibit a wide range of pH tolerance and range from 5-11 therefore can act as a backup system for ammonia removal if nitrification process fails.

While nitrification in aquaponic systems lowers the pH with nitric acid release algal growth under autotrophic conditions increases the pH of the water. In aquaponic systems the pH value must be slightly above 7 because nitrification drops when pH falls below 7 and stops below 6 (Nelson and Pade 2008). The algal presence therefore turns out to be the important counterpart for the nitrification process and the pH adjustment.

During photosynthesis in algae for every one mole of carbon dioxide fixed from the atmosphere, one mole of oxygen will be released. The carbon that is found in algal biomass comes from carbon dioxide that comes from the atmosphere. If 50% is the carbon content of algae, 1.3 g of oxygen is generated for every gram of algae produced. If algal cells are periodically harvested the consumption of oxygen by decomposed algae can be controlled and overcome. Some species of algae are very high in lipids and enriched with omega-3 fatty acids that are not found in vegetables grown in aquaponic systems. 20% of lipids in certain algal species are essential fatty acids therefore the addition of some of these in fish feed could result in improvement in the nutritional value and health of fish (Li et al 2011, Zhou et al 2012, Cheunbarn and Cheunbarn 2015, Tocher 2010).

It is worth mentioning here that apart from these beneficial effects of algae in the aquaponic systems, there are some other potential benefits to the plant with algae addition. Algae release growth hormone like molecules like Auxins and Gibberellins and other bioactive compounds while growing and these can benefit the growth and yield of vegetables and other plants in the aquaponic system (Banerjee and Modi 2010, Banerjee and Srivastava 2009, Banerjee et al 2006.

AQUAPONICS WITHOUT GROWING FISH: DIFFERENT VARIATIONS

It's not necessary to only grow fish in aquaponic systems and many variations are being considered recently like the use of turtles, duck, shrimps, yabbies and worms.

Turtleponics: The waste from turtle is more in quantity and therefore considered good for plants. They are much harder than fish and have varied diets and can be kept as pets.

Quaquaponics: Duck is a great alternative to fish and produce large amounts of waste for growing plants in aquaponics. They lay eggs, and their poultry meat with its rich flavor and juicy feel provides the recommended protein need.

Shrimponics: By using shrimps in aquaponics plants and oceanic creatures can be grown harmoniously. They are easy to breed, eat dead fish before the ammonia problem. They sell for a handsome profit and are considered healthy for consumption. They eat unwanted larvae, planktons and produce little waste and therefore they are very good for plants.

Yabbyponics: Yabbies and crayfish can be easily grown and make an excellent practical, inexpensive addition to the aquaponic system. They can be sold at great ornamental prices because of the fascinating colors they produce in the system. They also compensate for some of the cost of running the system.

Vermiponics: It is considered very beneficial to have worms populate aquaponic systems. They can break down waste and mineralize the grow beds. The worms provide the ammonia source instead of the fish in fish tanks. The worms decompose the solid material and feed on kitchen scraps that are kept on the bed instead of putting them in the water. Worms are hardier than fish and survive system failures much longer. Worms get their oxygen easily, and their feed is cheaper than fish feed. Worms tolerate much better fluctuations in environmental parameters and generate low volumes of waste. (Leaffin, Aquaponics 2019, (Kotzen et al., 2019).

Sandponics: Aquaponics with sand in growing media. Sandponics represents a progressive agricultural methodology that seamlessly combines aquaculture and hydroponics, using sand as the primary growth medium. A notable innovation characterized by efficient water supply management and minimal waste generation (Kotzen, et al 2019).

Algaeponics: Coined from the combination of “algae” and “aquaponics,” introduces an innovative approach that incorporates microalgae into aquaponic systems to use their distinctive attributes for the ecosystem's advantage. Studies have highlighted the positive impact of microalgae in aquaponic systems (Zhang et al., 2022).

Saline Aquaponics: Often referred to as maraponics or haloponics, represents an innovative agricultural approach geared towards regions with limited access to freshwater, particularly coastal, island, and estuarine areas. One of the defining features of saline aquaponics is its ability to harness the vast saline water resources available in our world's oceans and seas. By incorporating salt-tolerant crop cultivars and aquatic organisms, these systems can effectively operate in saline environments without the risk of soil salinization. This adaptability makes them resilient in the face of climate change and ensures the sustainability of agricultural practices (Spradlin & Saha, 2022 Chaudhari et al., 2024, Bordignon et al. (2024)).

TECHNICAL CHALLENGES

Designing an aquaponic system requires a very multidisciplinary approach where civil, mechanical engineering and environmental concepts are used together with biology, biotechnology and biochemistry of plants and aquatic systems. In addition, knowledge and know-how of computer science and related subjects for automatic control systems are required for system specific measurement and control.

For commercial aquaponics the greatest challenge is its multidisciplinary structure and operations requiring further knowledge in marketing, finance and economics. An in-depth theoretical and practical knowledge is required for high degree field specific insights. Thus, this is highly complex and this in turn affects the efficiency of running the system. To achieve a high level of efficiency and success some recommendations like nutrient balance, pest management, phosphorus content and pH stabilization may be important.

FUTURE RESEARCH RECOMMENDATIONS

In response to the economic downturn triggered by the pandemic, there is a pressing need to enhance social protection for impoverished individuals (United Nations, 2020a). Considering these challenges, the global food industry is exploring sustainable and accessible approaches to producing nutritious foods, particularly fresh fruits and vegetables.

Sustainable agriculture, particularly soilless farming methods, in conjunction with hydroponics and aquaponics, offers a compelling solution by maximizing output while minimizing the use of resources such as space, soil, and water. Aquaponics aligns with the United Nations Sustainable Development Goals, as it provides a sustainable and scalable food production system. It yields pesticide-free, locally sourced fish, fruits, and vegetables in both urban and rural settings, contributing to reduced greenhouse gas emissions and the preservation of wild fish stocks (United Nations, 2020b). Despite facing challenges such as nutrient management, water quality control, and high initial investments, aquaponics offer significant opportunities for economic, environmental, and social sustainability. The integration of nutrient flows increased nutrient efficacy, and the incorporation of aquaponics into green infrastructure initiatives underscore its potential to transform food production practices.

The need of the day is to invest in research & development and education pertaining to aquaponics from a sustainability angle if we are to design a system that is economically and technically sound. To overcome scarcity of natural resources that lead to long term economic consequences it is essential to consider all factors related to this system and not just financial. There are many technical problems to be solved to come up with a sustainable system which needs to be addressed such as:

1. Looking for better nutrient solubilization processes that improve nutrient availability and uptake that reduces extra nutrient addition to the system.
2. Lower the water use so that water exchange necessity is reduced.
3. Pest management that is adapted and suited for the system.
4. Use CHP waste heat, geothermal heat, etc. as alternative energy sources for extreme climates such as arid hot and cold regions.
5. Use of fluidized lime-bed reactors as a novel pH stabilizing process.

It is important to assess market prices for system grown fish and vegetables, evaluate sales strategies and profitability of typical yields of crops grown in green houses. An ideal situation to consider may be retail sales directly from Greenhouses or roadside sales. Other innovative low cost and simpler alternatives in aquaponics need to be considered such as the bag culture of vegetables where plants are grown in the greenhouse in bags made of polyethylene that are filled with compost based potting mixes along with basic aquaponic systems. Growing vegetables in the greenhouse successfully is not a problem but having to deal with the daily marketing of fresh vegetables is one of the major challenges in the use of this system. Getting appropriate labor to harvest fresh vegetables packing after grading with brand labels, post harvesting handling for quality control and fast delivery of perishable products to the appropriate markets are significant.

CONCLUSIONS

The applied aquaponics are not only economic but also enhance the quality and the quantity of food products in the same land area. It also solves the problem of maintaining and protecting the green environment. It is more green and sustainable farming systems adapting to climate change by taking full advantage of all the natural resources: recycling local materials, agricultural scrap, reused and treated wastewater through closed recirculating systems. This green agricultural model system is a great way to educate kids and children in school to kindle their interest in green technologies and agriculture from that young age. It also provides employment for women, retired people who can take part in harvesting, fish feeding and other steps in the process.

Aquaponics with carefully chosen algal species can maintain pH stability, increase dissolved oxygen in the water and balance the ammonium present in the water therefore exerting a very positive effect on the system. Algae can remove nitrogen products from the system much faster than vegetables and no excess accumulation can take place. Algae are known to play an important role in wastewater clean-up so adding algae in the final stages of an aquaponic system can remove any extra nutrients present in the water so that environmental impact is greatly controlled. Finally, the growth of algae produces plant growth promoting substances and these bio stimulants have a profound stimulatory effect of plant growth and production. Therefore, applied aquaponic is more than just a method of food production for the growing population; it is a way of nourishing communities, increasing economics of developing farmers and creating a better sustainable future.

As we continue to navigate the complexities of a changing global landscape, aquaponics stands as a beacon of innovation, offering a pathway towards a more resilient, efficient, and sustainable food system. Through collaborative research, policy support, and industry engagement, aquaponics has the potential to play a pivotal role in shaping the future of agriculture and ensuring food security for generations to come.

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