



An overview of aquaponics: From cultivation techniques to environmental benefits

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Abstract

As the global population climbs, our traditional food systems are hitting a breaking point, putting immense pressure on land and water supplies. Enter aquaponics: an ingenious combination of aquaculture and hydroponics that could hold the key to a more sustainable future. While the technology has come a long way, it isn't perfect yet; we still need to improve how these systems recycle energy and nutrients while keeping potential diseases in check. But technology is only half the battle. To truly succeed, aquaponics needs to be economically viable, backed by smart government policy, and supported by better research and training. This article dives into why these factors are the missing pieces of the puzzle for sustainable food production."

Keywords: Aquaculture, hydroponics, fish, agriculture, plants, environment

Introduction

The aquaponics model combines fish farming with soil-less plant cultivation to create a self-sustaining ecosystem. The process relies on a natural cycle: waste generated by fish contains essential nutrients that, while toxic to aquatic life in high concentrations, serve as excellent liquid fertilizer for plants. Specialized nitrifying microbes break down these waste products, transforming them into forms that plants can easily absorb. As the plants extract these nutrients, they naturally purify the water, which is then recycled back to the fish (Goddek *et al.*, 2016) [13]. This method is highly productive; since high-density aquaculture systems allow for significant fish yields in limited space (Timmons *et al.*, 2002) [32], aquaponics provides a way to maximize output while minimizing water usage and waste. By repurposing dissolved nutrients, producers can cut down on operational costs and reduce the ecological footprint of their farming activities (Creswell, 2013) [6].

History of Aquaponics

In 1975, Sneed and his colleagues introduced the foundational model for aquaponics, a system designed to channel waste-rich water from fish tanks into vegetation beds. This approach established a dual-purpose strategy: the nutrient-dense effluent provided organic fertilizer for crop development, while simultaneously acting as a biological filtration method to purify the water before its return to the environment. Later, in 1993, Rakocy *et al.*, furthered this field by highlighting that effective aquaponic design relies heavily on our ability to precisely quantify nutrient absorption rates and manage the complex chemical behaviour of culture water.

These historical innovations are now increasingly relevant in light of the 2030 Agenda for Sustainable Development, which identifies sustainable food systems as a primary defence against climate change and systemic poverty (Brandi, 2017) [4]. A core objective of the United Nations' Sustainable Development Goal is addressing the nutritional requirements of a global population expected to reach 10 billion by mid-century. To achieve food security for these two billion additional residents, worldwide agricultural output must expand by 50% (FAO, 2017) [10]. This task is complicated by a significant decline in the agricultural

workforce, a trend driven by rapid global urbanization (dos Santos, 2016) [8]. Furthermore, research suggests that current technological advancements in crop yields will fall short of 2050 targets, indicating that, without radical changes in production methods, society may be forced to increase the total amount of land dedicated to farming (Bajzelj *et al.*, 2014) [3].

Description

Aquaponics represents a synergistic agricultural model that couple's aquaculture with hydroponics, creating a cyclical environment where fish waste provides essential nourishment for plants, while the plants simultaneously act as a natural filtration system for the water. By mirroring the processes found in nature, this self-sustaining method offers an eco-friendly alternative to conventional farming. Because it functions as a closed-loop system, it requires up to 90% less water than traditional soil-based methods and removes the necessity for synthetic fertilizers or pesticides (Lily, 2024) [23].

The inherent flexibility of this technology allows it to thrive in diverse settings, ranging from personal home gardens to expansive industrial operations. Its capacity to function in city environments helps shorten supply chains, bringing fresh protein and produce directly to urban centres to bolster food security. Furthermore, aquaponics supports a wide array of crops such as herbs and vegetables and various freshwater fish species, promoting a diverse and healthy food supply.

From an economic standpoint, the integration of these systems can drive local growth and job creation, particularly in regions hampered by scarce water or poor soil quality. Environmentally, the method mitigates harmful agricultural runoff, curbs carbon emissions, and encourages biological diversity. Socially, it serves as a platform for community building and environmental education regarding self-reliance. While practitioners must navigate obstacles like high starting expenses, sophisticated maintenance requirements, and the need for rigorous oversight, continuous innovation is making these systems increasingly streamlined and affordable for the general public (Francini and Moura, 2008; Albuquerque *et al.*, 2015) [1, 11]. Ultimately, by merging fish cultivation with soil-less plant

growth, aquaponics maximizes resource efficiency and presents a highly scalable solution for the future of sustainable food production.

Concept of sustainable Aquaponics system

Aquaponics represents a closed-loop, integrated agricultural model that merges aquaculture with hydroponics. In this arrangement, nutrient-dense wastewater from fish cultivation is circulated through plant beds. Naturally occurring bacteria process fish excrement, converting toxic nitrogenous compounds—such as ammonia and nitrites—into essential plant nutrients. As the vegetation absorbs these nutrients, the water is filtered and recirculated back to the aquatic environment. By fostering a symbiotic relationship between fish, plants, and microorganisms, this methodology optimizes resource efficiency and minimizes environmental impact compared to managing these systems independently (Goddek *et al.*, 2015) ^[12].

Scope and types of Aquaponic system

Aquaponics serves as a viable strategy for enhancing the economic well-being of both families and local populations. In low- and middle-income nations, where fish acts as a critical protein staple and vegetables are essential for dietary health (Tacon and Metian, 2013) ^[31], this method bolsters both food security and local autonomy. While establishing a commercial-scale operation requires a high level of technical expertise, basic setups are far more accessible. In tropical or subtropical regions, systems can be incredibly straightforward, often requiring only minimal infrastructure and few external inputs (Li *et al.*, 2018) ^[22]. Consequently, when environmental conditions are optimal, aquaponics offers a sustainable way to produce food while simultaneously mitigating many of the environmental burdens associated with traditional agriculture. There are typically three primary configurations of aquaponic systems:

Floating raft method

In a raft system (also known as float, deep channel and deep flow) the plants are grown on polystyrene boards (rafts) that float on top of water (Danaher *et al.*, 2013) ^[7]. A significant amount of nitrification occurs on the undersides of the polystyrene sheets. The system provides maximum exposure of roots to the culture water and avoids clogging. The sheets shield the water from direct sunlight and maintain lower than ambient water temperature, which is a beneficial feature in tropical systems (Rakocy *et al.*, 2004) ^[26]. Most often, this is in a tank separate from the fish tank. Water flows continuously from the fish tank, through filtration components, through the raft tank where the plants are grown and then back to the fish tank. The beneficial bacteria live in the raft tank and throughout the system. This is one of the greatest benefits of the raft system (Tyson, 2007).

Gravel system method

It is a cheap and readily available growing media that is filled in the grow bed (Nelson, 2008) ^[25]. To ensure adequate aeration of plant roots, gravel beds have been operated in a reciprocating mode, where the beds are alternately flooded and drained (Rakocy *et al.*, 2004) ^[26]. This method uses the fewest components and no additional filtration, making it simple to operate (Leonard and Lennard 2007) ^[21]. Gravel has several negative aspects. The weight

of gravel requires strong support structures. It is subject to clogging with suspended solids microbial growth and the roots that remain after harvest.

Nutrient Film Technique (NFT)

This is a method in which the plants are grown in long narrow channels. A thin film of water continuously flows down each channel, providing the plant roots with water, nutrients and oxygen (Nelson and Pade, 2007; Lennard, 2010) ^[20, 24]. Troughs are used in this method which is lightweight, inexpensive and versatile. Troughs can be mounted over rearing tanks to efficiently use vertical greenhouse space (Junge *et al.*, 2014) ^[18]. Few drawbacks of NFT method are a separate bio filter is required, because there is not a large amount of water or surface for the beneficial bacteria to live. In addition, the plumbing used in a hydroponic NFT system is usually not large enough to be used in aquaponics because the organic nature of the system (Rakocy *et al.*, 2004) ^[26]. The thin film of water that flows through NFT (nutrient film technique) channels absorbs oxygen by diffusion, but dense plant roots and associated organic matter can block water flow (Graber *et al.*, 2011) ^[15].

Recirculating Aquaculture System (RAS)

This technique represents a unique way for fish farming. Instead of the traditional method of growing fish outdoors in open ponds this system rears fish at high densities, in indoor "controlled" environment tanks. Recirculating systems filter and clean the water for recycling back through fish culture tanks (Helfrich and Libey, 2003) ^[17]. In RAS it is possible to combine wastewater treatment in constructed wetlands with the production of crop plants biomass. For each kilogram of fish produced in RAS aquaculture, the nutrients in the resulting wastewater allowed a vegetable biomass production of 7 kg (Graber and Junge, 2009; Junge *et al.*, 2014) ^[14, 18]. Aquaponics combines RAS with hydroponics (growing plants in a nutrient water source) in a balanced environment. The primary goal of aquaponics is to reuse the nutrients released by fishes to grow crop plants. RAS can be designed to be very environmentally sustainable, using 90-99 percent less water than other aquaculture systems. RAS can reduce the discharge of waste, the need for antibiotics or chemicals used to combat disease, and fish and parasite escapes. One of the key concerns in RAS is relating to the load of suspended solids and in particular to fine particles. The presence and accumulation of particulate wastes in RAS can negatively impact the water quality by affecting the performance efficiency of the water treatment or bio filter units and resulting in total ammonia nitrogen (TAN) spike (Resley *et al.*, 2006; Lee *et al.*, 2014) ^[28]. These drawbacks can be negated in modified RAS and aquaponic technology which involves growing plants (preferably raft method) for the filtration and nitrogen removal process.

Integrated Multi-Trophic Aquaculture (IMTA).

This technique involves cultivating fed species with other varieties of species at various trophic levels that utilise wastes from aquaculture for their growth (Siskey and Baldwin, 2011) ^[29]. IMTA systems not only produce valuable biomass, but also provide waste reduction services. Presently, the most advanced IMTA systems in open marine waters and land-based operations have three components – fish, suspension feeders or grazers such as shellfish, and

seaweed, in cages, rafts or floating lines – but they are admittedly simplified systems. More advanced systems will have several other components (e.g., crustacean such as sea cucumbers, sea urchins and polychaetes in bottom cages or suspended trays and bottom-dwelling fish in bottom cages) to perform either different or similar functions, but for various size ranges of particles, or selected for their presence at different times of the year (Guerrero and Cremades, 2011). Integrated marine aquaculture can cover a diverse range of co-culture/ farming practices with specialized forms of integration such as mangrove planting with aquaculture, called aqua silviculture (Angel and Freeman, 2009) [2]. Aquaponics, fractionated aquaculture, integrated agriculture-aquaculture systems (IAAS), integrated fisheries-aquaculture systems (IFAS) and integrated peri urban aquaculture systems (IPUAS) are all different forms of IMTA. With options for land and water combinations in both freshwater and marine environments, IMTA is a versatile and powerful food production tool that can be utilized in the Sundarbans for ecological stability; the technique has many benefits, among which bioremediation and bio mitigation with balanced fish production being the most relevant (Chopin *et al.*, 2010) [5].

Aquaponics is a circular food production system that combines fish and plant cultivation. Its benefits can further the urban agriculture movement through sustainable food production, community support, and education. While the growing system is well understood, its prospective integration into cities, regional foodsheds, and circular economy require detailed consideration from both built environment and economic perspectives. The proliferation of aquaponic operations beyond backyard hobbyists has emerged recently as technology to support industrial scale production. Aquaponics help alleviate food deserts, it is an educational tool in schools; anterior greening (providing a better climate in public buildings and homes), and a unit in social institutions. Our country is one of leading in ornamental fish production. Operation of these units is more demanding in terms of technology, techniques, biology of cultured fish and stringent water quality parameters. Therefore, Aquaponics has a huge potential for integrated fish and plant production in urban, suburban as well as rural settings.

Economic challenges

To ensure an aquaponics venture is financially viable, investors must carefully analyze three primary economic pillars: initial capital expenditure, ongoing operating expenses, and conservative projections for market pricing. Research by Engle (2015) [9] highlights that indoor fish farming typically incurs costs two to three times greater than traditional outdoor pond-based aquaculture. Consequently, success hinges on identifying niche markets where consumers are willing to pay a premium for indoor, sustainably produced goods. Furthermore, because operating a recirculating aquaculture system is generally more expensive than running a standard hydroponic unit, there is a distinct risk that fish production costs could overshadow vegetable revenue, potentially resulting in an overall net financial loss. Strategic planning is therefore essential to balance these disparate production costs and maintain profitability.

Conclusion

Given the current dynamics between national food production and population growth, there is a critical need to implement innovative, sustainable aquaculture practices. To bolster food security and maintain a reliable supply of fresh produce, it is essential to explore technologically advanced, integrated farming systems. Aquaponics stands out as a highly promising solution in this pursuit, offering a sustainable model that mitigates the water consumption and soil-related issues inherent in conventional agriculture. Consequently, aquaponics serves as a cornerstone for achieving environmental, social, and economic sustainability.

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