KARYA ILHAM PUBLISHING
CONNECTING MINDS, BRIDGING IDEAS, INSPIRING READERS

International Journal of Advanced Research in Computational Thinking and Data Science

Journal homepage:
https://karyailham.com.my/index.php/ctds/index
ISSN: 3030-5225

IoT-Based Monitoring and Optimization of Nutrient Film Technique Aquaponic Systems: Influence of Bio-Mechanical Filtration on Growth Rates of Oreochromis Niloticus and Brassica Rapa

Suzi Seroja Sarnin[1,*], Mohd Rizal Dohad[1], Norlela Ishak[1], Mohd Nor Md Tan[1], Ghulam E Mustafa Abro[2]

[1] School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia
[2] Interdisciplinary Research Centre for Aviation and Space Exploration, King Fahd University of Petroleum and Minerals Saudi Arabia

ARTICLE INFO

Article history:
Received 29 October 2024
Received in revised form 1 December 2024
Accepted 15 December 2024
Available online 31 December 2024

Keywords:
Nutrient Film Technique (NFT) aquaponic system; Bio-mechanical filtration; Oreochromis Niloticus; Brassica Rapa; Internet of Thing

ABSTRACT

This study investigates the effects of bio-mechanical filtration on the growth of Oreochromis Niloticus and Brassica Rapa in a Nutrient Film Technique (NFT) aquaponic system, focusing on water quality and system monitoring. Aquaponics integrates fish farming and hydroponics into a symbiotic system that requires precise nutrient and waste management. Bio-mechanical filtration, essential for removing waste and maintaining water quality, was paired with an IoT-based monitoring system that tracked ammonia, nitrate, pH, and temperature in real-time. This enabled timely filtration adjustments to sustain optimal conditions for both fish and plants. Growth rates were analyzed across various filtration configurations, revealing that enhanced filtration and monitoring significantly reduced ammonia and nitrate levels, resulting in improved growth rates. These findings highlight the potential of combining bio-mechanical filtration and IoT monitoring to optimize aquaponic systems, making them more efficient, scalable, and resource-conscious. This study contributes to aquaponic design advancements, aligning with Sustainable Development Goal 2 (SDG 2) by promoting sustainable food production and food security.

1. Introduction

Nutrient Film Technique (NFT) aquaponics is an advanced integration of aquaculture and hydroponics, offering an efficient, sustainable approach to agriculture that holds promise for addressing food security and resource conservation. Aquaponics has garnered significant attention for its potential to enhance food production by combining fish farming with plant cultivation in a

* *Corresponding author.*
E-mail address: suzis045@uitm.edu.my

https://doi.org/10.37934/ctds.4.1.1018a

closed-loop ecosystem, where nutrient-rich fish waste supports plant growth, and plants help purify the water before recirculating it to the fish tanks [1]. Among various aquaponic designs, NFT aquaponics stands out for circulating a thin, nutrient-laden film of water along shallow channels, allowing plant roots to absorb nutrients while being exposed to air, which enhances oxygen availability and promotes growth as illustrates in Figure 1 [2].

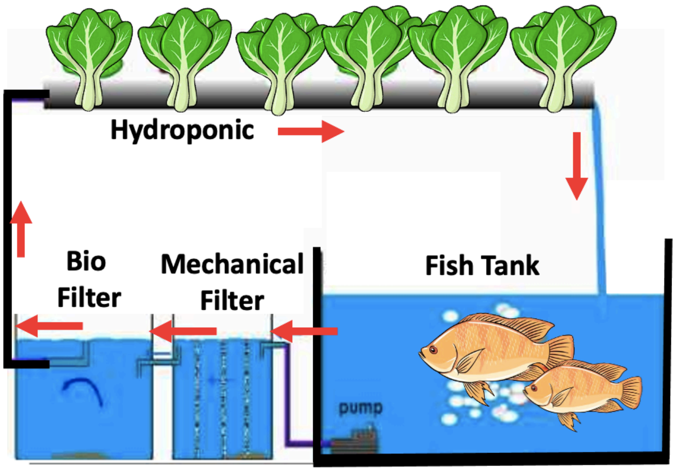

Fig. 1. Recirculated system

While most aquaponics research focuses on deep-water culture (DWC) and media-based systems, there is limited exploration of how NFT configurations interact with bio-mechanical filtration to improve water quality and growth. Bio-mechanical filtration is crucial for converting toxic ammonia from fish waste into plant-usable nitrates, stabilizing water quality and nutrient levels. While its effectiveness is well-documented in DWC and media-based systems, its adaptation and optimization for NFT setups—characterized by unique water flow and oxygenation dynamics—remain underexplored. The bio-mechanical process, essential for maintaining water quality, converts ammonia (NH_3) into nitrates (NO_3^-), benefiting both plants and fish as shown in Figure 2 [3-6].

Fig. 2. Nitrification process

This study fills a critical gap by implementing a cost-effective bio-mechanical filtration system, adapted from aquarium concepts and applied to NFT aquaponics for the first time. It examines the impact on water quality and the growth of Oreochromis Niloticus and Brassica Rapa. An IoT-based monitoring system tracks key water parameters like ammonia, nitrate, and pH, enabling real-time adjustments for optimal conditions. The findings provide insights into NFT-specific filtration needs, contributing to more efficient, scalable aquaponic systems aligned with the Zero Hunger goal.

2. Methodology

2.1 NFT Aquaponic with Bio-Mechanical Architecture

Figure 3 shows the structural of the aquaponic system, showcasing the integration of aquaculture and hydroponics in a symbiotic environment. This design emphasizes the layout of the fish tanks, plant beds, and the filtration components, highlighting how these elements work together to maintain water quality and support the growth of both fish and plants [17].

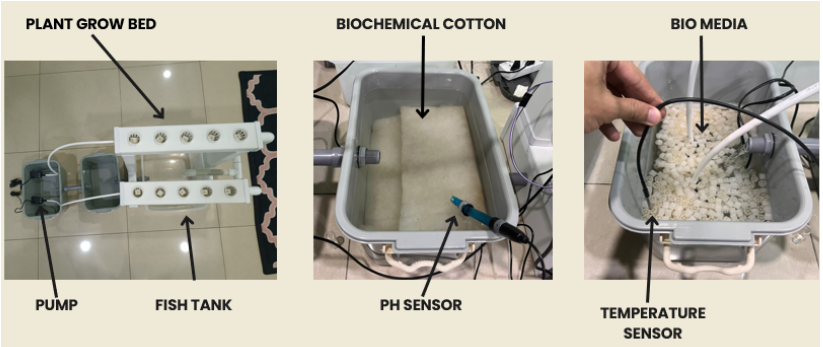

Fig. 3. Architecture design

The waste produced by the fish contains ammonia, which is in solid form. This waste cannot be directly passed to the grow bed for the plants. It needs to be converted into nutrients that the plants can absorb. This conversion is done by microorganisms.

Eq. (1) shows the oxidation of ammonia ($NH_4{}^+$) to nitrite ($NO_2{}^-$) when dissolved in water with the help of beneficial bacteria. At this point, the concentration of ammonia and nitrite is kept at minimum because of their high toxicity to the fishes [21].

$$\mathrm{NH_4}^+ + \frac{3}{2}\,\mathrm{O_2} \rightarrow \mathrm{NO_2}^- + \mathrm{H_2O} + 2\mathrm{H}^+ \quad (1)$$

Eq. (2) shows the oxidation of nitrite ($NO_2{}^-$) to nitrate ($NO_3{}^-$) which the plant utilizes it as a nutrient for growth. Nitrates are much less toxic to fish and are an important nutrient for plants.

$$\mathrm{NO_2}^- + \frac{1}{2}\,\mathrm{O_2} \rightarrow \mathrm{NO_3}^- \quad (2)$$

2.2 System Testing and Monitoring

The monitoring system ensures optimal water quality for Oreochromis niloticus and Brassica rapa in an NFT aquaponic setup. It includes sensors for ammonia, nitrate, pH, temperature, and dissolved oxygen, a CPU, IoT module, and actuator interface for real-time adjustments. The system continuously collects and processes data, which is transmitted to a cloud platform via Wi-Fi for remote monitoring and alerts, ensuring a healthy environment for both plants and fish.

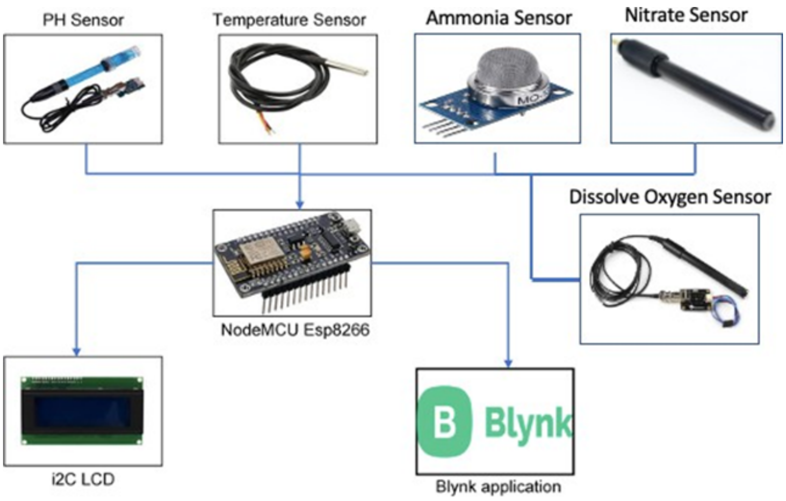

Fig. 4. Block diagram of monitoring system

The Blynk application is configured to display real-time data from sensors measuring key factors in the aquaponic system, allowing users to monitor plant growth and environmental conditions remotely. Table 1 shows optimal parameters for an aquaponic system, focusing on water quality to support both Oreochromis Niloticus and Brassica Rapa.

Table 1
Parameters for an Aquaponic System

Sensor	Optimal Parameters	Reason
pH	6.5 – 7.5	A neutral to slightly acidic pH ensures nutrient availability for plants and is non-toxic for fish.
Temperature	22°C to 28°C (72°F to 82°F	Oreochromis Niloticus thrive within this range, which supports their metabolic and immune functions. Brassica Rapa can tolerate a slightly lower range but adapts well within this temperature spectrum.
Dissolve Oxygen	>5 mg/L	Oreochromis Niloticus require sufficient oxygen to avoid stress and ensure proper metabolism and plant roots absorb oxygen for respiration, especially in NFT systems.
Ammonia	<0.5 mg/L (preferably 0 mg/L for free ammonia	Ammonia is toxic to fish at higher concentrations, causing stress or mortality. Efficient bio-mechanical filtration should maintain ammonia at near-zero levels.
Nitrate	5 to 150 mg/	Nitrate is the primary nitrogen source for plants, promoting growth without harming fish
Electrical Conductivity	0.5 to 2.0 mS/cm	EC reflects the total dissolved salts (nutrients) in the water. Both fish and plants require moderate EC levels for health and growth.

3. Result

This section presents findings from the aquaponic system's monitoring setup, with a focus on maintaining optimal pH level, water temperature, dissolved oxygen, ammonia, nitrite, nitrate, total TDS and humidity—critical factors for the health and growth of both plants and fish. Data collected during the monitoring period will be analyzed to evaluate the system's effectiveness in regulating these key parameters. The study utilized 20–30 Oreochromis Niloticus and 40–50 Brassica Rapa to maintain a balanced 1:2 fish-to-plant ratio, ensuring optimal nutrient availability for both. This manageable sample size allowed for detailed observations of growth patterns, water quality, and the efficiency of bio-mechanical filtration. The monitoring period spanned 1 to week 13, providing ample time to measure significant growth and assess seasonal or environmental variations in key water parameters.

3.1 Monitoring System

Table 2 shows the data collected over the monitoring period provides valuable insights into the performance and health of the aquaponic system. Key parameters such as pH level, water temperature, dissolved oxygen, ammonia, nitrite, nitrate, total dissolved solids (TDS) and humidity were tracked to understand the system's dynamics and its ability to maintain optimal conditions for growth.

3.1.1 pH Level

The pH levels recorded during the monitoring period remained within the ideal range for aquaponic systems, typically between 6.5 and 7.5. This range is essential for the availability of nutrients for plants and ensures that ammonia levels remain non-toxic to fish. Fluctuations in pH were relatively minimal, with the pH slightly dipping in the evenings (7.2 on week 2 at 20:00). Such fluctuations are common due to biological activity (fish excretion and plant uptake). Overall, the system demonstrated effective buffering, maintaining the pH within acceptable levels for both fish and plant health.

3.1.2 Water Temperature

Water temperature was consistently recorded within the optimal range for both fish and plants, generally between 23.2°C and 24.2°C. Aquaponic systems generally benefit from water temperatures between 22°C and 28°C for most fish species and plants. The slight rise in temperature observed during the day (24.2°C on week 3 at 20:00) is typical, as higher ambient temperatures can influence water temperature. Consistent monitoring of this parameter is crucial to ensure the system operates within safe limits for metabolic processes in both fish and plants.

3.1.3 Dissolved Oxygen

The dissolved oxygen levels (ranging from 6.4 mg/L to 6.9 mg/L) were within the desirable range for both fish and plant health. Healthy oxygen levels are vital for fish respiration and the growth of beneficial bacteria in the biofilter, which is essential for converting ammonia into less toxic compounds. The consistent levels of dissolved oxygen observed indicate that the aeration system is functioning effectively. Regular maintenance of aeration devices will ensure that oxygen levels remain adequate, preventing potential stress on the fish.

3.1.4 Ammonia, Nitrite, and Nitrate Levels

Ammonia levels fluctuated between 0.20 ppm and 0.30 ppm, with the highest value recorded on week 2 at 08:00. This is within the safe range for aquaponics, where ammonia levels should generally be kept below 1 ppm for fish health. Nitrite levels remained very low (0.04-0.06 mg/L), suggesting that the nitrification process (conversion of ammonia to nitrites and then nitrates) was functioning effectively. Nitrate levels varied between 28 and 32 ppm, which is ideal for promoting plant growth while still being safe for fish. These readings indicate that the biofilter is efficiently processing fish waste and converting it into plant-available nutrients.

3.1.5 Total Dissolved Solids (TDS)

TDS levels were relatively stable, ranging from 451 ppm to 460 ppm. This measurement provides an overall estimate of the nutrient concentration in the water. The consistency of TDS levels indicates that nutrient concentrations were well-maintained, supporting the healthy growth of plants. Fluctuations in TDS can occur with changes in water volume due to evaporation or plant uptake, but the steady levels recorded suggest that the nutrient cycle was balanced.

Table 2
The data collected over the monitoring period provides valuable insights into the performance and the health of the aquaponic system

Week	Time	pH Level	Water Temperature (°C)	Ambient Temperature (°C)	Humidity (%)	Dissolved Oxygen (mg/L)	Ammonia (mg/L)	Nitrite (mg/L)	Nitrate (mg/L)	Total Dissolved Solids (TDS) (ppm)
1	08:00	7.4	23.5	20.0	65	6.4	0.25	0.05	30	451
1	20:00	7.3	24.0	21.5	60	6.8	0.20	0.04	32	456
2	08:00	7.4	23.2	19.0	66	6.6	0.32	0.06	28	460
2	20:00	7.2	24.1	21.8	62	6.7	0.25	0.05	31	455
6	08:00	7.5	23.6	20.5	66	6.4	0.29	0.06	29	451
6	20:00	7.3	24.2	22.0	61	6.9	0.22	0.04	30	460
8	08:00	7.4	23.4	20.2	64	6.5	0.27	0.05	28	452
8	20:00	7.3	24.0	21.9	64	6.8	0.24	0.05	30	458
10	08:00	7.4	23.5	20.0	65	6.4	0.25	0.05	30	451
10	20:00	7.3	24.0	21.5	60	6.8	0.21	0.04	32	455
12	08:00	7.4	23.2	19.0	67	6.6	0.30	0.06	28	460
12	20:00	7.2	24.1	21.8	62	6.7	0.25	0.05	31	455
13	08:00	7.5	23.6	20.5	66	6.4	0.28	0.06	29	451

3.2 Oreochromis Niloticus and Brassica Rapa Monitoring

Table 3 presents the data collected during the monitoring period, offering valuable insights into the performance and health of the aquaponic system. Key parameters related to the health of both plants and fish were monitored to assess the system's effectiveness in maintaining optimal conditions for growth. The Brassica Rapa exhibited steady growth, with occasional signs of stress, such as slight leaf yellowing recorded on week 2. This could be attributed to minor fluctuations in nutrient availability or pH, which are common in aquaponic systems. However, overall plant health was positive, with new growth observed on week 3. The Brassica Rapa ability to thrive in this system suggests that the nutrient levels (particularly nitrates) were well-suited to their needs. Oreochromis Niloticus health was generally stable throughout the monitoring period, with no visible issues recorded. On week 2, slightly reduced activity was noted, which could be a response to the higher ammonia levels (0.30 ppm) recorded during that time. However, the fish returned to normal behavior by the next day. The consistent levels of dissolved oxygen and water temperature were likely factors contributing to the overall well-being of the fish.

Table 3
The data collected over the monitoring period provides valuable insights into the

performance and health of the both plants and fish

Week	Time	Brassica Rapa	Oreochromis Niloticus
1	08:00	Vigorous growth	Active
1	20:00		
2	08:00	Faint leaf yellowing	Slightly reduced activity
2	20:00		
6	08:00	New growth observed	Active
6	20:00		
8	08:00	Healthy, all leaves vibrant	Active
8	20:00		
10	08:00	Healthy, steady growth	Active
10	20:00		
12	08:00	Faint leaf yellowing	Slightly reduced activity
12	20:00		
13	08:00	New growth observed	Active, normal behavior

The data in the Table 4 illustrates the height growth patterns of Brassica Rapa in an aquaponic system, comparing plants grown with and without bio-mechanical filtration over a 60-day period.

Height Growth Rate: Plants with bio-mechanical filtration showed a consistently higher growth rate in height across all time intervals. Starting from an average height of 3.0 cm, Brassica Rapa in the filtered system reached an average height of 22.0 cm by day 60, with an overall growth rate of approximately 0.333 cm/day. In contrast, plants grown without filtration grew at a lower rate, reaching an average height of 15.0 cm by day 60, with a growth rate of 0.200 cm/day.

Effect of Filtration: The faster growth rate observed in plants within the filtered system can be attributed to the improved water quality and nutrient availability provided by the bio-mechanical filtration. This filtration likely removed solid waste particles more effectively, reducing ammonia and nitrate levels, which could otherwise hinder plant growth. Additionally, enhanced oxygenation in the water might have contributed to more vigorous root and shoot development in the filtered system.

These findings demonstrate that bio-mechanical filtration positively influences the height growth of Brassica Rapa in aquaponic systems. By improving nutrient distribution and maintaining optimal water conditions, filtration supports healthier and more robust plant growth. This insight emphasizes the importance of incorporating effective filtration mechanisms to enhance plant yield and system sustainability in aquaponic setups.

Table 4
Growth analysis of Brassica Rapa in terms of height

Time (Days)	Condition	Average Height (cm)	Height Growth Rate (cm/day)
0	Filter	3.0	-
0	No Filter	3.0	-
15	Filter	7.0	0.267
15	No Filter	5.5	0.167
30	Filter	12.0	0.333
30	No Filter	9.0	0.200
45	Filter	17.0	0.333
45	No Filter	22.0	0.200
60	Filter	15.0	0.333
60	No Filter	6.8	0.200

The data presented in Table 5 demonstrates that fish in an NFT aquaponic system with bio-mechanical filtration exhibit higher growth rates in both length and weight compared to those without filtration.

Table 5
Growth Rates of Oreochromis Niloticus

Time (days)	Fish ID	Length (cm)	Growth Rate (cm/day)	Weight (g)	Growth Rate (cm/day)	Condition
0	1	5.0	-	10	-	Filter
0	2	5.0	-	10	-	No Filter
15	1	5.8	0.053	12	0.133	Filter
15	2	5.5	0.033	11	0.067	No Filter
30	1	6.7	0.057	14	0.133	Filter
30	2	6.1	0.037	12	0.067	No Filter
45	1	7.0	0.056	17	0.200	Filter
45	2	6.0	0.038	14	0.089	No Filter

Growth in Length: Fish with bio-mechanical filtration grew at an average rate of approximately 0.057 cm/day, while fish without filtration grew at a slower rate of about 0.038 cm/day. This difference suggests that bio-mechanical filtration, by improving water quality and reducing ammonia and other waste, likely created a more favourable environment for fish development.

Growth in Weight: The fish in the filtered system also showed a significant advantage in weight gain, growing at an average rate of 0.200 g/day, compared to 0.089 g/day for fish in the unfiltered system. This finding indicates that the improved water quality and nutrient balance provided by bio-mechanical filtration can directly support healthier fish metabolism and faster weight gain.

Overall, the results highlight the positive impact of bio-mechanical filtration on fish growth within an NFT aquaponic system. Enhanced water quality likely led to better oxygenation and nutrient availability, supporting more robust fish growth. These findings underscore the importance of filtration systems in optimizing aquaponic setups for sustainable and efficient fish and plant production. However, bio-mechanical filtration may struggle to accommodate sudden changes in system inputs, such as increased feed or stocking density, potentially affecting its performance and system stability.

4. Conclusions

In conclusion, this project demonstrated the significant benefits of bio-mechanical filtration in enhancing both fish and plant growth within an aquaponic system. The filtration system maintained excellent water quality, efficiently removed waste, and supported microbial processes that converted ammonia into plant-usable nitrates. This not only reduced toxicity for fish but also provided essential nutrients for plants, resulting in healthier growth. The optimized system led to accelerated growth of Oreochromis niloticus and increased biomass and height in Brassica Rapa. These findings highlight the value of advanced filtration techniques in improving aquaponic system efficiency, water management, and sustainability, offering a practical solution for sustainable food production. The study contributes to the development of high-performance aquaponic systems and emphasizes the potential of bio-mechanical filtration in addressing global food security challenges.

Acknowledgement
The authors would convey their profound appreciation and gratitude to the College of Engineering, Universiti Teknologi MARA, Shah Alam, Selangor, Malaysia for permitting us to perform this study. Special thanks to those who contributed to this project directly and indirectly.

References

[1] Baganz, Gösta FM, Ranka Junge, Maria C. Portella, Simon Goddek, Karel J. Keesman, Daniela Baganz, Georg Staaks, Christopher Shaw, Frank Lohrberg, and Werner Kloas. "The aquaponic principle—It is all about coupling." *Reviews in Aquaculture* 14, no. 1 (2022): 252-264. https://doi.org/10.1111/raq.12596

[2] Mahkeswaran, R., and Andrew Keong Ng. "Smart and sustainable home aquaponics system with feature-rich Internet of things mobile application." In 2020 6th International Conference on Control, Automation and Robotics (ICCAR), pp. 607-611. IEEE, 2020. https://doi.org/10.1109/ICCAR49639.2020.9108041

[3] Wan Azhar, Wan Ahmad Firdaus, Mahanijah Md Kamal, Zuhani Ismail Khan, and Kama Azura Othman. "Realtime control and monitoring aquaponic system via Blynk." Journal of Electrical and Electronic Systems Research (JEESR) 16 (2020): 73-80. https://doi.org/10.24191/jeesr.v16i1.011

[4] Hadi, Mokh Sholihul, Yohannes Pandi Sihombing, Soraya Norma Mustika, Muhammad Alfian Mizar, Dyah Lestari, and Che Ani Adi Izhar. "Aquaponic Plant Control and Monitoring System Using Iot-Based Decision Tree Logic." In 2022 6th International Conference on Information Technology, Information Systems and Electrical Engineering (ICITISEE), pp. 705-710. IEEE, 2022. https://doi.org/10.1109/ICITISEE57756.2022.10057752

[5] Khaoula, Taji, Rachida Ait Abdelouahid, Ibtissame Ezzahoui, and Abdelaziz Marzak. "Architecture design of monitoring and controlling of IoT-based aquaponics system powered by solar energy." *Procedia Computer Science* 191 (2021): 493-498. https://doi.org/10.1016/j.procs.2021.07.063

[6] Mansor, Muhammad Naufal, Mohd Zamri Hasan, Mohamed Mydin M. Abdul Kader, Wan Azani Mustafa, Syahrul Affandi Saidi, Mohd Aminudin Jamlos, and Noor Anida Abu Talib. "Aquaponic Ecosystem Monitoring with IOT Application." Journal of Advanced Research in Applied Sciences and Engineering Technology 31, no. 3 (2023): 345-357. https://doi.org/10.37934/araset.31.3.345357

[7] Zaini, A. K. A. H. A., A. Kurniawan, and A. D. Herdhiyanto. "Internet of Things for monitoring and controlling nutrient film technique (NFT) aquaponic." In 2018 International Conference on Computer Engineering, Network and Intelligent Multimedia (CENIM), pp. 167-171. IEEE, 2018. https://doi.org/10.1109/CENIM.2018.8711304

[8] United Nations. 2021. "SDG Indicators." Unstats.un.org. 2021.

[9] Ntulo, Mpho P., Pius A. Owolawi, Temitope Mapayi, Vusi Malele, Gbolahan Aiyetoro, and Joseph S. Ojo. "IOT-based smart aquaponics system using Arduino Uno." In 2021 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME), pp. 1-6. IEEE, 2021. https://doi.org/10.1109/ICECCME52200.2021.9590982

[10] Bracino, Amir A., Ronnie S. Concepcion, Elmer P. Dadios, and Ryan Rhay P. Vicerra. "Biofiltration for recirculating aquaponic systems: A review." In 2020 IEEE 12th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment, and Management (HNICEM), pp. 1-6. IEEE, 2020. https://doi.org/10.1109/HNICEM51456.2020.9400136

[11] Palao, Charlotte, Glyda Aricon Marquez, Kenneth Ibasco, Lady Claudette Ferrer, Patricia Sagge, and Maria Teresa B. Mendoza. "Renewable waste water Filtration system with phytoremediation used in aquaculture of freshwater ornamental fish." In Proceedings of the International Conference on Industrial Engineering and Operations Management, pp. 1333-1334. 2020.

[12] Sriram, Gnana Yashaswini, and NB Sai Shibu. "Design and Implementation of Automated Aquaponic System with Real-time Remote Monitoring." In 2021 Advanced Communication Technologies and Signal Processing (ACTS), pp. 1-6. IEEE, 2021. https://doi.org/10.1109/ACTS53447.2021.9708396

[13] Uddin, Mohammad Salah, Jannat Binta Alam, and Suraiya Banu. "Real time patient monitoring system based on Internet of Things." In 2017 4th International conference on Advances in Electrical Engineering (ICAEE), pp. 516-521. IEEE, 2017. https://doi.org/10.1109/ICAEE.2017.8255410

[14] Lennard, Wilson, and James Ward. "A comparison of plant growth rates between an NFT hydroponic system and an NFT aquaponic system." Horticulturae 5, no. 2 (2019): 27. https://doi.org/10.3390/horticulturae5020027

[15] Vernandhes, Wanda, Nur Sultan Salahuddin, A. Kowanda, and Sri Poernomo Sari. "Smart aquaponic with monitoring and control system based on IoT." In 2017 second international conference on informatics and computing (ICIC), pp. 1-6. IEEE, 2017. https://doi.org/10.1109/IAC.2017.8280590

[16] Rani, Muhammad Al Baihaqi Mat, and Izanoordina Ahmad. "Development of IoT Based Aquaponic Monitoring System for Agriculture Application." Journal of Engineering Technology 10, no. 1 (2022): 1-6.

[17] Mahmoud, M. M. M., Rania Darwish, and A. M. Bassiuny. "Development of a Smart Aquaponic System Based on IoT." In 2023 23rd International Conference on Control, Automation and Systems (ICCAS), pp. 1592-1597. IEEE, 2023. https://doi.org/10.23919/ICCAS59377.2023.10317034

[18] Fisheries and Aquaculture Department, "Management of the Aquaponic Systems," in Food and Agriculture Organization of the United Nations, pp. 1–10. 2015.

[19] Yanes, A. Reyes, P. Martinez, and R. Ahmad. "Towards automated aquaponics: A review on monitoring, IoT, and smart systems." Journal of Cleaner Production 263 (2020): 121571. https://doi.org/10.1016/j.jclepro.2020.121571

[20] Yang, Teng, and Hye-Ji Kim. "Characterizing nutrient composition and concentration in tomato-, basil-, and lettuce-based aquaponic and hydroponic systems." Water 12, no. 5 (2020): 1259. https://doi.org/10.3390/w12051259

[21] Somerville, Christopher, Moti Cohen, Edoardo Pantanella, Austin Stankus, and Alessandro Lovatelli. "Small-scale aquaponic food production: integrated fish and plant farming." FAO Fisheries and aquaculture technical paper 589 (2014): I.