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Development and Implementation of a Microcontroller-Based Smart Modular Aquaponic System for Sustainable Food Production

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Abstract

Aquaponics integrates aquaculture and hydroponics into a symbiotic, soil-free agricultural system that offers a sustainable solution to global food production challenges. In response to the increasing demand for environmentally sustainable and resource-efficient farming methods, this study presents the development and implementation of a microcontroller-based smart modular aquaponic system aimed at automating water quality regulation, with a focus on pH level control. Traditional aquaponic systems rely heavily on manual monitoring and adjustment of critical parameters, often leading to inefficiencies and inconsistencies. The proposed system integrates a pH sensor with a microcontroller that triggers a pumping mechanism to adjust water conditions when pH levels exceed 7.1. Experimental validation across three monitoring intervals (08:00, 14:00, and 20:00) demonstrated the system's ability to maintain pH within the optimal range of 6.8–7.1. The findings confirm that the automated approach significantly improves operational stability, enhances water resource efficiency, and promotes environmental sustainability within aquaponic systems. Moreover, the modular configuration facilitates scalability and customization across diverse settings. This study underscores the transformative potential of automation in advancing aquaponics as a viable model for sustainable and technologically integrated food production.

Keywords: Aquaculture-Hydroponics Integration; pH Control; Microcontroller-Based Aquaponics; Sustainable Agriculture; Water Quality Management

INTRODUCTION

Aquaponics is a sustainable farming method that combines aquaculture, where aquatic animals like fish are raised, with hydroponics, the practice of growing plants in water (Md Noor & Harun, 2022). In this system, fish waste supplies nutrients to the plants, creating a mutually beneficial environment. Interest in aquaponics has grown due to its potential to improve food security and address environmental issues (Francisco et al., 2025). Compared to conventional agriculture, aquaponics uses significantly less water, produces minimal waste, and eliminates the need for synthetic fertilizers by relying on natural nutrient cycling. This makes it an effective solution for promoting sustainable agricultural practices (Francisco et al., 2025).

Aquaculture has long faced challenges such as excessive resource use and environmental damage. Traditional fish farming methods often lead to the depletion of natural resources and the destruction of habitats (Okomoda et al., 2023). Aquaponics offers a more sustainable solution by creating a closed-loop system that recycles water and nutrients, thereby minimizing environmental harm. By integrating fish and plant cultivation, aquaponics not only improves resource efficiency but also has the potential to enhance both productivity and (Kovrigin et al., 2021). Aquaponic systems can be categorized into different types, including media-filled beds, nutrient film technique (NFT), and deep-water culture (DWC) (Das et al., 2022; Ghosh et al., 2024; Mehrim & Refaey, 2023). Each type has its advantages and disadvantages. The choice of system depends on specific project goals and constraints. Because of their versatility, aquaponic systems can be utilized in a variety of settings, from small-scale urban farms to larger commercial operations, which contributes to their growing popularity (Ahmed & Turchini, 2021). Recent technological advancements have greatly improved the efficiency and effectiveness of aquaponics systems. Innovations, including automated monitoring and control systems, enhanced water filtration, and optimized nutrient management, have significantly increased the feasibility and scalability of aquaponics. These developments optimize resource utilization and reduce labor and operational costs, positioning aquaponics as a more viable and attractive option for sustainable food production (Rahman et al., 2022).

Although aquaponics offers numerous advantages, its widespread adoption is impeded by several challenges. One major issue is the complexity of maintaining the delicate balance between the needs of fish and plants. Ensuring optimal water quality parameters—such as pH, temperature, and nutrient levels—is essential for the health and productivity of both organisms. Variability in these parameters can lead to system imbalances, causing poor growth, disease outbreaks, and potential system failure (Apine et al., 2023).

Another significant challenge is the high initial cost of establishing an aquaponics system. The need for specialized equipment, such as pumps, filters, and sensors, can create financial barriers for small-scale farmers and hobbyists. Furthermore, a lack of technical knowledge and expertise required for designing, constructing, and efficiently operating aquaponics systems may deter potential users. Educational and training programs are crucial for equipping individuals with the skills and knowledge needed to effectively implement and manage aquaponics systems.

The author in (Verdegem et al., 2023) examined the integration of aquaponics systems, concentrating on the combination of aquaculture and hydroponic production technologies. It underscored the effectiveness of nutrient recycling and water management within aquaponics, highlighting the environmental advantages and sustainability of these systems. The findings indicated that aquaponics has the potential to considerably decrease water consumption and waste generation in comparison to traditional farming practices. Authors in (Das et al., 2023; Mitra et al., 2024) studied the nutrient dynamics in aquaponics systems, specifically focusing on how fish waste is transformed into nutrients accessible to plants. The study highlighted the importance of maintaining optimal water quality parameters for the well-being and productivity of both fish and plants. The researchers pinpointed critical factors affecting nutrient availability, including pH levels, temperature, and microbial activity, which offer valuable insights for enhancing system performance (Schubert et al., 2025).

This study focuses on developing and implementing a modular, microcontroller-based aquaponics system to enhance plant growth using waste from aquatic animals. Key objectives include developing an automated system for monitoring water quality, establishing efficient nutrient management protocols to optimize growth for both plants and fish, and implementing cost-effective, scalable solutions for various system sizes. Additionally, the study seeks to provide training and educational resources to promote the adoption of aquaponics technology.

METHODS

The proposed technique used in the success of an aquaponics system heavily depends on the selection of fish species, with tilapia, catfish, and ornamental fish like koi being popular choices. Tilapia is often preferred for its hardiness and fast growth. Commonly grown plants include leafy greens and herbs such as lettuce, basil, and spinach due to their quick growth and nutrient uptake; however, vegetables like tomatoes, cucumbers, and peppers may need more specific nutrient management. Nitrifying bacteria, such as Nitrosomonas and Nitrobacter, play a vital role in converting fish waste into nutrients that plants can absorb. These bacteria typically reside in the biofilter and on the surfaces of media in an aquaponics system.

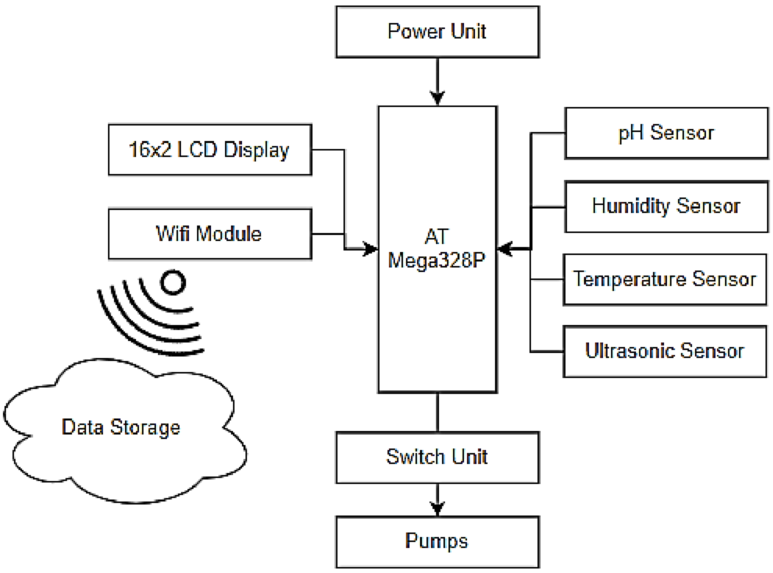


Figure 1: Microcontroller-Based Modular System

In this system, water serves as the primary medium for transporting nutrients and waste, making water quality essential. Regular monitoring of key water parameters, including pH, ammonia, nitrite, and nitrate levels, is crucial for maintaining the health of the system. While fish waste provides most of the necessary nutrients, specific supplements may be needed to address deficiencies in elements like iron or potassium. Adjusters, like potassium hydroxide or calcium carbonate, are employed to sustain optimal pH levels, thereby supporting the health of both fish and plants (Mitra et al., 2024). Each component plays a critical role in the integrated cycle of fish and plant production, highlighting the importance of proper selection and management to achieve a balanced and productive aquaponics ecosystem.

Figure 1 illustrates the design and components of an innovative aquaponics system developed by the authors. This system integrates both aquaculture and hydroponics, showcasing how fish waste can be utilized as a nutrient source for plant growth. The microcontroller serves as the central unit, managing various parameters essential for maintaining optimal conditions for both fish and plants. Key features of the system include automated monitoring of water quality, which is crucial for sustaining the health of aquatic life and ensuring effective nutrient delivery to plants. The figure depicts sensors that measure parameters such as pH, temperature, and nutrient levels, which are vital for the system's stability and efficiency (Andersen, 2024). The modular design allows for scalability, meaning that the system can be adjusted to fit different sizes and types of operations, from small urban farms to larger commercial setups. Overall, the main goal is to enhance sustainability and efficiency in aquaponics through advanced automation and effective resource management, as highlighted in their findings on maintaining optimal pH levels and improving system performance.

Figure 2: Nursery of Garden cress

Figure 3: Implementation Processes

In modeling the microcontroller-based modular aquaponic system, the following equations are typically employed:

Henderson-Hasselbalch Equation (for pH control) (Franco & Pessoa Filho, 2022a, 2022b; Schenck et al., 2022):

$$pH = pK_a + log\left(\frac{[A^-]}{HA}\right) \quad (1)$$

This equation helps determine the pH level based on the concentrations of the acid ($[HA]$)and its conjugate base ($[A^-]$).

Mass Balance Equation (for nutrient dynamics) (Ring, 2023):

$$\frac{dN}{dt} = R_{in} - R_{out} - U \quad (2)$$

In this equation, Nrepresents nutrient concentration, R_{in} is the rate of nutrient input from fish waste, R_{out} is the rate of nutrient loss, and U is the rate of nutrient uptake by plants.

Arrhenius Equation (for temperature effects) (Kohout, 2021):

$$k = Ae^{-\frac{E_a}{RT}} \quad (3)$$

This equation models the rate constant k of biochemical reactions as a function of temperature T where A is the pre-exponential factor and E_a is the activation energy.

Logistic Growth Equation (for growth rates) (Jose et al., 2023):

$$P(t) = \frac{K}{1+\left(\frac{K-P_0}{P_0}\right)e^{-rt}} \quad (4)$$

In this equation, *P(t)* represents the population size at time *t*, *K* is the carrying capacity, P_0 is the initial population size, and *r* is the growth rate. These equations work together to facilitate the automation and optimization of the aquaponics system, ensuring a balanced environment for both fish and plants.

RESULTS

The aquaponics system is monitored using best practices to ensure water quality, nutrient concentrations, and the health of both aquatic and terrestrial creatures. This balance is crucial for improving system performance and efficiency, utilizing accepted engineering techniques.

pH Level

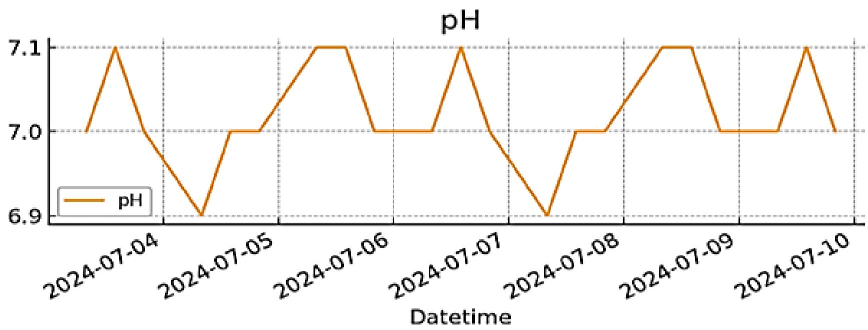


Figure 4: pH Level against Date/ Time

The pH levels, maintained between 6.8 and 7.1, are critical for both nutrient availability to plants and the overall health of fish in an aquaponics system. This range is ideal, as it creates the right environment for plants to absorb nutrients effectively while also providing suitable conditions for fish. The graph illustrates how pH levels fluctuate throughout the day at different times (08:00, 14:00, and 20:00), showing the system's ability to regulate pH within this narrow range. The stability of the pH levels, achieved through modern monitoring and control technologies, indicates that the system effectively buffers against fluctuations. This consistency is essential for maintaining a healthy, balanced ecosystem that supports optimal growth for both plants and fish.

Water Temperature

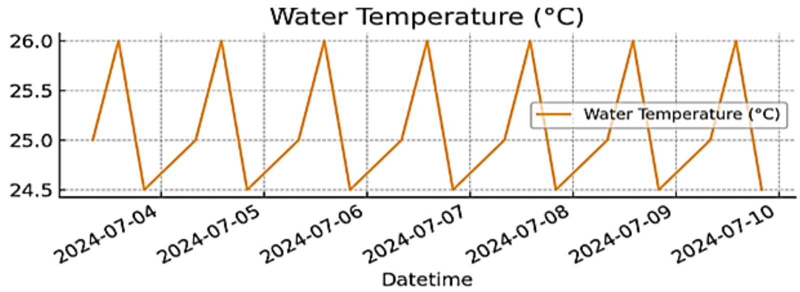
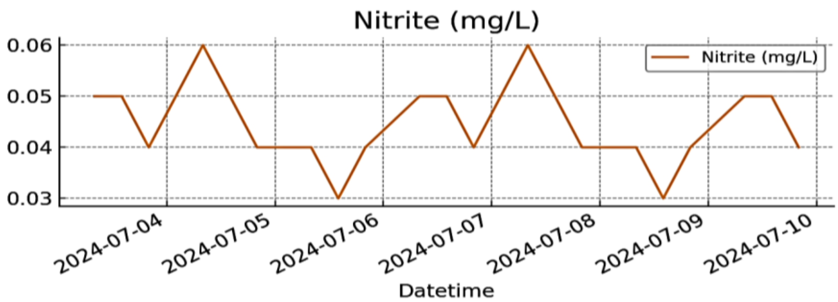
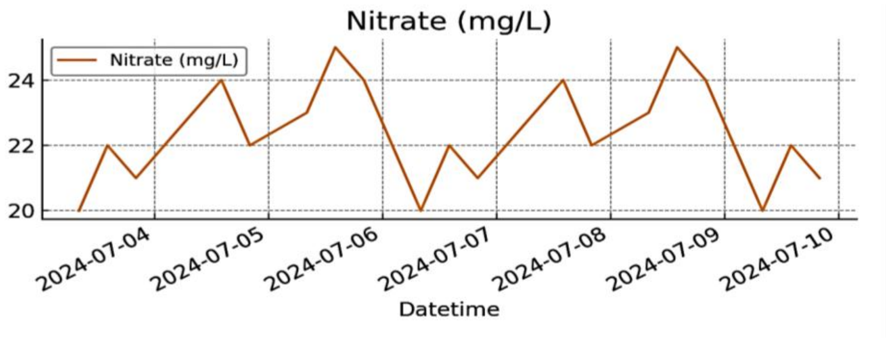


Figure 5: Water Temperature (OC) against Date/Time

Water temperature in the aquaponics system was maintained within an optimal range of 24.5°C to 26°C, promoting healthy growth for both fish and plants. As water temperature rises, the fish's metabolic rate increases, leading to more frequent feeding and faster growth in warmer conditions. Temperature readings fluctuated slightly throughout the day, with morning temperatures between 24.5°C and 25.1°C, afternoon temperatures from 25.0°C to 25.6°C, and evening temperatures from 24.0°C to 24.5°C. These minor variations are typical in natural aquatic environments and remain within acceptable limits for most aquaponics species. The system likely incorporates temperature regulation mechanisms to prevent drastic fluctuations, ensuring a stable environment that enhances the overall health and productivity of the system.



(a) Nitrite (mg/L)



(b) Nitrate (mg/L)

Figure 6: Nitrite/Nitrate (mg/L) Measurements

In an aquaponics system, it is essential to regularly monitor ammonia, nitrite (NO-2), and nitrate (NO-3) levels to maintain a healthy environment for both fish and plants. Ammonia, primarily produced from fish waste and uneaten food, can become toxic to fish even at low concentrations, leading to stress, gill damage, and potentially death. Nitrite, which is formed as bacteria break down ammonia in the nitrification process, is equally harmful, as it interferes with the fish's ability to absorb oxygen, causing stress and fatal conditions if levels remain high. Nitrate, the final product of nitrification, is crucial for plant growth as it provides necessary nitrogen. However, nitrate levels must be carefully balanced—too high (above 5 ppm) and it can become toxic to fish, while levels too low will not support proper plant nutrition. Thus, regular monitoring and management of these compounds are vital to prevent toxic conditions, promote fish health, and ensure plants receive the nutrients they need for optimal growth.

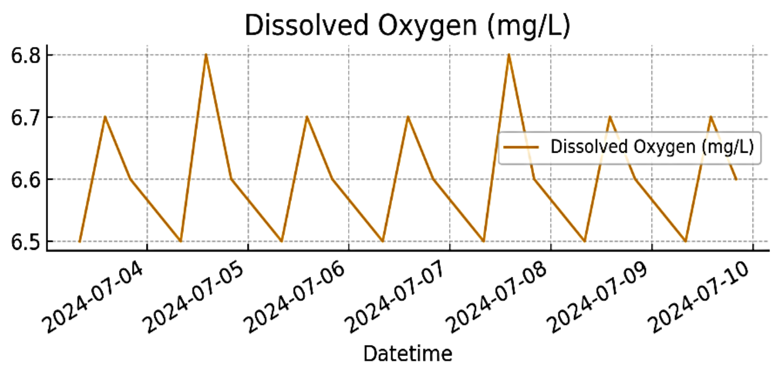


Figure 7: Dissolved Oxygen (mg/L)

Dissolved oxygen (DO) refers to the amount of oxygen present in water and is essential for the survival of aquatic organisms, such as fish, in the same way that humans require air to breathe. In an aquaponics system, where fish farming and plant cultivation are combined, maintaining proper dissolved oxygen levels (around 6.5-6.8 mg/L) is crucial for fish health and plant growth. Low oxygen levels can lead to fish stress, illness, or death, while poor water quality can hinder plant development. Dissolved oxygen is measured in milligrams per liter (mg/L), with optimal levels for most fish species ranging from 5 to 8 mg/L. Several factors affect DO levels, including water temperature, which inversely affects oxygen capacity, and water movement, which increases oxygen through aeration. Additionally, plant activity plays a role, as plants produce oxygen during the day but consume it at night. Proper monitoring and regulation of dissolved oxygen levels are essential for the success of an aquaponics system, ensuring the health and productivity of both fish and plants and promoting sustainable agricultural practices.

CONCLUSION

The research introduces a novel approach to aquaponics by integrating microcontroller technology, significantly improving system automation and efficiency. The developed system effectively regulates key water quality parameters, maintaining pH levels between 6.8 and 7.1, which are vital for both plant growth and fish health. Also, temperature control plays a critical role, with water temperatures kept within the optimal range of 24.5°C to 26°C, promoting ideal metabolic rates for both fish and plants. Monitoring ammonia, nitrite, and nitrate levels is essential to prevent toxic conditions and maintain a balanced ecosystem that supports both aquatic and terrestrial life. The findings also demonstrate the potential of aquaponics systems to minimize water consumption and waste compared to traditional farming methods, highlighting their environmental sustainability. Overall, the research emphasizes the value of advanced automation in optimizing aquaponics for modern agricultural practices, contributing to enhanced sustainability and scalability

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REFERENCES

Ahmed, N., & Turchini, G. M. (2021). Recirculating aquaculture systems (RAS): Environmental solution and climate change adaptation. *Journal of Cleaner Production*, *297*. https://doi.org/10.1016/j.jclepro.2021.126604

Andersen, J. E. T. (2024). Comments on the Concept of Buffers. *Chemistry Africa*, *7*(3), 1401–1410. https://doi.org/10.1007/s42250-023-00848-4

Apine, E., Ramappa, P., Bhatta, R., Turner, L. M., & Rodwell, L. D. (2023). Challenges and opportunities in achieving sustainable mud crab aquaculture in tropical coastal regions. *Ocean and Coastal Management*, *242*. https://doi.org/10.1016/j.ocecoaman.2023.106711

Das, S. K., Mandal, A., & Khairnar, S. O. (2022). Aquaculture Resources and Practices in a Changing Environment. *Sustainable Agriculture Systems and Technologies*, 169–199. https://doi.org/10.1002/9781119808565.ch8

Das, S. K., Mondal, B., Sarkar, U. K., Das, B. K., & Borah, S. (2023). Understanding and approaches towards circular bio-economy of wastewater reuse in fisheries and aquaculture in India: An overview. *Reviews in Aquaculture*, *15*(3), 1100–1114. https://doi.org/10.1111/raq.12758

Francisco, E. C., Freato, T. A., Piolli, A. L., & Poz, M. E. S. D. (2025). Analysis of the Aquaponic System Sustainability via System Dynamics Modelling – FEW Nexus Approach. *Circular Economy and Sustainability*, *5*(3), 2577–2592. https://doi.org/10.1007/s43615-024-00408-z

Franco, L. F. M., & Pessoa Filho, P. de A. (2022a). Mathematical Description of the Enzymatic Activity of Proteins with Ionizable Groups Exhibiting Deviations from the Henderson-Hasselbalch Equation. *Applied Biochemistry and Biotechnology*, *194*(3), 1221–1234. https://doi.org/10.1007/s12010-021-03700-y

Franco, L. F. M., & Pessoa Filho, P. de A. (2022b). Mathematical Description of the Enzymatic Activity of Proteins with Ionizable Groups Exhibiting Deviations from the Henderson-Hasselbalch Equation. *Applied Biochemistry and Biotechnology*, *194*(3), 1221–1234. https://doi.org/10.1007/s12010-021-03700-y

Ghosh, S., Anju, P., Pattanayak, R., & Sahu, N. C. (2024). Fisheries and Aquaculture in Wetland Ecosystems: A Review of Benefits, Risks, and Future Prospects in India. *Journal of Coastal Research*, *40*(3). https://doi.org/10.2112/jcoastres-d-23-00045.1

Jose, J., Raj, V., Seaban, S. V., & Jose, D. V. (2023). Machine Learning Algorithms for Prediction of Mobile Phone Prices. *Lecture Notes in Networks and Systems*, *537 LNNS*, 81–89. https://doi.org/10.1007/978-981-99-3010-4_7

Kohout, J. (2021). Modified Arrhenius Equation in Materials Science, Chemistry and Biology. *Molecules*, *26*(23). https://doi.org/10.3390/molecules26237162

Kovrigin, A., Pokhodnya, G., Breslavets, Y., Breslavets, A., & Zhabinskaya, V. (2021). Growing fish and plants using aquaponic, hydroponic and mixed technologies. *E3S Web of Conferences*, *282*. https://doi.org/10.1051/e3sconf/202128203028

Md Noor, N., & Harun, S. N. (2022). Towards Sustainable Aquaculture: A Brief Look into Management Issues. *Applied Sciences (Switzerland)*, *12*(15). https://doi.org/10.3390/app12157448

Mehrim, A. I., & Refaey, M. M. (2023). An Overview of the Implication of Climate Change on Fish Farming in Egypt. *Sustainability (Switzerland)*, *15*(2), 1679. https://doi.org/10.3390/su15021679

Mitra, S., Khan, M. A., Nielsen, R., Kumar, G., & Rahman, M. T. (2024). Review of environmental challenges in the Bangladesh aquaculture industry. *Environmental Science and Pollution Research*, *31*(6), 8330–8340. https://doi.org/10.1007/s11356-023-31630-1

Okomoda, V. T., Oladimeji, S. A., Solomon, S. G., Olufeagba, S. O., Ogah, S. I., & Ikhwanuddin, M. (2023). Aquaponics production system: A review of historical perspective, opportunities, and challenges of its adoption. *Food Science and Nutrition*, *11*(3), 1157–1165. https://doi.org/10.1002/fsn3.3154

Rahman, M. A., Kanon, K. F., Islam, M. J., Mojumdar, S., Ashik, A. A., & Molla, M. H. R. (2022). Impacts of climate change on aquaculture and fisheries: an integrated approach for adaptation and mitigation. *Journal of Biological Studies*, *5*(1), 171–188. https://doi.org/10.62400/jbs.v5i1.6623

Ring, T. (2023). Strong ions and charge-balance. *Scandinavian Journal of Clinical and Laboratory Investigation*, *83*(2), 111–118. https://doi.org/10.1080/00365513.2023.2180658

Schenck, G., Baj, K., Iggo, J. A., & Wallace, M. (2022). Efficient p KaDetermination in a Nonaqueous Solvent Using Chemical Shift Imaging. *Analytical Chemistry*, *94*(23), 8115–8119. https://doi.org/10.1021/acs.analchem.2c00200

Schubert, M., Monikh, F. A., Yang, Y., & Grossart, H. P. (2025). Nutrient availability modulates the effects of plastic leachates on the growth and community dynamics of free-living freshwater bacteria. *Frontiers in Environmental Science*, *13*. https://doi.org/10.3389/fenvs.2025.1589648

Verdegem, M., Buschmann, A. H., Latt, U. W., Dalsgaard, A. J. T., & Lovatelli, A. (2023). The contribution of aquaculture systems to global aquaculture production. *Journal of the World Aquaculture Society*, *54*(2), 206–250. https://doi.org/10.1111/jwas.12963