CHAPTER II
REVIEW OF LITERATURE

This chapter deals with the reviews of previous research works in aquaponics carried out by researchers, scientists and published through peer reviewed journals. It comprises of review of soilless culture, aquaponics overview, water quality management, automation, IoT integration, and evaluates aquaponics systems in terms of crop yield, water quality.

2.1 SOILLESS CULTURE

Schwarz (2012) discussed the potential benefits of soilless systems, such as reduced water usage and the ability to cultivate crops in non-arable areas. The FAO has promoted these methods globally, particularly in regions with limited soil quality, emphasizing the importance of managing nutrient levels, pH, and water quality for optimal plant growth.

Putra and Yuliando (2015) highlighted the significance of closed-loop soilless cultivation systems, which enhance water use efficiency and improve crop quality. These systems offer precise control over growing environments, including nutrient delivery and the root zone, leading to higher yields and better-quality products. Moreover, they minimize environmental impacts by reducing water waste and nutrient runoff, making them a sustainable approach to modern agriculture.

Savvas and Gruda (2018) reviewed the application of soilless culture technologies in modern greenhouse farming. They focused on hydroponics, a subset of soilless culture, which uses nutrient solutions instead of soil. These systems offer better control over nutrients, water efficiency, and the ability to grow crops in poor soil conditions. However, it also discussed the challenges like the need for precise nutrient management and the high initial costs of setup.

Fussy and Papenbrock (2022) discussed the increasing scarcity of fertile soil and clean water, which makes conventional agriculture more challenging. Soilless cultivation systems, such as hydroponics, aquaponics, and vertical farming, address these issues by saving water and enabling plant growth without soil. These systems also allow for urban food production, including rooftop farming. The authors assessed the economic viability, sustainability, and environmental impacts of these systems, comparing them to traditional farming methods and highlighting their potential for more efficient, localized food production.

2.2 OVERVIEW OF AQUAPONICS SYSTEMS

Rakocy *et al*. (2004) conducted an experiment on a commercial-scale aquaponics system in the tropics on 0.05 ha of land, concentrating on the use of batch and staggered cropping strategies for the production of basil and tilapia. 4.37 t of tilapia were expected to be produced annually by the batch system. The yields of basil were 0.6 kg m^{-2} for field cropping, 2.0 kg m^{-2} for batching, and 1.8 kg m^{-2} for staggered. With staggered cropping, 5 t of basil were produced annually. The only basil that showed nutrient deficits was batch-cultured. For batch production, the feed input ratio was 81.4 g day^{-1} m^{-2}, while for staggered production, it was 99.6 g day^{-1} m^{-2}. Moderate nutrient intake was aided by staggered production.

Goddek *et al*. (2015) recognized aquaponics as a promising solution to global challenges like water scarcity, soil degradation, and food security. While it offers sustainable nutrient and water reuse, further research is needed to address technical, socio-ecological, and economic challenges. Improvements are required in nutrient recovery, pest management, water consumption, energy use, and pH stabilization. Aquaponics systems must be adaptable to various climates, and interdisciplinary research is essential for optimization. Despite cost advantages, rising energy and fertilizer prices and environmental policies are expected to enhance aquaponics' competitiveness.

Khater and Ali (2015), focused on combining fish and vegetable production in a sustainable, closed-loop system. The research demonstrated that fish waste provided essential nutrients for plant growth, particularly nitrogen (15-25 mg L^{-1}) and phosphorus. By increasing the length of the gully (2, 3, and 4 meters), changing the flow rates (1.0, 1.5, and 2 L min^{-1}), and examining the source of nutrients (fish farm waste and stock nutritional solution), the study examined the effectiveness of aquaponics systems. It was found that both the flow rate and the length of the gully negatively affected nutrient uptake, as well as fresh and dry weights of shoots and roots. Nutrient solution resulted in higher nutrient uptake, fresh weight of shoots (by 8.09%), and dry weight of shoots and roots (by 11.64% and 6.68%, respectively) compared to effluent fish water. The nitrate-N content was also higher in plants grown in nutrient solution, by 110.79%. Optimal flow rates were identified as 1.5 L/min for 2 m and 3 m gully lengths, and 2 L min^{-1} for 4 m length.

Bailey and Ferrarezi (2017) analyze the UVI (University of the Virgin Islands) commercial aquaponics system, which integrates fish and vegetable production in a recirculating aquaculture setup to optimize land use, conserve water, and recycle nutrients. The system, designed for tilapia production, yields 5 MT annually and features hydroponic troughs with a surface area of 214 m^2 and a water flow rate of 125 L min^{-1}, ensuring a retention time of 3 hours. pH is maintained at 7 using calcium and potassium hydroxide, and chelated iron (2 mg L^{-1} Fe) is added every three weeks. The study emphasizes the economic evaluation of crops, enabling farmers to prioritize high-value crops while balancing market demand. This system demonstrates the potential for efficient, sustainable, and profitable aquaponics farming.

Da Rocha *et al.* (2017) compared lettuce production in hydroponic, aquaponics (Aqua), and aquaponics with bioflocs (Aqua-BF) systems using silver catfish. The study found that lettuce productivity was significantly higher in Aqua and Aqua-BF compared to hydroponics, with no major differences between Aqua and Aqua-BF in terms of plant growth or fish performance. Lettuce was stocked at 20 plants m^{-2}, and water quality varied among systems, with Aqua-BF showing higher ammonia, nitrite, and turbidity, while hydroponics had higher dissolved oxygen and lower pH. The Aqua and Aqua-BF systems demonstrated potential for integrated fish and vegetable production, suggesting that bioflocs could enhance productivity, though further optimization is needed.

Maucieri *et al.* (2017) studied an aquaponics system producing Pangasianodon hypophthalmus, with Cichorium intybus (red chicory) and Lactuca sativa (lettuce) interplanted in the hydroponic area. The study, which used the nutrient film method (NFT) and nine small-scale systems (400 L each) in a greenhouse, showed no discernible effects of intercropping on water quality metrics like temperature, pH, and EC. However, intercropping with red chicory increased the sugar content of lettuce, enhancing glucose and fructose levels by 16% and 25.3%, respectively. Lettuce also showed higher organic nitrogen content compared to red chicory. This suggests that intercropping can improve vegetable quality, enhancing the nutritional and sensory attributes of aquaponically grown produce.

Danner *et al.* (2019) studied the integration of aquaponics in small-scale greenhouse farming in Iceland, focusing on economic viability and sustainability. Using tilapia and leafy greens like pakchoi, they achieved a fish feed conversion ratio (FCR) of 0.9-1.2 and a plant-to-fish production ratio of 4:1. The study highlighted the benefits of Iceland's long summer daylight, increased nitrate and phosphate concentrations for better yields, and recommended commercial NFT systems for efficiency. They also emphasized the importance of filtration, decoupled system designs, and diversifying production to enhance sustainability and value.

Mohapatra *et al.* (2020) created and conducted a 90 day trial of a portable NFT aquaponics system at ICAR-CIFA in Bhubaneswar. A 200 L HDPE sump, a 2.64 m^2 FRP hydroponics tank, a 100 L polypropylene biofilter, and a 2800 L FRP fish culture tank were among the system's essential parts. The system included a specially made automatic water recirculation system that used gravity for 75% of the cycle and had an average flow rate of 94.7 L h^{-1}. 54 pangas fish fry and 27 marigold plants per square meter were added, resulting in a 77.04% increase in fish length and a 397.2% increase in weight, as well as 107 marigold flowers harvested per m^2. Additionally, the biofilter achieved a 61.97% reduction in Total Ammoniacal Nitrogen (TAN), demonstrating the system's effectiveness in nutrient management and plant growth.

Oladimeji *et al.* (2020) evaluated the effectiveness of a catfish-pumpkin aquaponics system and contrasted it with traditional methods, such as irrigated and nonirrigated land for pumpkin cultivation and recirculatory and static aquaculture for fish production. According to the study, the aquaponics system outperformed recirculatory and static aquaculture by 29% and 75%, respectively, and the higher fish survival rate was probably caused by the higher water quality. The aquaponics system performed five times better than irrigated land and eleven times better than nonirrigated land in terms of pumpkin yield. This study proves that aquaponics is more effective than traditional food production techniques.

Colt *et al*. (2022) provided a comprehensive analysis of the engineering principles involved in the design of aquaponics systems, focusing on optimizing system performance and sustainability. The study highlights critical aspects such as water quality management, system hydraulics, and energy efficiency to ensure the effective integration of aquaculture and hydroponics. Specific recommendations include maintaining dissolved oxygen levels above 5 mg L^{-1} for fish health and using biofilters with a surface area of at least 300 m^2 m^{-3} to support adequate nitrification. The importance of maintaining balanced nutrient flow was highlighted, with recommended nitrate concentrations of 40-100 mg L^{-1} to support optimal plant growth. Additionally, the use of energy-efficient pumps and aeration systems was emphasized to minimize operational costs.

Kralik *et al*. (2022) investigated the effects of aquaponics on the sensory, quality, and safety attributes of tomatoes (Solanum lycopersicum) compared to soil-grown counterparts across three years. The study analyzed two tomato varieties for physical composition, sensory characteristics, and pathogen presence. While aquaponics tomatoes were generally lighter and yellower in color with lower brix levels, differences in sensory attributes, such as taste and texture, were inconsistent across years and varieties. Iron supplementation improved nutrient deficiencies, but overall, consumer acceptance remained comparable between aquaponics and soil-grown tomatoes. The study confirmed minimal E. coli risk in aquaponics tomatoes, demonstrating that aquaponics systems can produce safe and consumer-acceptable products.

2.2.1 Aquaculture

Subasinghe *et al*. (2009) highlight fastest-growing industry in food production is aquaculture, which is essential to supplying the growing demand for aquatic food worldwide brought on by stagnant catch fisheries. The sector's growth is influenced by intensification, diversification, market demands for safe, high-quality products, and improved governance. Sustainable aquaculture development relies on farmer participation, self-regulation, and better management practices. The study underscores aquaculture's potential to contribute to sustainable development, poverty reduction, and global food security while addressing challenges through innovation and responsible practices.

Integrated Multi-Trophic Aquaculture (IMTA) is a practice where the waste from one species serves as a nutrient source for another. This system combines finfish and shrimp farming with shellfish, herbivorous fish, and marine algae. Polyculture allows for the co-cultivation of different fish species at the same trophic level (Nelson and Pade, 2008).

Freshwater finfish, especially species of carp from China and India, dominate global aquaculture production, followed closely by molluscs. Although some groups, like shrimp and marine fish, contribute less in terms of volume, they hold significant economic value due to their high market prices. Silver carp and Pacific cupped oyster have been among the most harvested species in recent years. By 2006, 51.7 million tons, or about 50%, of the world's fisheries production came from aquaculture (FAO, 2010).

Dhenuvakonda and Sharma (2020) highlighted the potential of mobile applications and IoT technologies in transforming the Indian fisheries and aquaculture sector. Their study emphasized that real-time monitoring, data-driven decision-making, and automation through IoT can enhance productivity, reduce manual labor, and ensure timely interventions. The integration of these technologies was found to improve fish health management, optimize feeding practices, and support sustainable aquaculture practices. This underscores the relevance of IoT-based solutions in modern aquaponics systems.

2.2.1.1 Fish selection

Diver, 2006 stated that, choosing fish for an aquaponics system depends on the local climate and the temperature that can be maintained, as well as the legal specifications set by local fisheries departments regarding native species.

Consumer preferences and the availability of fish feed also influence this choice. Tilapia, trout, perch, and Arctic char are just a few of the many freshwater fish species that can be raised in recirculating aquaculture systems, both warm- and cold water. Rakocy *et al*. (2006) concluded that, the hybrid striped bass, however, does not thrive in aquaponics systems due to its inability to tolerate high potassium levels, which are commonly used as plant growth supplements.

Tilapia (Tilapine cichlid) is the most commonly cultivated fish in aquaponics due to its hardiness, rapid growth, and popularity as a food fish. It thrives in temperatures around 23.5°C, which aligns well with the optimal conditions for many vegetable crops in aquaponics systems. Tilapia's resilience to varying water quality makes it an excellent choice for aquaponics farming (Nelson and Pade, 2008).

Nelson (2017) suggested suitable fish species include bluegill, largemouth bass, channel catfish, koi carp, goldfish, barramundi, Murray cod, jade perch, crappies, rainbow trout, common carp, and Asian sea bass. Some ornamental fish also adapt well to commercial feeds and crowded conditions.

A number of fish species, such as bass, tilapia, trout, perch, and Arctic char, are suitable for recirculating aquaculture systems. Specifically, tilapia requires temperatures ranging from 15.5°C to 32°C, reaches a mature size of about 0.68 kg in 9 to 12 months, and has low oxygen needs. Trout, on the other hand, thrives in cooler temperatures (1.6°C to 20°C), matures at 0.36 kg in approximately 12 months, and requires high oxygen levels. Catfish can tolerate temperatures from 1.6°C to 35°C, reaching maturity at 0.56 kg in 12 to 18 months (Ani *et al*., 2022).

2.2.1.2 Feeding Practices for Tilapia

Tilapia are omnivorous fish that thrive on well-balanced commercial feed, containing essential nutrients such as amino acids, proteins, fats, vitamins, minerals, and carbohydrates. In natural habitats, tilapia feed on algae, which are low in protein, and small animals like worms, which provide higher protein content. In this aquaponics system, commercial feed pellets were preferred for optimal growth, as they provide a controlled and nutrient-dense diet. Unlike wild fish, aquaculture-raised tilapia required less food since they expend minimal energy searching for food. This controlled feeding not only supports fish growth but also helped regulate nutrient input into the aquaponics system. In recirculating systems, feeding rates were determined as a percentage of the fish's average body weight, decreasing as the fish grow larger (Riche and Garling, 2003).

In aquaponics systems, tilapia grow best when fed three times a day, offering them an amount they can consume in 30 minutes (Rakocy *et al.*, 2004), with feed containing around 32% protein. Experts in aquaponics suggest simplifying the process of calculating daily fish feed by focusing on empirical values based on the area of the hydroponic grow bed, rather than determining amounts per tank based on average fish weight. This approach helps to estimate the number of fish the system can support and the corresponding volume of water needed. It’s important to avoid overfeeding, as this can lead to uneaten food that compromises water quality, lowers feed efficiency, affects fish health, and increases costs.

2.2.2 Hydroponics

Hydroponics is a technique that eliminates the need for soil by growing plants in a nutrient-enriched water solution, according to Fumiomi (1997). Compared to conventional soil culture, this approach enables plants to focus energy that is often used for root growth on vegetative growth and fruit production, leading to faster growth rates and larger yields. Compared to plants grown in soil, plants cultivated hydroponically can grow 30-50% faster and yield three-four times as much. Additionally, the technology enables for high-density planting, with space savings of up to 90% compared to conventional soil farming.

The soilless cultivation technique known as hydroponics uses a water solution to supply nutrients to plants. While aggregate systems employ inert media such as expanded clay, perlite, and vermiculite, common systems include the NFT, floating rafts, and non-circulating water culture. Nutrients are supplied through fertigating, with soluble fertilizers like calcium nitrate (typically 15.5% nitrogen and 19% calcium) and other minerals. For organic hydroponics, fertilizers such as fish hydrolysate are gaining popularity. Controlled nutrient delivery and environmental adjustments in greenhouses are critical for successful hydroponic systems (Diver and Rinehart. 2000).

Siswanto and Widoretno (2017) designed and constructed a hydroponic system incorporating both semi-continuous and continuous nutrient cycling methods. The nutrient film technique (NFT) and an ebb and flow system were used in the system, which was constructed using polyvinyl chloride (PVC) pipes. The system used pipes with a 4° slope that were 197 cm long and 16 cm in diameter. In the semi-continuous system, nutrients flowed four to six times daily for ten minutes, based on plant needs and evapotranspiration, while the continuous system provided a constant nutrient flow at a maximum rate of 13.7 L s^{-1}. The design was adaptable for 24-hour irrigation, allowing independent flow rate adjustments for each pipe, making it suitable for diverse hydroponic applications.

Substrate selection plays a crucial role in aquaponics, affecting plant growth by providing structural support and a medium for microbial nutrient conversion. Jordan *et al.* (2018) conducted an experiment to assess how four different growing substrates affect the yield of lettuce in aquaponics systems. Four treatments-coconut shell fiber with crushed stone, expanded vermiculite, zeolite, and phenolic foam, each with six duplicates were used in the randomized block design study. The results showed that whereas crushed stone and coconut shell fiber provided the maximum output (39.9 t ha^{-1}), phenolic foam was the least effective, yielding just 20.8 t ha^{-1}. These results demonstrate how crucial substrate properties are to maximizing lettuce output in aquaponics systems.

Chowdhury *et al.* (2020) designed an automated indoor vertical hydroponic system tailored for Qatar's harsh desert climate. The system, suitable for small indoor spaces, was controlled by a microcontroller to automate environmental conditions and monitored via an IoT platform for real-time updates and minimal human intervention. It consumed 120.59 kWh of energy (13.26 QAR) without air conditioning and 230.59 kWh (25.36 QAR) with it. Monthly, it circulated 104,000 gallons of nutrient solution while consuming only 8-10 litres of water, demonstrating exceptional water efficiency. This system offers a sustainable solution for localized food production in arid regions and contributes valuable insights for advancing indoor farming technologies.

Nandhini *et al.* (2023) proposed an IoT-based automated nutrient management system for vertical hydroponics, aimed at enhancing indoor cultivation efficiency. Mint was grown in the system, where fluid parameters like pH and EC were continuously monitored and regulated. The system demonstrated a water use efficiency of 43.46 kg/m^3 and nutrient use efficiency of 2.83 kg/kg. Their findings indicated that the integration of automation significantly improved resource utilization, making the system well-suited for high-value crop cultivation in space-constrained urban settings, supporting sustainability and profitability.

Integration of aquaculture and hydroponics into cohesive aquaponics models presents unique challenges that are still underexplored. Recent research highlights that balancing nutrient concentrations, maintaining optimal water quality, and ensuring the health of both fish and plants are complex tasks requiring comprehensive strategies. For instance, Rodgers *et al.* (2022) demonstrated that supplementing nutrients in decoupled aquaponics systems significantly enhanced basil performance, underscoring the need for tailored nutrient management approaches in integrated systems. This gap underscores the necessity for further interdisciplinary research to develop sustainable and efficient aquaponics systems that can reliably produce both aquatic and plant-based food sources.

2.2.2.1 Media Bed Technique (MBT)

The media bed technique involves completely filling the grow bed and then draining it on a timed schedule. Regular cleaning of the media bed is necessary, as it does not facilitate solids removal. Among the three aquaponics system types, this method tends to yield the lowest production levels. Over time, the organic matter in the media can lead to clogging, which may create anaerobic zones that can hinder plant growth or even harm plant roots. A depth of 30 cm is typically recommended for media beds, with common depths ranging from 18 to 30 cm. A deeper bed, such as one that is 30 cm deep, can support a greater population of beneficial bacteria responsible for converting ammonia to nitrates.

Additionally, solids tend to decompose and sink to the bottom of a deeper bed, so regular emptying is not necessary. (Nelson and Pade, 2008).

Dutta *et al.* (2016) described media bed systems are cost-effective to build and are well-suited for small-scale or home production. They are versatile and can accommodate multiple crops, making them ideal for garden-style aquaponics. These arrangements, called gravel bed systems, use containers that are filled with expanded clay or another porous rock medium that absorbs air and water. While water from the fish tank flows through the containers, giving the plants vital nutrients, seedlings are put straight into this medium. The rocks in this system serve as a biological filter and a solids-trapping mechanism.

2.2.2.2 Nutrient Film Technique (NFT)

The Nutrient Film Technique (NFT) is a widely used method in hydroponic production, where plants are grown in channels that continuously pump nutrient solution. The lowest portions of the plant roots should ideally be in contact with the nutritional solution. while the tops remain moist but not overly saturated. Comparisons of lettuce yields among gravel, faceting, and NFT hydroponics have indicated that the NFT system is less efficient than gravel bed or floating raft systems. This inefficiency arises from the reduced contact time between roots and water in NFT systems, resulting in poorer nitrate removal (Lennard and Leonard, 2006).

Castillo-Castellanos *et al.* (2016) designed and tested an experimental NFT type aquaponics system for growing Carolina cucumber (*Cucumis sativus*) and Parris Island lettuce (*Lactuca sativa*) with tilapia (*Oreochromis niloticus*). The system, which excluded a sump pump, operated efficiently with no significant issues during the production cycle. Tilapia had specific growth and food conversion ratios of 4.95 and 0.99, respectively, and a survival rate of 97.2% ± 2.4%. While lettuce yield (wet/dry weight) was higher in hydroponics ($p < 0.05$), cucumbers showed higher fruit yield in hydroponics ($p < 0.05$). These findings highlight the NFT aquaponics system's effectiveness for fish growth and the potential of hydroponics for higher plant yields.

2.2.2.3 Deep Water Culture (DWC)

Saaid *et al*. (2013) developed an automated microcontroller system to control a hydroponic Deep Water Culture (DWC) system. The system ensures continuous nutrient delivery to plant roots by maintaining proper water levels and oxygenation. pH levels in the nutrient solution are automatically controlled using a pH sensor and a solution mixer, while water levels are monitored and adjusted through a level control system. The system needed 5.64 mL of acidity and alkalinity adjustments for every 0.312 and 0.244 pH changes, respectively, according to experiment. demonstrating its efficiency in maintaining optimal growing conditions for plants with minimal intervention.

DWC is the most common method used in large commercial aquaponics, typically growing a single crop such as lettuce, salad leaves, or basil. This method is well-suited for mechanization. The system operates by allowing plants to float on the water's surface, with their roots submerged in the water below. Long channels hold water at a depth of approximately 30- 40 cm, and floating boards made of Styrofoam or plastic support the plants. Plants can be transplanted from other growing places or sown directly into the net pots, which are made possible by holes made in the boards. With this technique, the roots stay submerged in the nutrient-rich water underneath all the time. (Dutta *et al*., 2016).

2.2.2.4 Vertical system

Khandaker and Kotzen. (2018) found that aquaponics, which integrates fish and vegetable cultivation in a recirculating system, can enhance sustainability by allowing more plants to be grown per square meter compared to traditional agriculture. To reduce spatial requirements, they investigated the integration of living wall and vertical farming technologies. The study revealed that a pot system improved management efficiency, with horticultural grade coconut fiber and mineral wool outperforming other substrates in vertical aquaponics systems. Nutrient-rich water is circulated from the fish tank to the tops of these vertical columns by a pump. This setup is typically enclosed, resulting in minimal waste and eliminating the need for fertilizers or pesticides.

2.2.2.5 Plants adapted to aquaponics

Plant selection for aquaponics depends on fish stocking density and nutrient availability in the effluent. Leafy greens such as lettuce, spinach, chives, basil, and watercress, with low to medium nutrient requirements, are ideal for aquaponics systems. Other greens like Swiss chard, Pak Choi, and Chinese cabbage are also suitable due to reduced pest issues. Tomatoes, bell peppers, cucumbers, and other fruit-bearing crops thrive in systems with high fish stocking densities and have greater nutrient requirements. Greenhouse tomato varieties adapt well to low-light and high-humidity conditions (Rakocy *et al*., 2006).

Aquaponics systems face challenges with nutrient deficiencies, particularly iron (Fe), impacting plant growth. Tsoumalakou *et al*. (2023) evaluated spinach (*Spinacia oleracea*) co-cultivated with red tilapia under three treatments: no supplementation, Fe supplementation, and Fe+ potassium (K). Control plants exhibited Fe deficiency, chlorosis, and stunted growth, while Fe-treated plants showed improved photosynthesis, chlorophyll content, and yield. The study concluded that Fe supplementation alone effectively enhances spinach growth in aquaponics without affecting fish growth.

2.3 WATER QUALITY MANAGEMENT IN AQUAPONICS

Nelson (2004) reported that the pH of tank water also affects the solubility of other substances, some of which, like ammonia, can be toxic to fish. At neutral pH (7), less toxic forms of these compounds dominate. Most fish thrive at a pH of 7.5 to 8.0. Tilapia can tolerate a wide pH range (5 to 10), with optimal functioning between pH 6 and 9. In a recirculating aquaculture system with a biofilter, the pH of the fish tank must also support the nitrifying bacteria in the biofilter. Aquaponics plants prefer a pH of 6.0 to 6.5, while nitrifying bacteria thrive best at pH 6.8 to 9.0. Therefore, a compromise pH of 6.5 to 7 is often maintained. In aquaponics, tilapia are typically raised at temperatures between 22.2 and 23.3 °C, which suits the needs of the fish, nitrifying bacteria, and plants, as plants tend to perform better at slightly lower temperatures.

Rakocy *et al*. (2006) highlight the need to maintain a pH range of 6.4-7 to support both fish (optimal at 7-7.5) and plants (optimal in the mid-6 range) in aquaponics. Ideal temperatures around 26.7°C enhance both growth and dissolved oxygen levels, despite reduced oxygen solubility at higher temperatures. Nitrite is efficiently converted to nitrate, with biofiltration typically keeping nitrate levels well below the harmful range of 300-400 mg L^{-1}. Key parameters for optimal system performance include temperature, dissolved oxygen, and ammonia control.

Different tilapia species require specific temperature ranges for optimal growth; none can survive below 10°C. And ammonia, a byproduct of fish waste, can be highly toxic when it accumulates in culture water. Tilapia can remain healthy with ammonia concentrations between 0.00 and 0.04 mg L^{-1} (Nelson, 2008).

The unionized form (NH_3) is highly toxic to fish and other aquatic life, while the ammonium ion (NH_4^+) is much less harmful. Also low oxygen levels should be avoided in aquaponics systems, and aeration should be implemented to maintain optimal DO concentrations. While tilapia can survive short periods with DO levels as low as 0.5 mg L^{-1}, they prefer a range of 3 to 10 mg L^{-1}, with ideal growth occurring at levels above 5.0 mg L^{-1} (Love *et al*., 2015).

Estim *et al*. (2019) demonstrated the effectiveness of aquaponics sub-systems as biological and mechanical filters in maintaining water quality in aquaculture systems. Over a 70-day trial with Nile tilapia, green beans, and Chinese cabbage, the system maintained an average temperature of 25.2 ± 0.25 °C, dissolved oxygen at 6.6 ± 0.13 mg L^{-1}, pH at 7.14 ± 0.06, ammonia at 0.23 ± 0.02 mg L^{-1}, nitrite at 0.39 ± 0.22 mg L^{-1}, nitrate at 0.89 ± 0.37 mg L^{-1}, and phosphate at 0.45 ± 0.04 mg L^{-1}. This study highlighted the efficiency and cost-effectiveness of aquaponics in filtering toxic wastes and ensuring water quality remediation through biofiltration.

Lennard and Ward (2019) highlights key parameters for successful aquaponics: maintain pH between 6.8-7.2 for nutrient availability and fish health, keep dissolved oxygen above 5 mg L^{-1} to prevent hypoxia, and control ammonia and nitrite levels below 0.5 mg L^{-1} and 1 mg L^{-1}, respectively, to avoid toxicity. Nitrate levels should range from 5-150 mg L^{-1} for plant growth without stressing fish. Fish and plants thrive in temperatures between 20-28°C, and salinity should remain below 2 ppt for compatibility with freshwater species.

Water quality management is essential for efficient crop growth and nitrogen use efficiency (NUE) in aquaponics systems. Yang and Kim (2019) found that the uniform feeding regime (AUF) significantly improved water quality compared to the standard increasing feeding (AIF). Key parameters such as dissolved oxygen (7.1-7.7 mg L^{-1}), pH (6.7-7.0), and electrical conductivity (EC) increased from 0.36 to 1.20 mS cm^{-1} under AUF, while harmful compounds like nitrite (NO_2-N) were reduced. This improved water quality led to better nutrient availability, enhanced crop growth, and a 30% to 600% increase in NUE, making AUF an effective strategy for optimizing aquaponics production.

Ujjania *et al*. (2021) evaluated water quality in an aquaponics system co-culturing rohu, tilapia, and tomato plants across two treatments (T1 and T2) with 10 replications. Key findings included air temperature (25.30-29.80°C in T1, 25.45-27.86°C in T2), water temperature (25.85-27.83°C in T1, 25.45-27.86°C in T2), pH (7.39-7.63 in T1, 7.40-7.64 in T2), dissolved oxygen (5.46-6.0 mg L^{-1} in T1, 5.45-6.0 mg L^{-1} in T2), and electrical conductivity (222.38-229.63 mS cm^{-1} in T1, 220.75-228.75 mS cm^{-1} in T2). Total hardness (578.25-635.75 mg L^{-1} in T1, 581.25-633 mg L^{-1} in T2), total alkalinity (110.5-118 mg L^{-1} in T1, 107.25-119.75 mg L^{-1} in T2), ammonia (0.001-0.003 mg L^{-1} in T1, 0.001-0.002 mg L^{-1} in T2), nitrate (0.05-0.07 mg L^{-1} in both), and nitrite (0.03-0.05 mg L^{-1} in T1, 0.04-0.06 mg L^{-1} in T2) were maintained within acceptable ranges, demonstrating the importance of water quality management in enhancing aquaponics efficiency.

2.4 ADVANCEMENTS IN AUTOMATION AND IoT FOR OPTIMIZING AQUAPONICS SYSTEMS

Endut *et al*. (2010) emphasized the importance of pH sensors in maintaining the balance between ammonia and nitrate, which is vital for fish health and efficient plant nutrient absorption. Optimal pH levels in aquaponics systems range between 6.8 and 7.2, and IoT-based automated systems equipped with pH sensors can continuously monitor and adjust pH levels to prevent adverse effects caused by fluctuations. Additionally, DO sensors played a critical role in ensuring adequate oxygen levels in fish tanks, which is essential for the overall health and productivity of the aquaponics system.

Despite the clear advantages of IoT integration in aquaponics, several challenges remain. Sensor accuracy, reliability, and cost can be limiting factors, particularly in large-scale or commercial operations. Some studies have noted that sensor calibration can be difficult in fluctuating environmental conditions, and wireless communication can be disrupted in remote locations (Kaur and Verma, 2017). Nevertheless, ongoing advancements in IoT technology, combined with the increasing accessibility of cloud platforms and AI tools, are likely to overcome these challenges in the near future.

Moreover, automated water flow management has been addressed through the use of IoT-enabled water pumps and solenoid valves, which regulate the flow of nutrient-rich water between the fish tanks and grow beds. Through continuous monitoring and control, IoT systems can optimize water circulation, ensuring that the plants receive adequate nutrients while maintaining a healthy environment for the fish (Kowalski *et al.*, 2017). These automated systems can also alert users to potential problems, such as blocked pipes or pump failures, preventing system breakdowns and ensuring smooth operation.

Kyaw and Ng (2017), developed a system that can synergize fish farming and plant growing by gathering all the data from various sensors monitoring the sensor information and controlling the system accordingly. This system was developed by integrating seven modules which are a data acquisition unit that uses five sensors, an alarm unit that consists of a green LED, red LED, and a buzzer, a system rectification unit to activate or deactivate the actuators, a central processing unit that contains two sections which are arduino mega and raspberry Pi, web application, mobile application, and cloud server. Mamatha and Namratha (2017) also developed a system used Arduino Uno as a microcontroller and several sensors such as a pH sensor, temperature sensor, and LDR sensor.

Manju *et al*. (2017) designed an IoT-based real-time monitoring system for aquaponics using sensors to measure pH, temperature, and turbidity, interfaced with an Arduino Mega 2560 and an ESP8266 Wi-Fi module. The system was capable of transmitting live data to a web application, allowing remote monitoring and immediate action in case of parameter fluctuations. Their results showed enhanced control over the aquaponics environment, with the system maintaining water temperature within the optimal range of 26-28°C and pH between 6.5-7.0. The study demonstrated that automation significantly reduced manual workload and improved the reliability of water quality monitoring. A similar purpose of monitoring the aquaponics system was also designed by Murad *et al.* (2017) with the aquaponics water monitoring system using arduino microcontroller project to specifically monitor and control the water parameters in the fish tank.

In smart aquaponics with monitoring and control system based on IoT authored by Vernandhes *et.al*. (2017), smart growbox was created specifically for this project to assist with the hardware design, which included sensors, relays, an ethernet shield, and an arduino. The amount of water vapor in the air was measured using DHT22 sensors, which can affect the rate of transpiration and how nutrients were obtained. Light-emitting diodes (LEDs) were utilized to substitute the sunlight that is most effective in boosting plant growth. To calculate the output value of the amount of electricity, a soil moisture sensor was utilized to measure the moisture in the soil.

Al Mamun *et al*. (2018) demonstrated the effectiveness of integrating microcontrollers like Arduino and Raspberry Pi into aquaponics systems for enhanced automation. These low-cost, programmable devices act as central processors in IoT setups, receiving sensor data and controlling pumps, aerators, and heaters. Combined with cloud-based platforms, they enable real-time monitoring and adjustments of water quality, feeding schedules, and system alerts via mobile applications. This integration not only improved operational efficiency but also minimized human intervention and errors by automatically correcting imbalances in water quality and nutrient levels based on sensor feedback.

Nichani *et al*. (2018) developed an automated IoT-based aquaponics system on a test farm, integrating local servers and real-time monitoring via a VPS and internet-accessible dashboard. The system streamlined farm management, reducing time and effort, and proved ideal for urban settings with limited space. It facilitated pesticide-free, organic vegetable and fruit production. While lacking monitoring for nitrate, nitrite, and ammonia, these parameters could be added in future versions. IoT enabled autonomous functioning of interconnected sensors and actuators, showcasing its scalability, ease of use, and potential to enhance agricultural efficiency.

Pantazi *et al.* (2019) used three different types of sensors to monitor the system which include two DHT11 sensors to keep an eye on the humidity and temperature of the air. These sensors send data every two seconds. To track the temperature of the water, this project used a resin-encapsulated metal SNS-TMP10 analogue sensor while the light sensor was used to monitor the lighting level in the environment. The water was pumped out of the fish tank to the greenhouse using nutrient enrichment.

Karimanzira and Rauschenbach (2019) developed an IoT-based predictive analytics to improve aquaponics management by integrating Supervisory Control and Data Acquisition (SCADA), Enterprise Resource Planning (ERP), and Manufacturing Execution Systems (MES). The project involved five interconnected modules managed via IoT, which allowed for real-time monitoring and predictive adjustments using sensor data. Predictive models provided actionable insights, enabling proactive decision making to optimize resource use and system performance. This integration improved productivity, minimized waste, and streamlined information management. The study emphasized the potential of IoT and predictive analytics in modernizing aquaponics operations for better efficiency and sustainability.

Oommen *et al.* (2019) developed an IoT-based automated water quality monitoring system for aquaponics, using a NodeMCU ESP8266 microcontroller for remote management via a mobile app. The system accurately measured ammonia levels in ppm using a VEML6040 color sensor and the Beer-Lambert law. A peristaltic pump injected reagents into water samples, with automated rinsing and flushing cycles ensuring precision and reliability. This real-time monitoring system minimized manual labour, maintained consistent water quality, and improved the overall efficiency of aquaponics systems.

Egargue *et al*. (2020) developed an automated aquaponics system featuring a hybrid smart switching power supply to improve energy efficiency and sustainability. The system automates water circulation, nutrient delivery, and environmental monitoring, ensuring a balanced ecosystem. The hybrid power supply optimizes energy use by dynamically adjusting power distribution, reducing waste and costs, making it suitable for commercial-scale applications. The design is adaptable, scalable, and compatible with IoT and automation technologies.

Lee and Wang (2020) developed a cloud-based IoT monitoring system for fish metabolism and activity in aquaponics. Fish activity was sensed according to the dissolved oxygen and water temperature. Based on the established oxygen transfer rate model, the systemic metabolic rate and fish's locomotion-induce metabolic rate are calculated through the daily regression analysis.

Additionally, data analytics can be applied to predict system behaviors, optimize resource use, and even anticipate potential problems before they arise. Machine learning algorithms have been employed to fine-tune system parameters, enabling proactive management and improving long-term sustainability (Hussain *et al*., 2020).

Menon (2020) designed an IoT-enabled aquaponics system that integrated wireless sensors to monitor water quality parameters such as pH, temperature, and turbidity in real time. The system employed an ESP8266 microcontroller connected to cloud storage via Wi-Fi, with sensor data accessible through a mobile app interface. The prototype achieved a stable temperature range of 25-28°C and maintained optimal pH levels between 6.5-7.2, suitable for both fish and plant growth. Real-time alerts and data logging significantly reduced manual workload and improved response time to system changes. The study demonstrates the practicality and efficiency of IoT in small-scale aquaponics and supports its broader application for sustainable agriculture.

Afreen and Bardhan (2021) explored the integration of artificial intelligence (AI) in aquaponics, where AI-driven control systems can autonomously adjust water conditions based on real-time data and historical patterns, significantly reducing the need for human intervention. Ntulo *et al.* (2021) developed IoT-Based smart aquaponics system using Arduino Uno for monitoring water circulation and real-time water quality parameters. The study found that plants grew best when the water temperature was maintained between 20°C and 25°C. Plants were observed to thrive in water with a pH range between 6.5 and 8.5, ensuring optimal conditions for healthy growth.

Alselek *et al.* (2022) developed and tested an advanced IoT monitoring system for aquaponics health and fishery applications, focusing on improving communication and sensing technologies. The proposed system incorporates 5G communications for enhanced connectivity, while using LoRa for long-range communication between nodes and LTE-M/NB-IoT for Internet access. The sensing layer was upgraded with multiple sensors to enhance aquaculture performance, achieving faster processing times: 0.9-1.5 seconds for digital sensors and 0.3 seconds for analog ones. The average total sensing period was 7.5 seconds for nine sensors, with data transmission times averaging 463 milliseconds to the CORE. Additionally, the hardware architecture was optimized to reduce power consumption, extending battery life by approximately 70% with the integration of a switching IC (74HC237) on the I2C line. This system offers significant improvements in monitoring aquaponics systems, providing real-time data for better fishery management and health monitoring.

Bakar *et al.* (2022) developed a smart aquaponics monitoring system using Arduino microcontrollers and sensors (pH, temperature, humidity, ultrasonic) to manage water quality and environmental factors. The system tracked pH levels, temperature, and humidity, providing real-time data and sending SMS or push notifications when parameters deviated from optimal ranges. For example, when pH, temperature, or ultrasonic sensor readings were out of range, GSM notifications were sent to mobile devices. The system showed improved plant growth, with daily data revealing consistent increases in growth, demonstrating the effectiveness of automation in enhancing aquaponics system efficiency.

Gayam *et al.* (2022) emphasized the importance of automation and wireless technologies in aquaponics, proposing an IoT-based system equipped with sensors for pH, temperature, ammonia, and dissolved oxygen monitoring. The study highlights the use of wireless sensor networks and edge computing to enable real-time control and predictive maintenance. Their model improved system responsiveness and reduced manual labor, demonstrating a 25-30% increase in operational efficiency. These findings support the integration of IoT in aquaponics for better sustainability and productivity.

Udanor *et al*. (2022) developed an IoT-based system for monitoring water quality in aquaponics fish ponds, collecting a dataset crucial for optimizing operations. The system used Arduino 1.8.4 software programmed in C to control sensors that measured key parameters such as pH, DO, temperature, and electrical conductivity. These values were transmitted to the ThingSpeak IoT cloud for real-time monitoring and analysis. The system maintained pH levels within the optimal range of 6.5–7.5, DO above 5 mg L^{-1} and EC below 2 dS m^{-1}, ensuring conditions suitable for both fish and plants. This research emphasized how IoT-based automation enhances aquaponics management by ensuring water quality and reducing manual interventions.

Wan *et al*. (2022) introduced a modularized IoT monitoring system with edge-computing capabilities specifically for aquaponics systems. This system integrates modular sensors to monitor key water quality parameters such as pH, dissolved oxygen, and temperature, ensuring optimal conditions for both plant and fish growth. Edge computing was employed to process the collected data locally, reducing latency and improving system responsiveness. The modular design allows scalability, making the system adaptable for different sizes of aquaponics setups. IoT and edge computing technologies enhance real-time monitoring and control, offering precise environmental management. By optimizing water quality and plant growth conditions, the system reduced manual labour and improved overall system efficiency. This innovation demonstrated the potential of combining IoT and edge computing to create cost-effective and user-friendly solutions for sustainable aquaponics farming.

Pramono *et al*. (2023) developed an IoT-based water quality monitoring system for aquaponics, aimed at improving system sustainability and efficiency.

The system integrates sensors that continuously monitor key water parameters, ensuring optimal conditions for both fish and plants. A mobile application enables remote monitoring and alerts users to any deviations in water quality. By automating the monitoring process, the system reduces the need for manual intervention, increases accuracy, and optimizes resource management. This innovation enhances the overall efficiency and sustainability of aquaponics systems, improving both environmental and operational performance.

In conclusion, the application of IoT in aquaponics has shown tremendous potential in enhancing system efficiency, sustainability, and scalability. Automated monitoring and control of water quality parameters not only reduce labour but also help maintain the delicate balance required for optimal fish and plant growth. As IoT technology continues to evolve, further research is needed to address existing limitations and expand the commercial viability of these automated aquaponics systems.