INNOVATIONS IN AQUAPONIC SYSTEMS FOR SUSTAINABLE AGRICULTURE: A TRANSNATIONAL REVIEW

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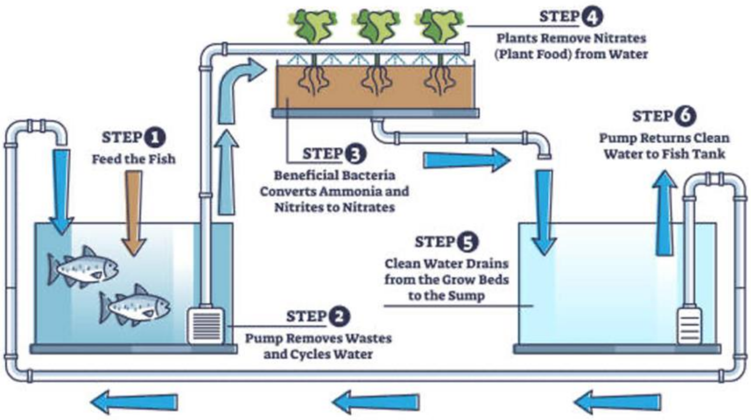
Abstract. *This article examines aquaponic systems, which represent an innovative agriculture method that combines aquaculture and hydroponic techniques with the purpose of growing vegetables, fish, and microorganisms. Also called "aquaponics", these systems are an environmentally friendly alternative to traditional agriculture, because they require less land, less water, close to no fertilizers and/or pesticides to ensure food production and food safety. The current review of 25 studies from the scientific literature aims to contribute to the understanding of recent innovations in aquaponic systems by providing a comprehensive analysis thereof. The goal is to help identify the best practices, challenges, and potential improvements in aquaponics. The analysis reveals that recent innovations in aquaponics encompass a multitude of aspects, including system design, operation, and the optimization of plant and fish growth. These innovations have expanded the feasibility of aquaponics, making it increasingly adaptable to diverse environmental conditions and production goals. The degree of novelty observed in recent aquaponic innovations underscores the dynamic nature of this field, with numerous ongoing efforts to address emerging challenges and opportunities. We conclude that the reviewed studies offer a valuable repository of knowledge, offering the potential to shape future research, guide practical applications, and influence policy decisions aimed at harnessing the full potential of aquaponic systems on a global scale.*

Keywords*: innovation, aquaponics, aquaculture, hydroponics, sustainability.*

INTRODUCTION

An aquaponic system is a sustainable and innovative food production approach that merges aquaculture, or the nurturing of aquatic animals, and hydroponics, which is the growing of plants without soil (RAKOCY, 2006). Aquaponics stands as an agricultural technique that utilizes a closed-loop water recirculation system (Fig. 1) to produce vegetables, fish, and microorganisms. In recent years, this method has surfaced as a promising substitute for traditional agriculture due to its potential to minimize environmental impact whilst ensuring food security. The aquaponic system efficiently produces both fish and vegetables without the necessity for vast land, water, fertilizers, or pesticides. Consequently, it serves as an ideal choice for situations where space and resources are scarce.

The working principle behind aquaponics revolves around a closed cycle in which fish waste present in the fish tank water is circulated to the biofilter medium, in which microorganisms



are responsible for converting fish waste filled with ammonia into nutrient forms readily accessible to plants, which in turn, through the extraction of nutrients, purify the water for the fish, creating a suitable environment for both (KÖNIG, ET AL., 2018). Aquaponics essentially allows plants to grow without soil while utilizing natural nutrients derived from fish. In this mutually beneficial system, constant water recirculation between fish farming and plant cultivation ensures that both activities are optimized, resulting in high-quality commercial produce.

Figure 1. Aquaponic system working principle.

This integrated approach can take many different configurations and, as such, is successfully employed in various countries, such as the United States, Australia, as well as in European nations. Notably, in Romania, while the three first operational aquaponic systems have been set up in Focsani, Snagov, and Timisoara (ROTARU ET AL., 2019). Research in this field is however becoming more extended in agronomy universities throughout our country, as well as in national research institutes, the National Institute for Research-Development of Machines and Installations for Agriculture (INMA, 2016) being a prime example. However, there is a lack of commercial aquaponic production reports.

The aim of this article is to explore current innovations in aquaponics internationally. The research focuses on the most recent advances in this area, as there is a global exponential increase of scientific studies on this topic. The purpose is to provide a comprehensive understanding of these developments, drawing on over 30 articles from the scientific literature.

MATERIAL AND METHODS

The approach to conducting this review was based on a set of objectives and a structured methodology. We began by accessing reputable scientific databases, including ResearchGate, MDPI, Science Direct, Springer, and Google Scholar, to identify articles relevant to our research inquires. A combination of keywords and phrases related to aquaponics was used in our search strategy. These included terms such as “aquaponics system”, “aquaponics”, “hydroponics”, “aquaponic design”, “aquaponic monitoring”, “automation of aquaponics" and others.

The initial search produced a substantial pool of potential articles, from which we carefully screened and selected those that best aligned with our research objectives. This rigorous screening process ensured that we focused our review on articles that were most likely to provide valuable information.

Subsequently, we retrieved the full texts of these selected articles and reviewed them thoroughly. During this phase, we extracted essential data, including research methodologies, findings, and key insights. The data extraction process was organized to ensure consistency across all reviewed articles.

RESULTS AND DISCUSSIONS

Innovations in aquaponic systems technology are continuously surfacing as researchers worldwide tackle the topic from different perspectives. This review includes studies regarding the nutrient cycle inside an aquaponic system, system design options, aquaponic system automation, sustainable sources of fish feed and others, aiming to highlight aspects that can be used to optimize aquaponics and make such systems even more sustainable globally.

- Designs of the hydroponic subsystem of an aquaponic system

As previously mentioned, an aquaponic system can take on different configurations. Those configurations mainly consist of the setup choice for the hydroponic subsystem. In other words, what differs is the way in which the plants are in contact with the water and/or the media bed. The media bed is the biofilter medium of the system, in which *Nitrosomonas* bacteria that convert ammonia into nitrites, and *Nitrobacter* bacteria that convert nitrites into nitrates, that the plants absorb from the water, through their roots (FRINCU ET. AL., 2016). The efficiency of an aquaponic system greatly depends on the understanding and management of the nutrient cycle within the system, *Nitrosomonas* and *Nitrobacter* bacteria being key drivers. This understanding of the nutrient cycle has also been supported by other studies (FEBRIANI ET AL., 2018, ECK ET AL., 2019).

In order to establish a comparative review between the different types of aquaponic systems, first it is necessary to illustrate them as such. Although hydroponic systems can function in many designs, some examples being the Deep Water Culture (DWC) or floating rafts setup, the Nutrient Film Technique (NFT) system, the drip system, the wick system, and others, the most utilized configurations in aquaponics are: the Nutrient Film Technique (NFT), the Deep Water Culture (DWC) system, and the Media-Bed system and shown in fig. 2.

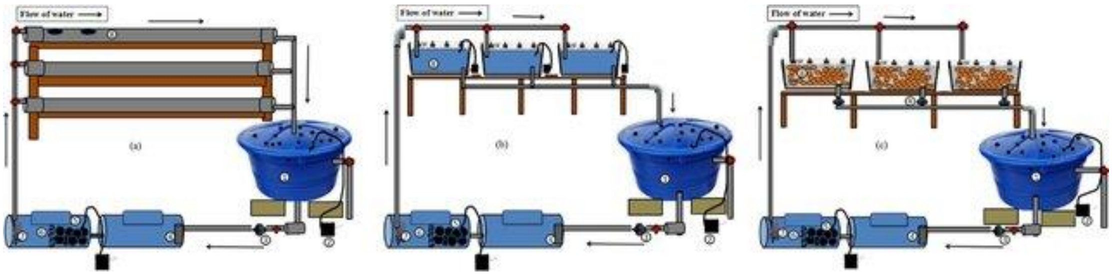


Figure 2. Aquaponic systems (a) Nutrient film technique (NFT), (b) Deep Water Culture (DWC), and (c) media bed (MBD) (Aquaculture International, 2022)

A Deep Water Culture (DWC) system, also called floating rafts system, is a type of hydroponic subsystem where plants are placed in a floating foam raft, made from Styrofoam or similar material, and their roots dangle into the nutrient-rich water below. It's an efficient system for growing leafy greens and herbs (LENNARD ET AL, 2006; QUÍ ET AL., 2020).

The media bed or gravel bed system is another type of hydroponic subsystem used in aquaponics. In this system, plants grow in a bed of inert media such as gravel or expanded clay pebbles. The bed serves as a biological filter, on which surface the bacteria act upon the fish waste and convert the ammonia into nutrients for the plants. This type of system is versatile and offers a great addition of physical support for the plants, allowing for the cultivation of a wide variety of plants, from leafy greens to larger plants like tomatoes, peppers, and even root vegetables (LENNARD ET AL., 2006; SIRAKOV ET AL., 2017).

The Nutrient Film Technique (NFT) uses a thin film of water filled with nutrients, which is recirculated over the roots of plants in a sloping trough. NFT is highly effective for growing smaller, fast-growing plants, but it might not be suitable for larger, fruiting plants. One of the advantages of NFT is that it uses water very efficiently, the flow rate being more easily manageable than in a DWC system, for example (LENNARD ET AL., 2006; ESTIM ET AL., 2019).

In a comparative analysis from 2006, Murray Cod fish and Green Oak lettuce were tested in three hydroponic subsystems: Media Bed, Deep Water Culture, and Nutrient Film Technique (NFT). All systems had similar results for Murray Cod. Lettuce yields were however best in the Media Bed subsystem, followed by DWC and NFT. NFT was less efficient at removing nitrates, but there were no differences in phosphate removal, dissolved oxygen, water replacement, or conductivity. In summary, NFT hydroponic subsystems are thus less effective at nutrient removal and plant growth compared to media bed and DWC systems in an aquaponic setup (Lennard et al. 2006).

A study conducted in 2022 aimed to determine the most suitable aquaponics system for rearing empurau (Tor tambroides) fish fries in a nursery. Four aquaponics systems were tested: nutrient film technique (NFT), deep water culture (DWC), media bed culture (MDB), and a newly designed combined aquaponics system (CAS). The empurau fries were stocked in the four systems along with two other carp species using a polyculture method. Growth, survival, specific growth rate (SGR), length-weight relationship, and condition factor of empurau fries were compared after 12 weeks. Leaf celery was grown. Results showed the NFT system performed significantly better than the others for empurau nursery based on growth and survival. The trend was NFT > DWC ≥ CAS > MDB. SGR of empurau was highest in NFT throughout. Length-weight relationship was also best fit in NFT. Condition factor indicated all systems provided a robust environment. Leaf celery growth was highest in NFT. A cost-benefit analysis found NFT to be the most profitable system. It was concluded that the NFT aquaponics system is most suitable for empurau fries nursery. The study showed that aquaponics can be effectively used for fish nursery management (WAN ALIAS ET AL., 2022).

Thus, it is difficult to affirm which subsystem is optimal for the overall efficiency of the aquaponic system as this choice is dependent on many variables ranging from the scale of the system to the type of plants and fish being grown, to the age, lifespan, and growth rate of the fish, to the specific environmental conditions that the fish and plants require and so on. Further comparative studies are necessary to draw conclusions on this matter.

- Coupled versus decoupled aquaponic system design

Aquaponics systems can also be categorized into coupled and decoupled systems (fig.3). Each of these designs has its unique working principles and advantages.

Coupled aquaponics systems follow a direct relationship between the aquaculture and hydroponics components. In these systems, water flows directly from the fish tank to the plant growing area. It is a simple, efficient, and usually cost-effective approach for small scale and hobbyist applications (BAGANZ ET AL., 2021). However, coupled systems can sometimes limit the flexibility in managing the growth conditions for fish and plants. For instance, to optimize plant growth, the nutrient levels might need to be increased, which can be toxic to the fish. Conversely, optimal fish growth might require water conditions that are less conducive to plant growth (KÖNIG, ET AL., 2018).

To overcome these limitations, the concept of decoupled aquaponics has been introduced. Decoupled systems operate the fish and plant components separately. This separation allows for more control over the different growth conditions for fish and plants, enabling farmers to optimize the conditions for each component independently. The decoupling is achieved by incorporating a water treatment step, which not only cleans the water before it returns to the fish tank but also enables the nutrient concentrations to be adjusted to optimal levels for plant growth (BAGANZ ET AL., 2021).

Decoupled systems are gaining popularity as they offer enhanced flexibility and control. They are particularly beneficial in commercial scale aquaponics, where optimizing the productivity of both fish and plants is crucial. Real-world applications of decoupled systems have been explored in various studies, showing a significant improvement in plant growth and yield (MONSEES ET AL., 2017; GODDEK ET AL., 2016).

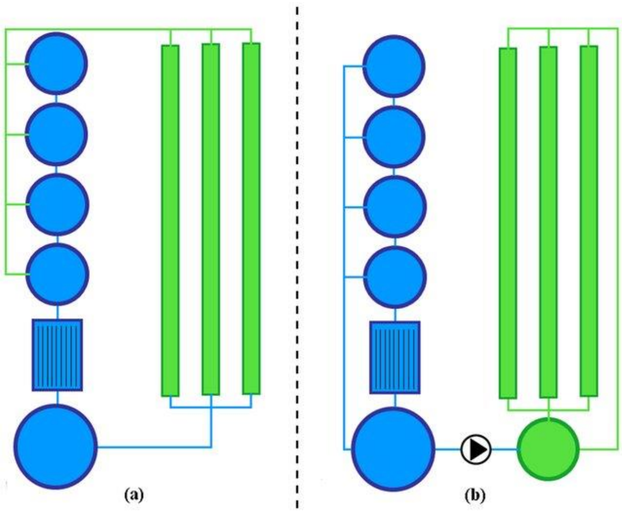


Figure 3. Schematic illustration of classical (coupled) and decoupled aquaponics. (a): Classical aquaponic system with a RAS (blue: rearing tanks, clarifier and biofilter) directly connected to the hydroponic unit (green: NFT-trays). (b): Decoupled aquaponic system consisting of a RAS connected to the hydroponic unit (with additional reservoir) via one-way-valve. (MONSEES ET AL. 2017)

In a pilot study comparing the production in a decoupled aquaponic system with a coupled system, it was found that the fruit yield was 36% higher in decoupled aquaponics. The pH and fertilizer management were more effective in the decoupled system, whereas the fish production was comparable in both systems (MONSEES ET AL., 2017).

These findings clearly illustrate the main advantages of decoupled, two-loop aquaponics, demonstrating how bottlenecks commonly encountered in coupled aquaponics can be managed to promote application in aquaculture. The results of this pilot study show how a decoupled system can provide a higher yield and more effective management of pH and fertilizers. Moreover, the decoupled system allows for better control of the production parameters for both fish and plants. It also makes it possible to adjust the nutrient solution as well as the temperature for each production unit, which can be compromised in coupled systems (MONSEES ET AL., 2017).

- Automation of aquaponic systems

Automation in the field of aquaponics represents a significant leap forward as it is capable to offer numerous advantages over traditional manual monitoring methods.

Aquaponic systems have a wide range of parameters that need to be monitored and controlled for optimal productivity. These parameters include factors like water temperature, pH, nutrient levels, electric conductivity (EC), water hardness, overall water quality. Traditionally, monitoring these factors required manual effort through constant laboratory tests of water samples, for example, which are time-consuming and potentially less accurate.

The advent of automation technologies has transformed this landscape. Automated systems can monitor these parameters in real-time and make immediate adjustments as needed. The real-time monitoring and control systems not only improve productivity but also significantly reduce the need for constant manual intervention, saving both time and effort (YANES REYES ET AL., 2020; VERNANDHES ET AL., 2017). For instance, an automated system can adjust pH levels in the system based on real-time readings, ensuring optimal conditions for fish and plant health. In contrast, manual monitoring might only occur at set intervals, potentially missing sudden changes in pH that could gravely affect the system (YANES REYES ET AL., 2020).

Furthermore, automation technologies often come with data logging features, allowing for the continuous recording of conditions over time. This data can provide valuable insights into trends and potential issues, aiding in informed decision-making and proactive management of the system. Such capabilities are typically beyond the scope of manual monitoring methods (OOMMEN ET AL., 2019; AUTOS ET AL., 2020).

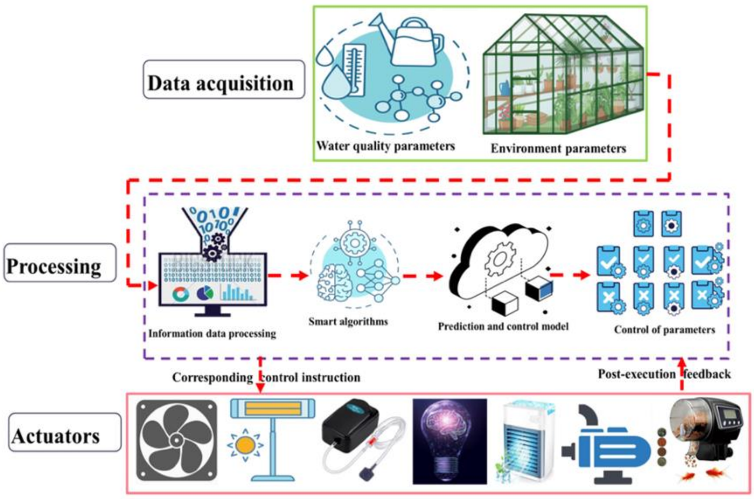


Figure 4. Schematic diagram of detection and control system for aquaponics (Taha et al. 2022)

The study by TAHA ET AL. (2022) provides an extensive review and analysis of the application of smart systems and Internet of Things (IoT) technology to aquaponics (fig.4). The study emphasizes how automation and IoT technologies can significantly enhance the efficiency and productivity of aquaponics systems, making real-time data collection and proactive decision-making possible. For instance, the study highlights the use of artificial intelligence (AI) and deep learning (DL) methods for predicting water quality parameters, detecting and classifying fish species, estimating fish size, making feeding decisions, and detecting plant growth. The paper discusses the future of smart aquaponics in the context of Industry 4.0, highlighting how technologies like Supervisory Control and Data Acquisition (SCADA), Enterprise Resource Planning (ERP), and Manufacturing Execution System (MES) can be integrated with IoT to further optimize aquaponic operations.

While automation technologies represent an upfront investment, the potential improvements in productivity and efficiency, coupled with the savings in time and effort, make them a worthwhile investment. Studies show that such optimizations could lead to a 50% reduction in labor costs and achieve a 20% increase in productivity compared to manually monitored systems (YANES REYES AT AL. 2020).

- Sustainable fish feed made from yeast

In aquaculture, the cost of fish feed can represent over 50% of the operational cost. Therefore, finding high-quality feed at a reasonable price is a significant challenge for many commercial farmers. Moreover, traditional fish feed often relies heavily on fishmeal and soy derivatives, raising sustainability and ethical concerns. Studies suggest that yeast could be a solution to this problem, capitalizing on non-food lignocellulosic biomass as valuable protein resources (DUMITRACHE ET AL., 2022; ØVERLAND ET AL., 2016). Thus, fish feed derived from yeast is an emerging approach that is contributing significantly to the optimization of aquaponic systems. Yeasts are rich in vitamins, especially B-group vitamins, and can produce microbial proteins, β-glucans, and mannans (DUMITRACHE ET AL., 2022). Table 1 shows how yeast integration into fish feed affects the fish growth rate, according to multiple scientific literature references on the topic (DUMITRACHE ET AL. 2022).

Table 1

Effect of different diets containing some levels of yeast on fish growth performance (Dumitrache et al. 2022)

Yeast	**Yeast supplemented (%)**	**Crude protein (%)**	**Crude lipid (%)**	**Ash (%)**	**Daily growth coefficent (% day^{-1})**	**References**
Saccharomyces cerevisiae	0÷5	34.37÷37.78	5.21÷5.39	7.26÷7.52	1.9÷3.75	Xiang et al., 2017
Saccharomyces cerevisiae	0÷40	26.3÷27.4	10.3÷11.9	8.5÷10.2	1.02÷2.08	Ozório et al., 2012
Saccharomyces cerevisiae	0÷100	34.5÷37.07	3.48÷6.2	9.36÷9.89	1.81÷5.64	Solomon et al., 2017
Saccharomyces cerevisiae + Wickerhamomyces anomalus	40÷60	46÷53	1÷6	5÷10	1.1÷1.3	Huyben, 2017
Saccharomyces cerevisiae	0÷2	31÷31.18	-	8.72÷8.86	3.75÷5.16	Essa et al., 2011
Saccharomyces cerevisiae	0÷45	37.31÷37.49	7.92÷7.99	2.93÷3.44	3.08÷4.96	Gumus et al., 2016
Saccharomyces cerevisiae	0÷15	30.28÷31.13	7.55÷7.98	10.46÷11.56	1.08÷2.23	Banu et al., 2020
Saccharomyces cerevisiae	0÷24	37.46÷38.92	8.3÷8.6	6.1÷7.4	3.5÷4.5	Guo et al., 2019
Saccharomyces cerevisiae	20÷50	41.5÷43.1	11.4÷13.0	7.9÷9.9	-	Rosale et al., 2017
Saccharomyces cerevisiae	7.5÷50	35.21÷35.82	6.47÷7.20	9.05÷10.60	2.21÷2.46	Omar et al., 2012

The exploration of yeast strains enhanced with probiotics presents an even more exciting frontier. The study by DIGUȚĂ, MIHAI, ET AL. (2023) investigated the probiotic potential of three yeast strains—BB06, OBT05, and MT07—sourced from natural agro-food environments. The in vitro assessment demonstrated promising results, suggesting that these yeast strains could play a significant role as probiotics in aquaculture applications. Another study showed that fish growth was enhanced through the application of a commercial probiotic mixture in aquaponics (KASOZI ET AL., 2021). Similarly, probiotic-enhanced yeast feed led to improved growth performance and survival of *Hemibagrus nemurus* in an aquaponics system (YOSMANIAR ET AL., 2022).

Interestingly, the benefits of probiotic-enhanced yeast feed extend beyond the fish component of the aquaponic system, positively impacting plant growth and health. The addition of probiotics to the fish component of the system rather than directly to the plant component was found to yield superior effects on plant growth and health (JOYCE ET AL., 2019).

While promising, further research, particularly in vivo assessments, are necessary to validate these findings. Such studies can provide deeper insights into how probiotics influence fish and plant growth and health in aquaponic systems.

CONCLUSIONS

In conclusion, our comprehensive review of recent innovations in the field of aquaponics has identified several promising advancements. These include innovative designs of the hydroponic subsystems, the superiority of decoupled aquaponic systems over coupled aquaponic setups, the integration of automation through Internet of Things (IoT) and machine learning, and the use of organic, probiotic-enhanced yeast as a sustainable fish feed source.

The comparison of the hydroponic subsystem designs in an aquaponic system have hinted to significant advancements, with designs becoming more efficient and effective in supporting plant growth and health, even if design choice is heavily dependent on many variables and differs from case to case. Meanwhile, the comparisons between coupled and decoupled aquaponic systems have clearly shown that decoupled aquaponics systems offer superior control over the separate aquaculture and hydroponics subsystems, enabling optimal growing conditions for both fish and plants.

The integration of IoT systems and machine learning into aquaponics has the potential to automate and optimize various processes within the system, enhancing efficiency, productivity, and sustainability. These steps forward reduce the need of manual labor - the latter consisting of manual monitoring and testing of samples in laboratories - as well as increase parameter monitoring precision and auto-regulation, leading to an overall enhancement in production yields.

The exploration of sustainable fish feed sources has led to the discovery of the promising potential of organic yeast. When enhanced with probiotics, this yeast can significantly boost fish and plant health and growth, presenting an exciting avenue for future research and application.

Despite these innovations, it's crucial to note that research in the field of aquaponics, while growing, is still in its nascent stage. Many of the studies conducted so far have been on a small scale, and there is a pressing need for more large-scale, robust studies to validate these findings and build trust in the sector. This will be a key factor in driving the adoption of aquaponics in commercial projects worldwide, thus paving the way for this sustainable method of food production to become more widely implemented.

Moreover, the organic nature of aquaponics, which doesn't require fertilizers and pesticides due to its ideally isolated and controlled environment, makes it an attractive alternative to traditional methods of food production. This is particularly relevant as environmental changes make traditional food production methods increasingly challenging.

In summary, while we have seen encouraging innovations in aquaponics, there is significant scope for further research and development. As we continue to push the boundaries of what is possible in this field, aquaponics holds the promise of a sustainable, efficient, and organic solution for food production on a global scale.

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