Aquaponics: A Potential Integrated Farming System for Sustainable Agriculture and Aquaculture

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Abstract—Aquaponics combines the hydroponic production of plants and the aquaculture production of fish into a sustainable agriculture system that uses natural biological cycles to supply nitrogen and minimizes the use of non-renewable resources, thus providing economic benefits that can increase over time. Several production systems and media exist for producing hydroponic crops (bench bed, nutrient film technique, floating raft, rockwool, perlite, and pine bark). Critical management requirements (water quality maintenance and biofilter nitrification) for aquaculture need to be integrated with the hydroponics to successfully manage intensive aquaponic systems. These systems will be discussed with emphasis on improving sustainability through management and integration of the living components [plants and nitrifying bacteria (*Nitrosomonas* spp. and *Nitrobacter* spp.)] and the biofilter system. Sustainable opportunities include biological nitrogen production rates of 80 to 90 g·m−3 per day nitrate nitrogen from trickling biofilters and plant uptake of aquaculture wastewater. This uptake results in improved water and nutrient use efficiency and conservation. Challenges to sustainability center around balancing the aquaponic system environment for the optimum growth of three organisms, maximizing production outputs and minimizing effluent discharges to the environment.

I. Hydroponics Vs Aquaponics

Aquaponics is defined as a food production system that combines conventional aquaculture (rearing aquatic animals such as snails, fish, crayfish or prawns in tanks) with hydroponics (cultivating plants in water) in a symbiotic environment. In normal aquaculture, excretions from the animals being raised can accumulate in the water, increasing toxicity. In an aquaponic system, water from an aquaculture system is fed to a hydroponic system where the by-products are broken down by nitrification bacteria into nitrates and nitrites, which are utilized by the plants as nutrients. The water is then recirculated back to the aquaculture system. As existing hydroponic and aquaculture farming techniques form the basis for all aquaponic systems, the size, complexity, and types of foods grown in an aquaponic system can vary as much as any system found in either distinct farming discipline [1, 2].

Aquaponics serves as a model of sustainable food production by following certain principles:

- The waste products of one biological system serve as nutrients for a second biological system.
- The integration of fish and plants results in a polyculture that increases diversity and yields multiple products.
- Water is re-used through biological filtration and recirculation.
- Local food production provides access to healthy foods and enhances the local economy.

II. Background History and Benefits

Aquaponics has been emerged from ancient roots, although there is some debate on its first occurrence:

• Aztec cultivated agricultural islands known as “Chinampas” in a system considered by some to be the first form of aquaponics for agricultural use [3, 4], where plants were raised on stationary (and sometime movable) islands in lake shallows and waste materials dredged from the Chinampa canals and surrounding cities were used to manually irrigate the plants [3, 5].

• South China, Thailand, and Indonesia who cultivated and farmed rice in paddy fields in combination with fish are cited as examples of early aquaponic systems [6]. These polycultural farming systems existed in many Far Eastern countries and raised fish such as the oriental loach [7], swamp eel, common carp and crucian carp [8] as well as pond snails in the paddies [9, 10].

Floating aquaponics systems on polycultural fish ponds were installed in China in more recent years on a large scale growing rice, wheat and canna lily and other crops [11] with some installations exceeding 2.5 acres (10,000 m^2) [12]. The development of modern aquaponics is often attributed to the various works of the New Alchemy Institute and the works of Dr. Mark McMurtry et al. at the North Carolina State University [13]. Inspired by the successes of the New Alchemy Institute, and the reciprocating aquaponic techniques developed by Dr. Mark, other institutes soon followed suit. Starting in 1997, Dr.

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James Rakocy and his colleagues at the University of the Virgin Islands researched and developed the use of deep water culture hydroponic grow beds in a large-scale aquaponics system [14]. The first aquaponics research in Canada was a small system added onto existing aquaculture research at a research station in Lethbridge, Alberta. Canada saw a rise in aquaponic setups throughout the ’90s, predominantly as commercial installations raising high-value crops such as trout and lettuce. A setup based on the deep water system developed at the University of Virgin Islands was built in a greenhouse at Brooks, Alberta where Dr. Nick Savidov and colleagues researched aquaponics from a background of plant science. The team made findings on rapid root growth in aquaponic systems and on closing the solid-waste loop, and found that owing to certain advantages in the system over traditional aquaculture, the system can run well at a low pH level, which is favored by plants but not fish.

Aquaponics is indeed a method of food production which combines the best aspects of aquaculture and hydroponics to create a highly productive living ecosystem for sustainable agriculture. The biofilter provides a location for bacteria to convert ammonia, which is toxic for fish, into nitrate, a more accessible nutrient for plants. This process is called nitrification. As the water (containing nitrate and other nutrients) travels through plant grow beds, the plants uptake these nutrients, and finally the water returns to the fish tank purified. This process allows the fish, plants, and bacteria to thrive symbiotically and to work together to create a healthy growing environment for each other, provided that the system is properly balanced. In aquaponics, the aquaculture effluent is diverted through plant beds and not released to the environment, while at the same time the nutrients for the plants are supplied from a sustainable, cost-effective and non-chemical source. Aquaponics can be more productive and economically feasible in certain situations, especially where land and water are limited. However, aquaponics is complicated and requires substantial start-up costs. The increased production must compensate for the higher investment costs needed to integrate the two systems. Although the production of fish and vegetables is the most visible output of aquaponic units, it is essential to understand that aquaponics is the management of a complete ecosystem that includes three major groups of organisms: fish, plants and bacteria.

Aquaponics combines two of the most productive systems in their respective fields. Recirculating aquaculture systems and hydroponics have experienced widespread expansion in the world not only for their higher yields, but also for their better use of land and water, simpler methods of pollution control, improved management of productive factors, their higher quality of products and greater food safety. However, aquaponics can be overly complicated and expensive, and requires consistent access to some inputs. The 15 important benefits of aquaponics are as follows:

1. Delivers nutrients directly to the plant roots
2. Completely programmable technology conserves energy
3. Closed-loop system conserves water
4. Conserves water through runoff absorption into roots
5. Moisture control for better plant growth
6. Can be combined with hydroponics
7. Crops are easier to harvest in the absence of soil
8. Higher density crops optimizes output
9. Reduce labor cost through automation
10. Produces higher quality food in a controlled environment
11. Reduced risk of disease and pest infestation in a controlled environment
12. No need to immerse roots in water, which offers more control
13. Roots are provided with better exposure to oxygen
14. Scalable systems can range from commercial level to apartment-sized gardens
15. Produces more food with less effort

Aquaponics is a technique that has its place within the wider context of sustainable intensive agriculture, especially in family-scale applications. It offers supportive and collaborative methods of vegetable and fish production and can grow substantial amounts of food in locations and situations where soil-based agriculture is difficult or impossible. The sustainability of aquaponics considers the environmental, economic and social dynamics. Economically, these systems require substantial initial investment, but are then followed by low recurring costs and combined returns from both fish and vegetables. Environmentally, aquaponics prevents aquaculture effluent from escaping and polluting the watershed. At the same time, aquaponics enables greater water and production control. Socially, aquaponics can offer quality-of-life improvements because the food is grown locally and culturally appropriate crops can be grown. At the same time, aquaponics can integrate livelihood strategies to secure food and small incomes for landless and poor households. Fish protein is a valuable addition to the dietary needs of many people, as protein is often lacking in small-scale gardening.

Aquaponics may be impractical and unnecessary in locations with land access, fertile soil, adequate space and available water. Strong agricultural communities may find aquaponics to be overly complicated when the same food could be grown directly in the soil. In these cases, aquaponics can become an expensive hobby rather than a dedicated food production system. Moreover, aquaponics requires consistent access to some inputs. Electricity is required for all of the aquaponic systems described in this publication, and unreliable electricity grids and/or a high cost of electricity can make aquaponics unfeasible in some locations. Fish feed needs to be purchased on a regular basis, and there needs to be access to fish seed and plant seed. These inputs can be reduced (solar panels, fish feed production, fish breeding and plant propagation), but these tasks require additional knowledge and add time to the daily management, and they may be too onerous and time consuming for a small-scale system.

Even so, the basic aquaponics system works in a wide range of conditions, and units can be designed and scaled to meet the skill and interest level of many farmers. There is a wide variety of aquaponics designs, ranging from high-tech to low-tech, and from high to reasonable price levels. Aquaponics is quite adaptable can be developed with local materials and domestic knowledge, and to suit local cultural and environmental conditions. It will always require a dedicated and interested person, or group of persons, to maintain and manage the system on a daily basis. Substantial training information is available through books, articles and online communities, as well as through training courses, agricultural extension agents and expert consultation. Aquaponics is a combined system, which means that both the costs and the benefits are magnified.

III. CURRENT ADVANCES

Vegetable production part of the low-cost Backyard Aquaponics System developed at Bangladesh Agricultural University. Dakota College at Bottineau in Bottineau, North Dakota has an aquaponics program that gives students the ability to obtain a certificate or an AAS degree in aquaponics. The Caribbean island of Barbados created an initiative to start aquaponics systems at home, with revenue generated by selling produce to tourists in an effort to reduce growing dependence on imported food.

In Bangladesh, the world's most densely populated country, most farmers use agrochemicals to enhance food production and storage life, though the country lacks oversight on safe levels of chemicals in foods for human consumption [15]. To combat this issue, a team led by Professor Dr. M.A. Salam at the Department of Aquaculture of Bangladesh Agricultural University, Mymensingh has created plans for a low-cost aquaponics system to provide chemical-free produce and fish for people living in adverse climatic conditions such as the salinity-prone southern area and the flood-prone haor area in the eastern region [16, 17] . Dr. Salam's work innovates a form of subsistence farming for micro-production goals at the community and personal levels whereas design work by Chowdhury and Graff was aimed exclusively at the commercial level, the latter of the two approaches take advantage of economies of scale.

With more than a third of Palestinian agricultural lands in the Gaza Strip turned into a buffer zone by Israel, an aquaponic gardening system is developed appropriate for use on rooftops in Gaza City [18].

There has been a shift towards community integration of aquaponics, such as the nonprofit foundation Growing Power that offers Milwaukee youth job opportunities and training while growing food for their community. The model has spawned several satellite projects in other cities, such as New Orleans where the Vietnamese fisherman community has suffered from the Deepwater Horizon oil spill, and in the South Bronx in New York City [19].

Whispering Roots is a non-profit organization in Omaha, Nebraska that provides fresh, locally grown, healthy food for socially and economically disadvantaged communities by using aquaponics, hydroponics and urban farming [20, 21].

In addition, aquaponic gardeners from all around the world are gathering in online community sites and forums to share their experiences and promote the development of this form of gardening [22] as well as creating extensive resources on how to build home systems.

Recently, aquaponics has been moving towards indoor production systems. In cities like Chicago, entrepreneurs are utilizing vertical designs to grow food year round. These systems can be used to grow food year round with minimal to no waste [23].

There are various modular systems made for the public that utilize aquaponic systems to produce organic vegetables and herbs, and provide indoor decor at the same time [36]. These systems can serve as a source of herbs and vegetables indoors. Universities are promoting research on these modular systems as they get more popular among city dwellers [24].

IV. CONCLUSIONS AND CONSIDERATIONS

In aquaponics, the grower needs to understand the fish system and the crop system and must integrate between them. Aquaponics can be a sustainable agricultural production system. Most plant nutrients can be derived from fish feed through fish digestion/excretion and biofilter nitrification, thus integrating nutrient flow. Plants can act as biofilters and take up system effluent that would otherwise be discharged to the environment. The difficulty in finding a median growing environment among plants, fish, and nitrifying bacteria culture in aquaponics has resulted in less integration of the systems than would be ideal for maximizing space and infrastructure, thus reducing the potential overall adaptability and profitability of aquaponics [25]. We know that aquaponic systems management has been established for the lettuce/tilapia floating raft system, but more long-term research/demonstrations should be conducted on sizing and managing other aquaponic crop/fish system combinations to reduce adoption uncertainty.

Even though plants provide a beneficial biofiltration role, nitrification is very important for the maintenance of water quality and conversion of potentially harmful NH_3 to NO_3^-. We suggest system sustainability could be improved by maintaining water pH nearer the optimum for nitrification (pH 7.5–8.0) rather than the optimum for plant production (pH 5.5–6.5), provided plant yields are not reduced. Aquaponic cucumbers were grown with recirculating water pH ranging from 6.0 to 8.0, thus increasing system nitrification rate and production of biologically produced NO_3^-–N at the higher pH levels, without affecting total yield. Other hydroponic vegetable crop species should be tested under aquaponic conditions to determine how crop yields are affected by operating at pH levels more suitable for biofilter nitrification to maximize long-term sustainability [25].

While there are many benefits to growing vegetables and fish using aquaponics, it is not without its challenges. Depending on the size and sophistication of the system, it can require a substantial capital investment. They also require some energy inputs, and because of the highly technical nature of aquaponics, a certain level of skill is necessary to manage the systems adequately. Prospective growers need to thoroughly research the different production methods to determine which are best suited to their needs. If our goal is to produce aquaponics products to generate income, we also need to identify and develop niche markets to ensure profitability. As with any new venture, embarking on a commercial aquaponics operation is not without financial risk and should be thoroughly researched before undertaking. Balancing the aquaponic system environment for the optimum growth of three organisms will also be an on-going subject of research and refinement. Further aquaponic systems' adoption will require more public and private resources to close many knowledge gaps in properly managing these systems and successfully marketing their products to the public. There are several sources of information available to learn more on the subject. Furthermore, there are a number of excellent courses taught by world-renowned experts offered throughout the year on all aspects of aquaponics that will increase adoption of this system by the agricultural communities to a greater extent.

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