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REVIEW

A Review of Aquaponics: Concept, Current Situation and Development

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Abstract

Y. Wang, Y. Yang, and J. Lu. 2024. A Review of Aquaponics: Concept, Current Situation and Development. Int. J. Agric. Nat. Resour. 140-156. In the face of global warming, environmental pollution, population growth, and the degradation of biodiversity and natural resources, sustainable farming practices have become crucial and should be explored and implemented. Aquaponics is an agricultural system that integrates aquaculture and hydroponics in the application of sustainable farming technologies. The nitrogen-rich biomass produced by aquatic life is used to feed crops, while the feeding process also acts as a natural filtering system that maintains the habitat of aquatic life. This article divides the development history of aquaponics into three stages: the origin stage (before the 1960s), the initial stage (1960s), and the development stage (after the 2010s). Five typical aquaponic models are compared and analyzed. This work suggests that the basic theory of the aquaponic system should be studied thoroughly, and the intelligent and industrial development trends of the system should be explored. These studies can provide sufficient evidence and concrete references for large-scale applications of aquaponics.

Keywords: Aquaponics, future trend, historical process, sustainable agriculture, typical models.

Highlights

- Provide a comprehensive overview of the historical development, current models, and future prospects of aquaponics.
- Analyze the theoretical foundations and technological advancements of aquaponics.
- Focus on the development and optimization of aquaponics as a viable solution that integrates aquaculture and hydroponics into a sustainable, closed-loop system.

Introduction

The increasing global eco-environmental, social, and economic challenges necessitate the develop-

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ment of innovative and sustainable food production and consumption solutions (United Nations, 2015). By 2050, the global population is projected to reach between 8.3 and 10.9 billion, thus requiring a 50% increase in food production worldwide (Viglizzo, 2014). As such, there is a pressing need for sustainable and scalable methods to expand food production. To achieve the goal of a circular economy, continuous innovation and optimization are necessary in stable and sustainable modes of food production (Pretty et al., 2010). For example, despite China's possession of 1.168×10^6 km^2 of arable land and food crop production reaching 6.69×10^8 t, the excessive use of chemical fertilizers and pesticides has caused water eutrophication, excessive agricultural residues, soil imbalance and hardening, and extreme algal growth (Our World in Data) (Roser, 2016). These problems are not unique to China as chemical fertilizers and pesticides are widely used in agricultural production worldwide, leading to significant environmental damage. Aquaculture, which is a major source of protein, has also caused problems such as nitrification and algal blooms. By 2030, the annual per capita fish consumption is expected to increase to 21.5 kg, and aquaculture will produce substantial amounts of pollutants, with up to 75% of nitrogen and phosphorus remaining in the water as pollutants (Rao, 2017). Aquaponics provides a sustainable solution by minimizing water consumption, the use of land resources, the utilization of fertilizers and pesticides, and the environmental hazards of waste loading into local rivers (Kloas et al., 2015; Amosu et al., 2016). Studies have shown that aquaponics effectively removes ammonia nitrogen, nitrate nitrogen, nitrite, total phosphorus, and suspended solids from aquatic systems (Lam et al., 2015). Moreover, tomato has a higher nutrient removal rate than does cucumber, with 69% of nitrogen converted into fruit (Graber & Junge, 2009). Aquaponics is a hybrid farming system that offers a sustainable solution to traditional farming practices that cause significant environmental damage. In 2015, the European Parliament listed aquaponics as one of the top 10 technologies that could change the way people live (Pretty et al., 2010) as it offers a sustainable and scalable solution that meets the demand for developing sustainable agricultural facilities.

Aquaponics is a hybrid term that combines "hydroponics" and "aquaculture." Essentially, aquaponics refers to the combination of hydroponics and aquaculture in a closed-loop system. In this system, the tail water is circulated through a fishpond after undergoing double filtration, including a microfiltration nitrification module and a vegetable cultivation bed (Oladimeji et al., 2020a). The entire filtration system uses physical filtration to separate solid fish excreta and feed residue, and then the soluble waste is treated by a biochemical system that sometimes requires a mineralization system. Biochemical systems provide a breeding ground for nitrifying bacteria that convert toxic nitrogen sources, such as ammonia and nitrite, into nitrates, which are essential for plant growth (Figure 1). As water containing nitrates and other nutrients flow through the beds, the plants absorb these nutrients, resulting in the harmonious coexistence of fish, plants, and bacteria, which is known as system equilibrium. This circulating water not only prevents water pollution but also provides nutrients for vegetable growth, resulting in a sustainable ecological and agricultural production mode with wastewater recycling and zero discharge. However, in aquaponic systems, balancing the nutrients produced by fish with the requirements of hydroponic plant growth is essential to optimize resource use and improve system productivity (Rakocy et al., 2006), a process has been confirmed in many studies (Oladimeji et al., 2020a; Oladimeji et al., 2020b). Studies have further shown that a fish-to-plant production ratio of 15:42 g fish feed m^{-2} plant growth area is an appropriate ratio. Above or below this optimal ratio, either fish or plant growth can be severely affected. Numerous studies have been conducted to identify species suitable for aquaponic systems. These species include *Oreochromis spp., Ipomoea aquatic* (Liang & Chien, 2013), *Oncorhynchus mykiss, Coriandrum* *sativum L., Petroselinum crispum, Lactuca sativa,* and *Plantago coronopus* (Buzby et al., 2016), *Oreochromis spp., Clarias gariepinus, Ocimum basilicum, Origanum majorana,* and *Petroselinum crispum* (Knaus & Palm, 2017), *Oreochromis niloticus, Oreochromis mossambicus* and *Ipomea aquatic* (Wang et al., 2016), *Clarias gariepinus, Amaranthus spp.,* and *Ipomea aquatic* (Mamat et al., 2016), *Osphronemus goramy, Lactuca sativa L. var. longifolia* (Purwandari et al., 2017), *Huso×Acipenser ruthenu, Lactuca sativa* (Dediu et al., 2012), *Clarias gariepinus, Pumpkin Telfairia occidentalis* (Oladimeji et al., 2020a, Oladimeji et al., 2020b), *Lemon fin barb hybrid, Chinese celery (Apium graveolens), Coriandrum sativum,* and *peppermint* (Ogah et al., 2020).

In this review, our objective is to address the urgent need for sustainable agricultural practices in response to the challenges posed by global environmental degradation, population growth, and resource scarcity. Specifically, we focus on the development and optimization of aquaponics as a viable solution that integrates aquaculture and hydroponics into a sustainable, closed-loop system. This paper aims to provide a comprehensive overview of the historical development, current models, and future prospects of aquaponics, highlighting its potential to contribute to food security, environmental resilience, and sustainable urban and rural development. By thoroughly analyzing the theoretical foundations and technological advancements of aquaponics, we seek to offer actionable insights that bridge existing knowledge gaps and pave the way for large-scale applications of this innovative agricultural system.

Development history of aquaponics

The origin of aquaponics (before the 1960s)

The origin of aquaponics begins with paddy farming in Asia and Aztec chinampas in Mexico (Ira-Adeline et al., 2017; Shabeer, 2016). Aquaponics has a long history, with traces of fish farming in rice fields dating back to ancient China. Historical records, such as Cao Cao's Food System of the Four Seasons of Wei and Wu Dynasties, dating back 1,700 years ago, mentioned fish from paddy fields being used for sauce (Pan & Zhuang, 1999). Similarly, records from the Qing Dynasty Guangxu period in 'Qingtian County Annals' described fish with red and black mottled colors as being raised by native people in paddy fields and country yards (Shabeer,

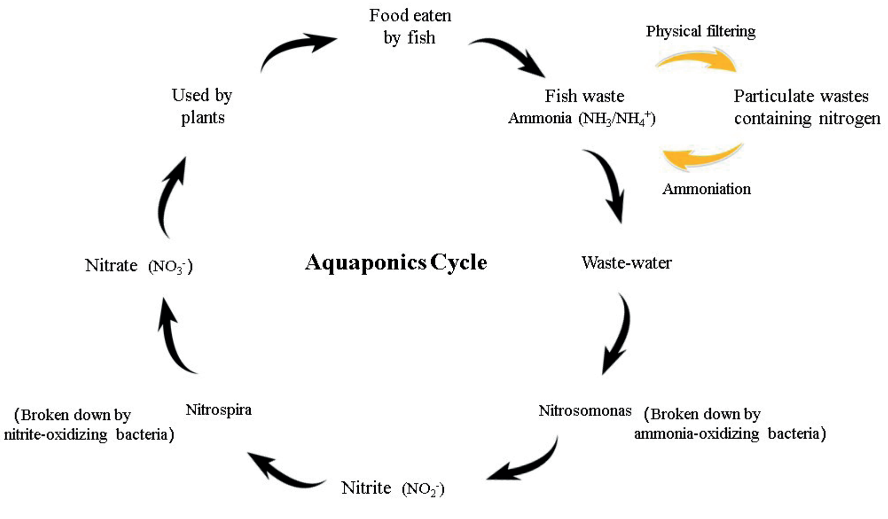

Figure 1. Diagram of an aquaponic cycle

2016). These references confirm the existence of integrated rice–fish cultivation practices in early China. Traditional agricultural production modes such as rice–fish symbiosis have been preserved in places such as Zhejiang, Yunnan, Guizhou, and other regions in China, contributing to a unique rice-fishing culture. The symbiosis model in Qingtian County, Zhejiang Province, has even been recognized as a world agricultural cultural heritage by the United Nations Food and Agriculture Organization. The use of the chinampas system in Mesoamerica dates back to at least the 7th century CE and continued until the arrival of the Spanish in the 16th century. Chinampas were raised garden beds built in shallow, nutrient-rich lake beds or swamps. The beds were constructed by layering mud and decaying vegetation, which created a fertile growing medium. These beds were then used to grow crops such as maize, beans, squash, and tomatoes. The chinampas system also included fish, such as tilapia and carp, which were raised in the canals surrounding the garden beds. The fish waste fertilized the plants growing in the chinampas, while the plants cleaned the water for the fish (Robertson, 1983). The chinampas were an important source of food for the growing Aztec population, and it is believed that at their height, the chinampas could have fed up to 300,000 people. In addition, references to the coculture of fish and plants can also be found in ancient history, such as the Hanging Gardens of Babylon.

Overall, paddy farming in Asia and the chinampas system demonstrate the potential for sustainable agriculture through the integration of fish and plants and have played an important role in the development of aquaponics as a modern agricultural practice. Unlike modern aquaponics, these natural symbiotic systems are considered the origin of modern aquaponics.

The initial stage of aquaponics (1960s-2010s)

In the 1960s, John Todd, Nancy Todd, and William McLarney of the New Alchemy Institute in Massachusetts created “The Ark,” a solar-powered greenhouse that produces enough fish and vegetables for a family of four for a year (Mclarney & Walton, 1974). Integrated fish and plant systems (originally termed “integrated systems”) began to emerge in the 1970s. Aquaponics was influenced by early aquaculture researchers who experimented with soilless plant systems as a means of treating fish waste and removing nitrogen compounds, which marked the beginning of contemporary aquaponics (Sneed et al., 1975; Naegel, 1977). Since then, engineers have developed various biofilters for treating fish waste that do not depend on plants (Timmons et al., 2018). Permaculture, which mimics natural ecosystems, has been practiced for thousands of years but was first codified by researchers in Australia in the mid-1970s (Mollison & Holmgren, 1982). In the late 1970s and early 1980s, Ron Zweig, John Todd, John Wolfe, and others at the New Alchemy Institute applied permaculture methods to aquaculture (Todd, 1980) and later experimented with linking hydroponics and aquaculture (Zweig, 1986). The first modern aquaponics system was credited to the Integrated Aqua-Vegeculture System (IAVS) and the North Carolina State University (NCSU) system invented by Dr. Mark McMurtry from NCSU in the 1980s (Mcmurtry et al., 1990; Rakocy et al., 2004). The NCSU system was later refined by Paula and Thomas Speraneo of S&S Aqua Farm in Missouri. In the 1990s and 2000s, Dr. James Rakocy from the University of the Virgin Islands (UVI) and other researchers developed the UVI system, which was further improved and successfully commercialized by Nelson and Pade, Inc. (Rakocy et al., 2006; Rakocy, 2012). After McMurtry’s and Rakocy’s innovations, more techniques were developed, including the Nutrient Film Technique (NFT) Aquaponics System. The NFT Aquaponics System is a combination model of NFT hydroponics and aquaculture. Even today, the Marsh Arabs of modern-day Iraq still grow food on rafts that are large enough to hold their homes and even enormous meeting halls (Somerville et al., 2014).

The development stage of aquaponics (after the 2010s)

Aquaponics has the potential to revolutionize agriculture and have a positive impact on the world. A search of the Web of Science database using the keyword ‘aquaponics’ revealed that it has been studied and practiced in at least 75 countries and regions (Figure 2). In recent years, there has been an increasing trend in the number and frequency of citations in studies on aquaponics (Figure 3). With a large and active community of participants experimenting with and adopting new technologies, aquaponics is a dynamic and rapidly evolving field (Love et al., 2014) that has become a popular topic in agricultural technology.

Typical models of aquaponics

Traditional model

Aquaponics has its origins in the concept of soil-free vegetation cultivation, in which plants

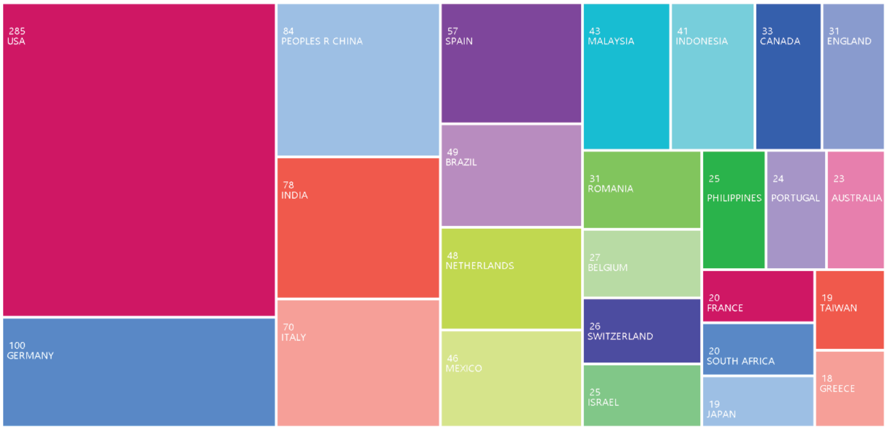

Figure 2. 1950–2023 Number of citations regarding ‘aquaponic*’ worldwide. Data were obtained from the Web of Science, and the keyword ‘aquaponic*’ was retrieved from the 1950–2023 data.

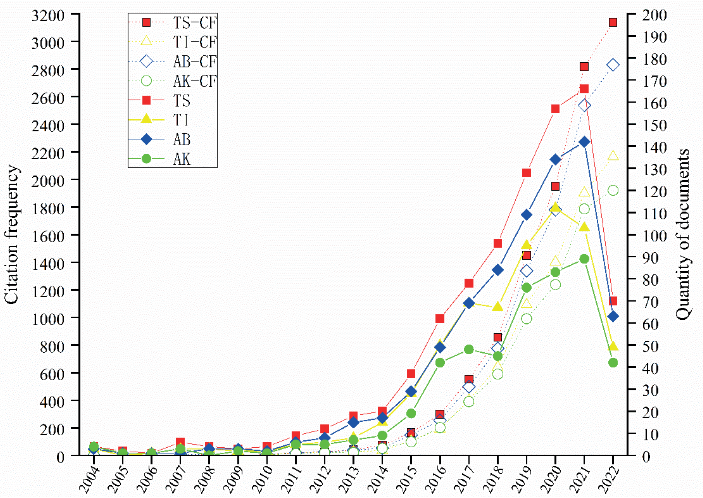

Figure 3. Frequency of citations of literature concerning ‘aquaponic*’. TS-topical subjust, TI-title, AB-abstract, and AK-author keywords; TS-CF denotes the citation frequency of topical subjust, TI-CF denotes the citation frequency of title, AB-CF denotes the citation frequency of abstract, and AK-CF denotes the citation frequency of author keywords.

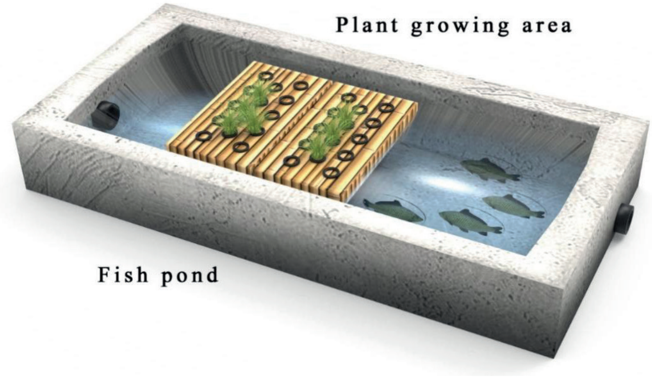

Figure 4. Traditional model. The traditional aquaponic system involves placing a hydroponic vegetable floating bed directly on the water surface of the pond. The floating bed can be made of materials such as bamboo rafts or dense polystyrene. However, for certain types of fish that feed on plants or are omnivorous, it is necessary to set up a dense net below the floating bed to protect the vegetables' root systems.

are grown over floating devices in a controlled nitrogen-level water system (Figure 4). This creates a sustainable cycle of fish-vegetation cohabitation, where the roots of the vegetation take up dissolved nitrogen, preventing eutrophication and providing a suitable habitat for fish. Wang and Gao (2017) reported that the introduction of water spinach (Ipomoea aquatica Forsk) into fishponds results in a 10%-20% increase in dissolved oxygen levels, a 5%-10% decrease in turbidity, and a significant 20%-30% decrease in dissolved nitrogen levels compared with those in ponds without water spinach. Additionally, compared with conventional fishponds, water spinach-growing fishponds achieve a 479.55 kg/acre increase in yield and a 20% reduction in antibiotic use. However, the traditional aquaponic system has several drawbacks, including low dissolved nitrogen intake by vegetation despite the nitrogen-rich environment, difficulty scaling up to larger systems, and the potential for aquatic life to damage the root systems of vegetation.

IAVS model

In the 1980s, Dr. Mark McMurtry invented the IAVS (Figure 5). The IAVS design requires minimal or no electric power to operate, making it ideal for sustainable farming. It consists of a pond and a sand filter bed, which is considered ideal for the IAVS vegetation growth because its pH and water permeability are similar to those of soil. The sand filter bed also provides sufficient concentrations of potassium, calcium, and iron, which are often lacking during vegetation growth. For aquatic organisms, the sand filter bed slowly filters organic waste from fish and quickly mineralizes it due to oxygen exposure. This filter bed efficiently utilizes organic waste without requiring mechanical means of water filtration for sedimentation, nitrification, and nitrate mineralization. Studies conducted in Raleigh, North Carolina, have shown that aquaponics can yield more than 50 kg of tilapia per year for each cubic meter of water (regularly harvested when individual fish reach 250 g), in addition to approximately 360 kg of tomatoes or other fruits and vegetables (Rakocy et al., 2004). A key management consideration for obtaining the best results is balancing the number of fish with the number of plants (i.e., the ratio of feed input to plant growth). Therefore, managing the IAVS requires hands-on experience to develop management skills.

NCSU model

The NCSU aquaponics model, originally invented by McMurtry, consists of a grow bed containing either sand or gravel and a fish tank that receives

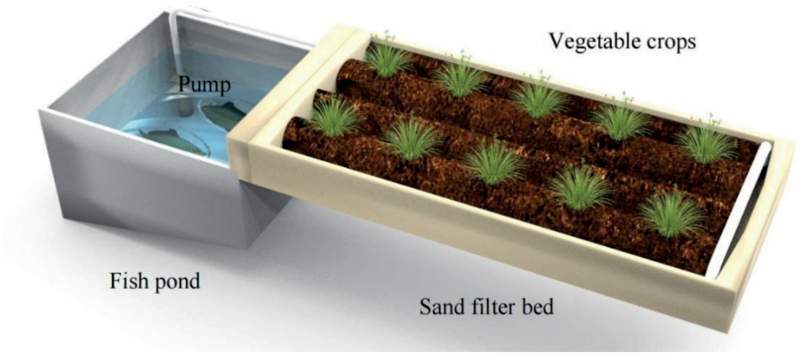

Figure 5. IAVS aquaponics model. The IAVS is a tightly coupled, symbiotic system that allows for the simultaneous production of fish and vegetables on a small plot of land. In this system, the water from the fish tank, along with any bottom residues, is either scooped or pumped to the surface of the sand bed, where it is then filtered through the sand. The sand bed serves as a habitat for both the vegetable crops and the microbiota that inhabit it. Importantly, the sand used in this system should be no less than 200 microns in diameter, with a consistency similar to that of common salt or sugar, and it should be free of powder. Once the water is cleaned and filtered through the sand bed, it is returned to the pond by gravity for the next cycle.

oxygen-rich water and nutrients from the grow bed. Many small-scale aquaponic systems are based on the NCSU model. Paula and Thomas Speraneo later refined the original model, resulting in a new NCSU model (Figure 6). Compared with the original version, the new NCSU model features a water-recycling system. The gravel-filled grow bed aids in the breakdown of organic matter, and the gravel filtration method, drip irrigation system, and water pressure provide the NCSU system with great flexibility, making it suitable for various agricultural projects because of its reduced costs. The NCSU system is simple and economical, and it can be combined in different forms, such as small-scale home systems, large three-dimensional agriculture, greenhouse agriculture, and other commercial purposes. As a result, the development and application of this system in the United States are relatively extensive and systematic (Goodman, 2011).

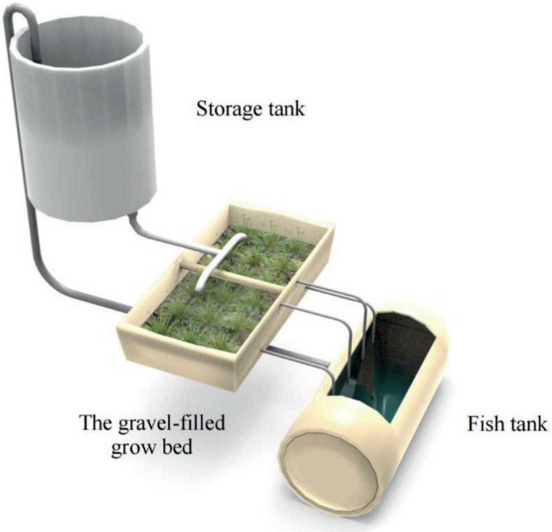

Figure 6. NCSU aquaponics model. The NCSU model is primarily composed of a water storage tank, a planting tank, and a fishpond. The planting tank is cultivated with solid substrate, which typically consists of fine sand and gravel. The fishpond is located underground and is planted with hydroponic crops on top. Water from the fishpond is circulated back to the planting tank through drip irrigation and gravity.

UVI model

In the late 1980s, Dr. James Rakocy introduced the UVI aquaponics system, also known as the deep water culture (DWC) or floating bed system, in which plants are suspended above a tank of water via a floating raft (Figure 7). The effluent from the fish rearing tanks is filtered to isolate the suspended organic particles, which are collected in nitrifying tanks for biodegradation. The nitrogen-rich particles are broken down into dissolved nitrogen, which is consumed by vegetation, as well as by nitric salt precipitates, which are further degraded by microbes residing underneath the polystyrene planks. The treated water in the hydroponic tanks is collected and recycled to feed into the fish rearing tanks. The UVI system is based on the DWC, which offers great flexibility to scale up. Additionally, the root system of the vegetation has extensive surface contact with water, making the system more efficient at purifying the water. The UVI commercial aquaponic system was designed to produce fish and vegetables (Bailey & Ferrarezi, 2017). The UVI system, with a planted area of 214 m^2, generates USD 110,000 per year from the sale of basil alone (Bailey & Ferrarezi, 2017; Ibrahim et al., 2023).

NFT model

The NFT aquaponics model is a combination of NFT hydroponics and aquaculture. The majority of NFT systems use a pipe as a grow bed, with a pipe-built platform covered with nonwoven fabrics that function as a platform for the grow bed (Figure 8). The nonwoven fabrics also act as filters and as a nitrification device. Finally, the water flowing out of the pipe is collected and recycled in a fish tank. The NFT model offers many advantages, including an industrialized growth process. Additionally, it is easy to manage the harvest for vegetation, and it has the ability to be set up as a vertical system, which is particularly useful for urban farming. However, the limited space and availability of suitable plant species for growth are factors that must be carefully considered.

The IAVS and NCSU models are media-filled bed units that offer a variety of substrate options and are capable of growing most plant types. These systems have a simple design with a high fault tolerance rate and low energy consumption, making them ideal for aquaponic beginners. However, they can be relatively heavy, and the cost of the substrate can be high. Compared with the UVI and NFT, these systems have high evaporation rates

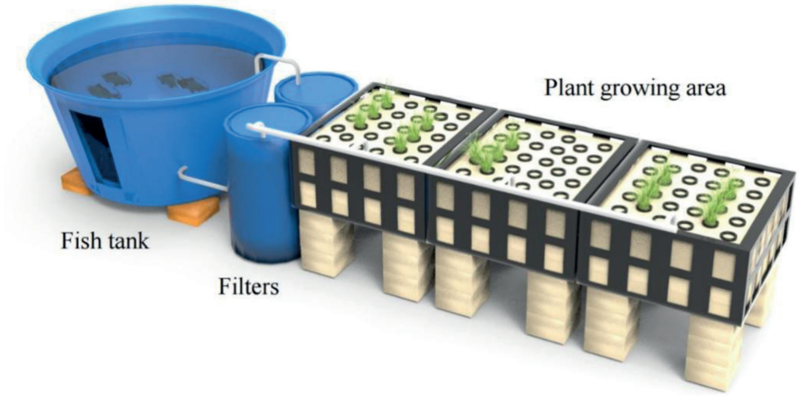

Figure 7. UVI aquaponic model. The UVI model is a comprehensive aquaponic system that comprises a fish tank, sedimentation tank, filter tank, aeration tank, hydroponic bed, and return pool. The water from the fish tank is initially filtered mechanically to decrease the presence of organic matter in the form of suspended solids, while the biofilter subsequently eliminates ammonia and nitrate from the water. The filtered water then passes through the hydroponic bed, where vegetation grows, and the water is further purified. Finally, the purified water is collected in a reservoir, commonly referred to as a cistern, and then returned to the feeding tank.

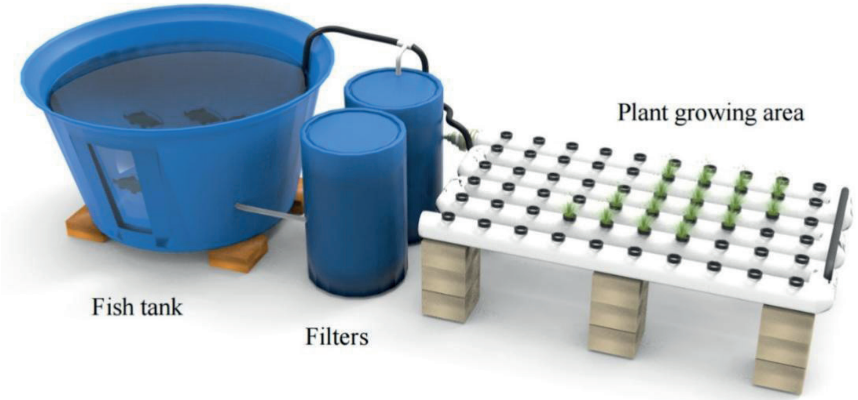

Figure 8. NFT aquaponics model. The NFT aquaponics model is a unique combination of NFT hydroponics and aquaculture. Water flows out of the tank under gravity, through mechanical filters, into a combination of biofilters and sump. The water is then pumped in both directions through Y connectors and valves. Some of the water is pumped directly back into the tank, and the remaining water is pumped into the NFT pipe. Owing to gravity, water flows down the growing tube where the plant is located. After leaving the growing pipe, the water is returned to the tank, thus completing the cycle.

and are prone to clogging over time. Additionally, they require a significant amount of labor, and large-scale production can be challenging to control. The UVI model is suitable for large-scale production and is the most widely used commercial model. The mobile foam bed is convenient for planting, harvesting, and expanding the nitration surface area, to a certain extent. However, the system design is more complex, particularly in factories, due to its high energy consumption and initial input costs. As large bodies of water increase humidity, there is a need to improve disease resistance. In contrast, the large-scale NFT model is more cost-effective than media-filled bed units and has the lowest evaporation rate. Moreover, the pipeline for planting vegetables can be adjusted according to the specific crop or other needs, and it has been subjected to numerous applications and studies on commercial hydroponic farms. However, the NFT requires a more complex filtration system with higher energy consumption. The low water volume of the pipeline places high requirements on water quality, and the intake pipe is easy to clog. Even a power failure can have a significant effect on the entire system. A review of aquaponic systems revealed that 43% used media-based systems, 33% used the UVI, 15% used the NFT, and 9% used other less common systems (Maucieri et al., 2018). By combining the growth characteristics of various plants and reducing the use of biofilters, media-filled bed units are ideal aquaponic systems for small-scale farming and research purposes. That said, UVI seems to be best suited for commercial applications because it has a low environmental impact, maximizes the root–water contact surface area, and maintains high yields.

Future perspectives

Currently, agriculture occupies approximately 33% of the world's land area, and it is projected to increase by 7%-31% by 2050 to meet the growing demand for food due to the population growth (Viglizzo, 2014). Aquaponics offers a promising solution for regions with scarce or polluted land resources, as well as urban and rural areas, especially arid regions or areas with nonarable soils (Goddek & Körner, 2019). In a study by Oladimeji et al. (2020a), the performance of a catfish–pumpkin aquaponics system was evaluated and compared with circulatory and static aquaculture systems and with irrigated and nonirrigated hydroponics systems. The results showed that catfish production was 29% more efficient in the circulatory system and 75% more efficient in the static system. The improved water quality in the aquaponic system contributed to the high yield and survival rate of the catfish. With respect to pumpkin yields, there was a fivefold increase in the irrigated system and an elevenfold increase in the nonirrigated system compared with the traditional pumpkin farming method. Aquaponics is considered an effective approach to address current agricultural challenges. However, the energy demand of aquaponics, especially in greenhouses and indoor environments, is primarily due to the artificial lighting and water pumping, which account for a significant portion of electricity consumption (Proksch et al., 2019; Singh et al., 2015; Turnšek et al., 2019).

According to previous article reviews, most studies have focused on plant and fish species pairing, microbial populations, nitrogen levels, choice of feed (Endut et al., 2010), pH control, management practices (Tyson et al., 2011), aeration and filtration techniques (Danaher et al., 2013), acceptable nutritional ranges (Delaide et al., 2016), socioeconomic feasibility (Junge et al., 2017), system design (Palm et al., 2018), and industry trends (König et al., 2018). At the interdisciplinary level, aquaponics is a complex system involving multiple disciplines, such as aquaculture, agriculture, ecology, microbiology, chemistry, mechanical engineering, the Internet of Things (IoT), and artificial intelligence (AI) (Agossou & Toshiro, 2021). Despite its potential, aquaponics faces significant challenges, including high start-up costs, the need for stable and continuous electricity, and the complexities of nutrient availability and disease management within the system (Okomoda et al., 2023; Yep & Zheng, 2019). For instance, Love et al. (2015) reported that a minimum of 1000 m² is required for commercial farmers to break even in the first year, with start-up investments ranging from USD 5000 to USD 9999. Moreover, the optimization of plant-to-fish ratios remains a topic of ongoing debate among researchers, as the nutrient supply from fish feed often falls short of plant requirements, necessitating supplementation (Eck et al., 2019; Oladimeji et al., 2020b). Therefore, while aquaponics holds promise for sustainable urban and rural food production, these challenges must be addressed through systematic research and technical evaluations, particularly in terms of energy consumption, economic feasibility, and operational efficiency (Konig et al., 2016).

Theoretical research on aquaponics fundamentals

Several factors contribute to the effectiveness of aquaponic production yields, including the optimal ratio of aquatic life and vegetation, efficient resource consumption, disease prevention, and water treatment technology (Dinev et al., 2023; Goddek & Keesman, 2018; Oladimeji et al., 2020a). First, maintaining an appropriate balance between fish and vegetable composition ratios and population quantities is key to ensuring the ecological balance of the entire system. Second, specific environmental factors, such as temperature, humidity, dissolved oxygen, pH, ammonia nitrogen conversion and utilization, water flow rate, and feed conversion rate, are interdependent and have a certain correlation in the system. Understanding the mechanisms of their mutual transformation is essential for guiding the production of aquaponic systems. Third, owing to the symbiotic nature of aquaponics, the use of antibiotics is less than ideal, and exploring better and less harmful biochemical pesticides is crucial for their development. Some studies have presented and briefly discussed the control of plant pests and diseases in aquaponic systems, with the authors concluding that emphasis should be placed on preventive measures to minimize infestations by pests and pathogens (Bittsánszky et al., 2015; Goddek et al., 2015).

Exploration of aquaponic AI

Aquaponics is widely recognized as a sustainable and efficient agricultural system that relies heavily on the precise management of dissolved oxygen (DO), nitrogen levels. and pH. Despite the availability of automated equipment, such as water recycling, feeding systems, and online monitoring and alarm systems for key parameters such as oxygen and ammonia nitrogen, there is still significant room for improvement in achieving more precise and labor-efficient operations. Recent advancements in artificial intelligence (AI) and related technologies have significantly increased the potential of aquaponic systems, driving what is now referred to as "Aquaponics 4.0. "(Ibrahim et al., 2023). The integration of Industry 4.0 concepts into aquaponics has led to a digital farming approach that incorporates remote monitoring, extensive automation, and smart decision-making aimed at optimizing both crop yield and quality (Eneh et al., 2023; Nayak et al., 2020; Oladimeji et al., 2020b). For example, digital twin technology is now being used to create virtual replicas of plant production lines, which allows for enhanced monitoring and control of the entire system, thereby improving overall efficiency (Taha et al., 2022). Predictive analytics software and leveraging machine learning algorithms optimizes fish feed rates by analyzing historical and real-time data, thus ensuring optimal growth conditions while minimizing waste (Reyes-Yanes et al., 2020).

Additionally, wireless sensors play a critical role in predicting and preventing disease outbreaks by continuously monitoring water quality parameters to enable early intervention before issues escalate (Haryanto et al., 2019). Convolutional neural networks (CNNs) are applied to assess crop quality and growth rates, providing farmers with actionable insights into optimal harvesting times and improving yield predictions (Abbasi et al., 2023). Deep learning models such as ResNet and Inceptionv3 have also been developed to diagnose nutrient deficiencies in crops such as lettuce, offering high accuracy in nutrient content classification and contributing to more effective nutrient management strategies (Badrinarayanan et al., 2017; Sohail et al., 2022). Moreover, the use of AI-driven maturity estimation systems allows for precise control over harvesting schedules, ensuring that crops and fish are harvested at their peak quality, thereby maximizing both efficiency and profitability (Oladimeji et al., 2020b). These AI-enhanced systems, which integrate real-time data monitoring, terminal control, and automated decision-making, lead to more stable, secure, and efficient aquaponics operations, ultimately advancing the sustainability and scalability of this agricultural practice (Khaoula et al., 2021).

Future development of aquaponics

Aquaponic design guidelines have been classified by Maucieri et al. (2018) on the basis of several factors, including objectives, system scales, operational modes, water cycle management, hydroponic system types, and space utilization. More recently, decoupled systems have been introduced, which have exhibited greater plant production and better growth performance and feed conversion for fish than other systems. Decoupled systems provide optimal conditions for fish and plant growth and can manage the imbalance between the two units through the independent regulation of pH and nutrient concentration. They are more suitable for large-scale specialized production, especially those with complex high nutritional requirements to protect animal welfare in fish units. However, classical systems may be more appropriate for small-scale production with simple and low-nutrient requirements. In summary, both systems have advantages and disadvantages, and selecting the appropriate system depends on the specific production needs.

Aquaponics has significant potential and adaptability for a wide range of production scenarios, from small family-run microfarms to large commercial operations. It can fulfill various economic and practical needs in urban settings, including agricultural production, green tourism, education, and personal use. Additionally, aquaponics has an educational function in many institutions, such as primary and secondary schools, colleges and universities, and community-based organizations. Even a small classroom system can offer diverse educational opportunities for different levels of learning (Graber et al., 2014). Furthermore, aquaponics is easily integrated into science, technology, engineering, and mathematics (STEM) disciplines, demonstrating not only fundamental biological and ecological principles but also principles related to chemistry, physics, and mathematics (Ranka et al., 2017). Additionally, aquaponics has been shown to foster system thinking and creativity (Ranka et al., 2017). In New York City, the greenhouse project aims to construct 100 rooftop greenhouses in public schools as science classrooms, introducing a novel approach to science education (Goddek et al., 2015). Urbanization trends predict that by 2050, 66% of the global population will reside in urban areas, necessitating innovative solutions for sustainable food production within cities. Aquaponics, with its advantages of reduced power consumption and efficient water recycling, is increasingly recognized as a viable option not only for rural environments but also for urban environments. The development of models such as the ICTA-ICP Rooftop Greenhouse represents significant progress in integrating aquaponics into urban planning (Sanyé-Mengual et al., 2014). Practical implementations, such as rooftop farms in The Hague by UrbanFarmers, demonstrate the feasibility of this approach in real-world settings (Ranka et al., 2017). Furthermore, photosynthesis reoxygenation aquaponics has shown promising results in enhancing urban food production, aligning with the goals of sustainable development in cities (Zhang et al., 2022). Despite the potential of various aquaponics models, further research is necessary to assess their economic viability, operational logistics, and environmental impacts, ensuring that they contribute effectively to sustainable urban ecosystems.

Conclusion

Aquaponics represents a promising solution to the challenges posed by global ecological change, urbanization, and the increasing demand for food. As arable land becomes insufficient to meet future population growth and rural populations continue migrating to urban areas, aquaponics offers a sustainable and scalable method of enhancing food security and local economic development.

The current models of aquaponics, including traditional, IAVS, NCSU, UVI, and NFT systems, each have distinct advantages and limitations. Traditional models provide simplicity and ease of setup but face challenges in scalability and efficiency. The IAVS model, with its minimal energy requirements, offers an eco-friendly solution but requires careful management to optimize results. The NCSU model is versatile and cost-effective and suitable for various scales but may present issues with clogging and labor intensity. The UVI model excels in large-scale production but is limited by high operational costs and complexity. Finally, the NFT model is efficient in space utilization and ideal for urban farming but demands a sophisticated filtration system and is sensitive to system failure.

Looking forward, the integration of AI and automation in aquaponics, as well as the development of decoupled systems, is expected to address some of these limitations, thereby enhancing the productivity and sustainability of aquaponics systems. Future research should focus on refining these models, understanding their economic and environmental impacts, and establishing industry standards to support their widespread adoption. Aquaponics has the potential to become a cornerstone of sustainable food systems, particularly in urban environments, as we move toward more resilient and circular agricultural practices.

Resumen

Y. Wang, Y. Yang, y J. Lu. 2024. Revisión de la Acuaponía: Concepto, Situación actual y Desarrollo. Int. J. Agric. Nat. Resour. 140-156. Ante el calentamiento global, la contaminación ambiental, el crecimiento demográfico y la degradación de la biodiversidad y los recursos naturales, las prácticas agrícolas sostenibles se han vuelto cruciales y deben ser exploradas y aplicadas. La acuaponía es un sistema agrícola que integra la acuicultura y la hidroponía para aplicar tecnologías agrícolas sostenibles. La biomasa rica en nitrógeno producida por la vida acuática se utiliza para alimentar los cultivos, mientras que el proceso de alimentación también actúa como un sistema de filtrado natural que mantiene el hábitat de la vida acuática. Este artículo divide la historia del desarrollo de la acuaponía en tres etapas: la etapa de origen (antes de la década de 1960), la etapa inicial (década de 1960-2010) y la etapa de desarrollo (después de la década de 2010). Se comparan y analizan cinco modelos típicos de acuaponía. Este documento sugiere que se estudie a fondo la teoría básica del sistema de acuaponía y se exploren las tendencias de desarrollo inteligente e industrial del sistema. Estos estudios pueden proporcionar pruebas suficientes y referencias concretas para las aplicaciones a gran escala de la acuaponía.

Palabras clave: Acuaponía, agricultura sostenible, modelos típicos, proceso histórico, tendencia futura.

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