Designing and Implementing IoT-Based Water Quality Monitoring and Control System of a Pilot Scale Deep Flow Technique Aquaponics for Enhanced Crop-Fish Production

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Abstract. Aquaponics is an agricultural model that combines aquaculture and hydroponic cultivation systems, which can be a solution for expanding agricultural land in urban areas. The success of an aquaponics system heavily relies on maintaining optimal pond water quality, which serves as a vital source of nutrition for plants and ensures the survival of fish. Many studies have been conducted to build a system that maintains the good quality of pond water, but much of it only utilizes a limited number of parameters. This study was conducted to develop a robust control system capable of monitoring and regulating the water quality parameters, temperature, pH, dissolved oxygen (DO), and total dissolved solids (TDS), in real-time using IoT based system and fuzzy logic as a control method for decision-making. Users can monitor the condition of the pond using web interfaces that can be accessed via desktop or mobile devices. The design implementation results on the DFT aquaponics system showed an increase in the growth of paddy crops and tilapia with precision data recorded on the cloud server of 94.11%.

1 Introduction

Amidst the population growth in developed countries that face limited land availability for agriculture, such as Japan and Singapore, extensive efforts are being made through urban farming as a means of agricultural expansion. Urban farming involves shifting from conventional farming practices to urban areas, utilizing minimal and sustainable land resources to achieve agricultural resource efficiency [1]. One of the implementations of urban farming is the development of vertical farming models, such as aquaponics. Aquaponics is a combination of aquaculture techniques with hydroponic model plant cultivation. The primary goal of this system is to maximize land utilization and utilize the ammonia cycle from aquaculture water as a nutrient supply for hydroponic plants. [2]. The success of an aquaponics system is determined by the water quality in the aquaponic ponds, as it significantly affects the growth of both plants and fish [3]. The parameters of pond water quality can be assessed through primary variables such as pH, dissolved oxygen (DO), and

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temperature, as well as secondary variables including turbidity, phosphate (PO_4), nitrite (NO_2), nitrate (NO_3), and ammonia (NH_3) [4]. Given the diverse range of parameters that influence water quality, a monitoring and control system is necessary to facilitate users in monitoring and maintaining these parameters at safe levels for the survival of fish and aquaponic plants.

In its development, various designs of aquaponics systems have been created. Megawati et al. [5] designed an IoT-based monitoring system for pH and temperature in aquaponic ponds. Muhammad Airlangga et al. [6] developed a nutrient control system for aquaponics using fuzzy algorithms as the decision-making model to enhance the growth quality of fish and plants. Lettuce and catfish were used as the observed objects in their study. The TDS (Total Dissolved Solids) and water turbidity parameters were observed, and their values were used as references by the control system to determine the output value of the pump.

Furthermore, Cahyantara [7] observed the dissolved oxygen conditions and engineered the ideal ones for tilapia fish's growth. The constructed system utilized a fuzzy logic controller as the determining factor for the output. In their research, lettuce, and tilapia fish were used as the subjects. Based on references [5] – [7], there is currently no implementation of a system that utilizes more than two water quality parameters as inputs and focuses on a specific plant object, such as rice. Usually, in this field of study hydroponic plants such as lettuce, pak choi, and water spinach are used. Current research related to paddy crops is limited to prototype-scale experiments using an aquarium and PVC pipes with a single planting point [8].

Therefore, in order to address the research gap previously outlined, this study was conducted to develop a robust control system capable of monitoring and regulating the water quality parameters, namely temperature, pH, dissolved oxygen (DO), and total dissolved solids (TDS), in real-time using fuzzy logic as a control method for decision-making. The aim is to create an ideal environment for tilapia fish and rice growth.

2 Methods

First, an aquaponic system was designed using the deep flow technique method. Once the aquaponic system was assembled, implementation was carried out without a control system. The aquaponics system was filled with eight samples of paddy crops and fifty tilapia fish with a seed size of 5 cm. Next, a fuzzy inference system was designed by selecting the Mamdani algorithm as the fuzzy inference engine. After the fuzzy model design was completed, the aquaponic control system assembly was performed, which involved hardware design and a dashboard interface for monitoring and control purposes. Prior to the implementation stage, the prepared system underwent observation and reliability testing to ensure its proper functioning. The stages of this research can be seen in Figure 1.

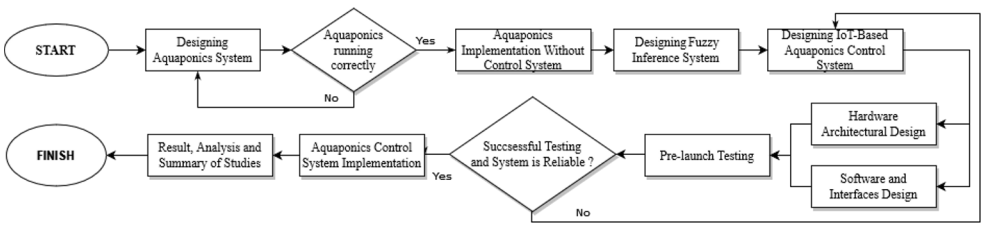


Fig. 1. Research flowchart diagram

2.1 Design of Aquaponics System

There are various types of aquaponic systems, such as media beds, nutrient film techniques (NFT), or deep flow techniques (DFT). This study uses the deep flow technique as the preferred method due to its advantages in water circulation and nutrient delivery [3].

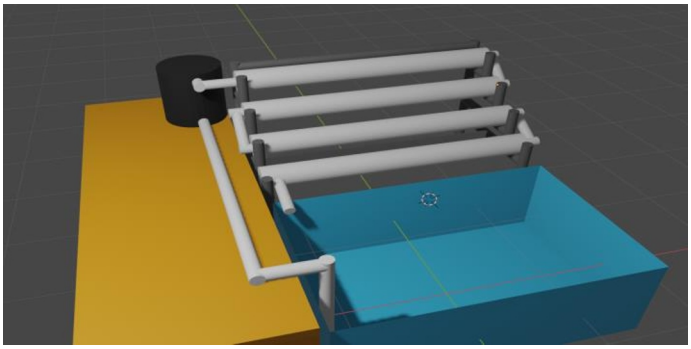


Fig. 2. Aquaponic design model

As shown in Figure 2, the system consists of a pond with a volume of 750 liters (1 x 1.5 x 0.5 m^3) and a hydroponic pipe with 16 planting points. The hydroponic container made from PVC pipe is designed to hold stagnant water at a height ranging from 2 to 4 cm. Throughout the research, the pond will be populated with 50 tilapia fish fry and eight rice seedlings placed in the hydroponic planting points. A pump with a maximum power of 100 watts is installed in the aquaponics system to circulate the water. This pump can deliver water at a flow rate of up to 4000 liters per hour.

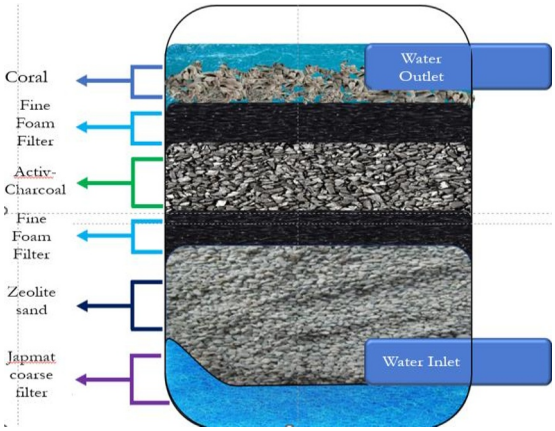


Fig. 3. Illustration of the water filter component

Before entering the hydroponic pipes, the pumped water is first filtered through a 20-liter filtration bucket. The filtration bucket is designed to maintain the water's pH and dissolved solids content before it is directed into the hydroponic system. Additionally, the filtration bucket serves as a medium for the growth of *Nitrosomonas sp.* and *Nitrobacter sp.* bacteria. The filter bucket comprises various filling materials, as depicted in Figure 3.

2.2 Design of Fuzzy Inference System

Fuzzy Inference System was used to control the water pump speed and aerator output in the aquaponics pond. The design uses MATLAB software and utilizes the Mamdani method in the FIS control system design. The design of the FIS involves three stages: fuzzification, inference, and defuzzification [9]. FIS control takes four inputs to generate two inputs. The inputs to the FIS are TDS, pH, DO, and temperature observed from the aquaponics pond. From these four variables, the FIS produces output as duty cycle percentage values for PWM signals, which will control the water pump and aerator.

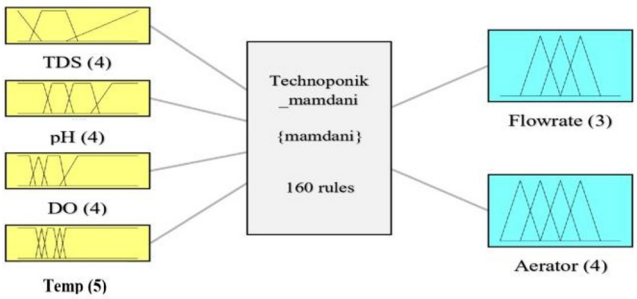


Fig. 4. FIS schema in Matlab

2.2.1 Fuzzification

The fuzzification process takes a crisp value from each input variable and converts it into a set of fuzzy linguistic terms. Based on previous literacy studies, each variable will be sorted into membership function categories that suit the condition.

Based on the literature collected, there is no specific statement regarding the optimal TDS value for cultivation. However, according to the research conducted by Christin [10], a range of 200 – 400 ppm was obtained. It is noted that for TDS values of 300– 400 ppm, the pond received the addition of 120 mg/L of calcium carbonate. Therefore, the TDS parameter has two triangular membership functions of $f_{[low]}$(0;0;200) and $f_{[lethal]}$(400;1000;1500), and one trapezoidal membership function of $f_{[optimum]}$(100;200;400;500).

The optimal range for water acidity (pH) for fish is typically between 6.5 and 8.5. Due to decreased red blood cells, Nile tilapia fish will experience reduced movement and decreased appetite at pH levels between 4 and 5.5. Mortality rates reach 100% at a pH of 3 [11]. Therefore, the pH has four trapezoidal membership function: $f_{[lethal\_low]}$(0;0;3;4), $f_{[inhibitory\_low]}$(3;4.5;5;6.5), $f_{[optimum]}$(5.5;6.5;8.5;9.5), and $f_{[lethal\_high]}$(8.5;11;15;15)

Good dissolved oxygen (DO) levels for fish are typically above 5 ppm. The average DO value in distilled water at temperatures between 25 – 32 °C ranges from 8 – 7 ppm. Distilled water can only hold oxygen up to 11 – 12 ppm before entering the oversaturated phase [7]. In natural ecosystems, however, aquatic environments can have saturation values of 150 – 200% compared to laboratory scenarios [12]. Research conducted by Vitas Atmadi et al. [13] states that low levels of dissolved oxygen cause hypoxia on fish. For Nile tilapia, a DO level below one ppm leads to 100% mortality, while in the range of 2 – 4 ppm, tilapia experience hypoxia with a significant decrease in oxygen consumption by up to 70% and a mortality rate of 50%. The study provides detailed insights into the specific oxygen conditions that induce hypoxia in Nile tilapia at various stages of dissolved oxygen levels.

Based on the result of the study, The fuzzy sets defined for the dissolved oxygen parameter are three trapezoidal membership functions of $f_{[lethal\_low]}$(0;0;2;3),

$f_{[optimum]}$(5.5;6.5;8.5;9.5), $f_{[oversaturated]}$(7;10;20;20) and one triangular membership function of $f_{[inhibitory\_low]}$(2;3.5;5.5),

Nile tilapia can grow optimally at room temperature within 25 – 30 °C range. The lowest critical temperature that Nile tilapia can tolerate is 13 °C, although this value can vary by 1 – 2 °C depending on water conditions, the presence of hypoxia in fish, and other factors. Therefore, a lower critical temperature set point of 15 °C was established for the fuzzy design. Similarly, the highest critical temperature set point was determined to be 38.8 °C with an offset of 1 – 2 °C, according to Leonard and Skov [14]. However, research conducted by Pandit and Nakamura [15] concluded that Nile tilapia could survive up to 40 – 42 °C as their cultured Nile tilapia exhibited a survivability rate of 57% at a temperature of 37 °C. Therefore temperature parameter consists of three trapezoidal membership functions of $f_{[lethal\_cold]}$(0;0;15;20), $f_{[optimum]}$(20;25;30;35), and $f_{[lethal\_hot]}$(35;40;100;100) and two triangular membership function of $f_{[inhibitory\_cold]}$(15;20;25) and $f_{[inhibitory\_hot]}$(30;35;40).

2.2.2 Inference

In the inference stage, fuzzy logic will map the inputs from the given parameters to determine the output based on their input values. Fuzzy logic employs if-then rules in drawing conclusions table and takes the implications based on the fuzzy rule set given, resulting in a complete rule–base constraint of aggregated linguistic variables. In this design, the system has 160 fuzzy rule bases. Table 1 is example of fuzzy rule base used in the design.

Table 1. Fuzzy inference rule–base.

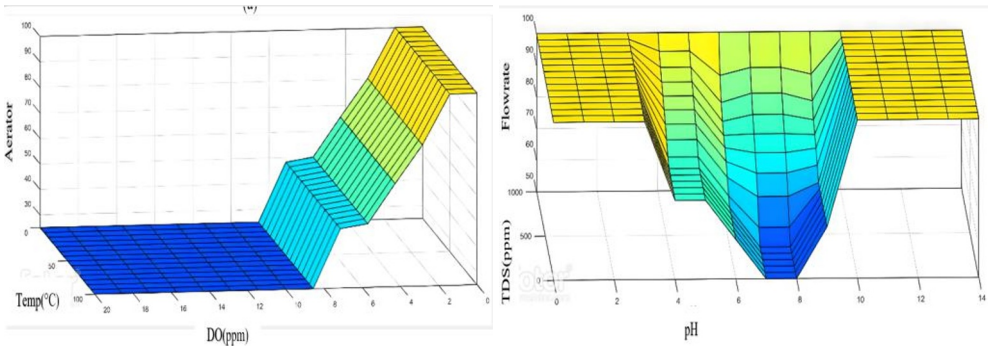
No	Rule Base
1	If(TDS is not lethal) and (pH is lethal_low) and (DO is lethal_low) and (Temp is optimum) then (Flowrate is high_perf)(Aerator is high_perf)
2	If(TDS is not lethal) and (pH is lethal_low) and (DO is lethal_low) and (Temp is inhibitory_cold) then (Flowrate is high_perf) (Aerator is high_perf)
…	……
53	If(TDS is not lethal) and (pH is lethal_low) and (DO is inhibitory_low) and (Temp is optimum) then (Flowrate is high_perf)(Aerator is high_perf)
54	If(TDS is not lethal) and (pH is lethal_low) and (DO is lethal_low) and (Temp is lethal_hot) then (Flowrate is high_perf)(Aerator is high_perf)
…	……
159	If(TDS is lethal) and (pH is inhibitory_low) and (DO is optimum) and (Temp is inhibitory_hot) then (Flowrate is high_perf)(Aerator is high_perf)
160	If(TDS is lethal) and (pH is inhibitory_low) and (DO is optimum) and (Temp is lethal_hot) then (Flowrate is high_perf)(Aerator is high_perf)

2.2.3 Defuzzification

In the defuzzification stage, a numerical value is generated from the aggregated linguistic variables inferred in the inference stage. This numerical value is obtained based on the membership functions of the fuzzy output values. This study the centroid method is used for defuzzification. Centroid or Center of Area method works by summing the result area divided by the product of max value of each set, resulting in a representative crisp value that summarizes the overall fuzzy output set.

For the pump output, in Figure 5 (b), the influencing fuzzy input values are temperature, pH, and TDS. Meanwhile the aerator is influenced by DO and temperature only as shown in

Figure 5 (a). The minimum output value for the pump is set at 50% power. It is because, below 50% power, the water output is insufficient to reach the hydroponic pipes positioned at the height of ± 1.3 meters from the pump. The aerator has a minimum output value of 25% of the maximum power. Below this threshold, the aerator is automatically turned off and does not supply air to the fish pond.



(a) (b)

Fig. 5. Defuzzification result area : (a) water pump, and (b) aerator

2.3 Control System Design

2.3.1 Hardware Design

The system is programmed based on the flowchart of the programming, which can be seen in Figure 6 The system consists of two parts: the ESP-32 is responsible for processing the inputs and generating PWM values for the outputs. Additionally, the ESP-32 circuit displays data to the user through the LCD interface. The Arduino Uno converts the PWM values into analog signal output for the pump and aerator through an AC dimmer.

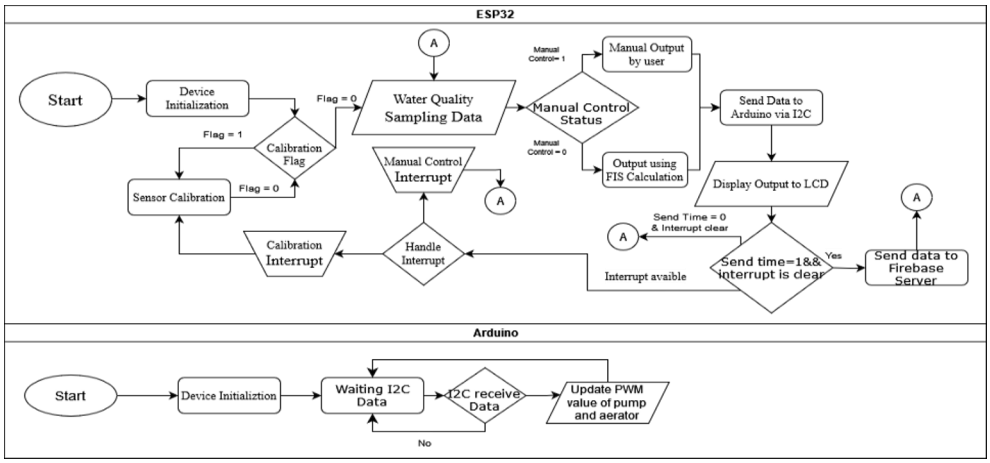


Fig. 6. Control system flowchart

On the sensor side, ESP-32 is connected to various sensors and LCDs for display information. As shown in Figure 7, ESP-32 communicates with Arduino Uno via UART to send the fuzzy output to be processed as pump and aerator speed output.

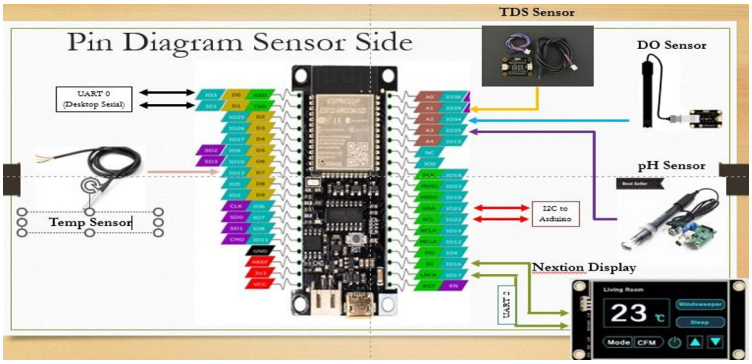


Fig. 7. Pin diagram on the sensor side

On the actuator side as depicted in Figure 8, Arduino Uno is connected to a dimmer module that regulates the AC current for the water pump and aerator. PWM from uno becomes the signal representing the On-Off time of the AC current reaching the pump and aerator.

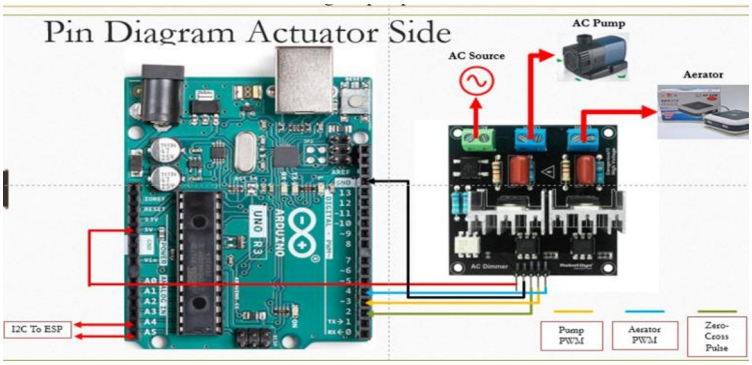


Fig. 8. Pin diagram on the actuator side

2.3.2 Software and Interface Design

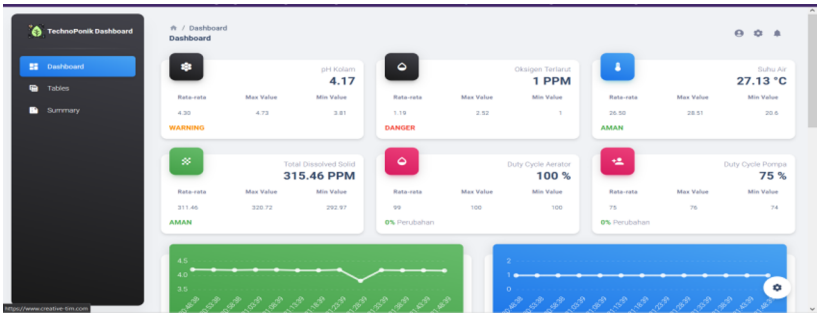


Fig. 9. IoT dashboard for the user interface.

The software is built using IoT-based architecture. According to IEE [16], IoT is a group of infrastructures that connects objects through the internet, enabling them to communicate with each other in activities such as management, data mining, and sharing access to generated data. For the user interface shown in Figure 9, an IoT dashboard is designed using the React.Js platform to facilitate interoperability and mobile access through a browser. Through the dashboard interface, users can view real-time monitoring results. Data is stored in scalable storage provided by Google Firebase.

2.4 Control System Implementation

Figure 10 is the system implementation used paddy crops and tilapia fish as the observed objects. There were eight planting cups, each cup contains four to six rice seeds and a pond with fifty tilapia fish. The implementation lasted four weeks, with the control system fully utilizing FIS as the decision-making mechanism for the aerator and water pump outputs. The implementation began on October 4th, 2022, and concluded on November 5th, 2022.

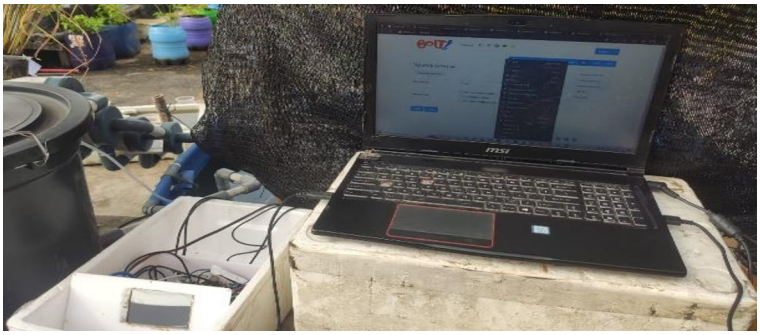


Fig. 10. System deployment

3 Research results and discussion

3.1 Control System Reliability Test

Reliability testing was conducted to ensure the system's proper functioning by examining the collected data over one week. If reliable results were not obtained, the design of the control system would be revised. The system can be considered reliable if it meets several criteria, the first one is consistency. The system must consistently produce accurate and consistent results over multiple trials or measurements, represented by noise and data deviation over vendor specification below 10%. The second one is stability, the system must be able to maintain its performance and functionality over an extended period without significant fluctuations or deviations represented by data lost below 5%. The last one is validity, the system's outputs must be aligned with the expected outcomes based on established scientific principles and theoretical foundations from previous studies that have been collected.

Table 2. Data noise occurrence during reliability test.

No	Parameter	Data Noise	Total Data	Percentage (%)
1	TDS	0		0
2	pH	60	1622	3.699
3	DO	0		0
4	Temperature	5		0.308

Data noise in Table 2 was determined using threshold value from a simple moving average of data recorded ± the given vendor accuracy value, Figure 11 is example of data noise occurance in one day.

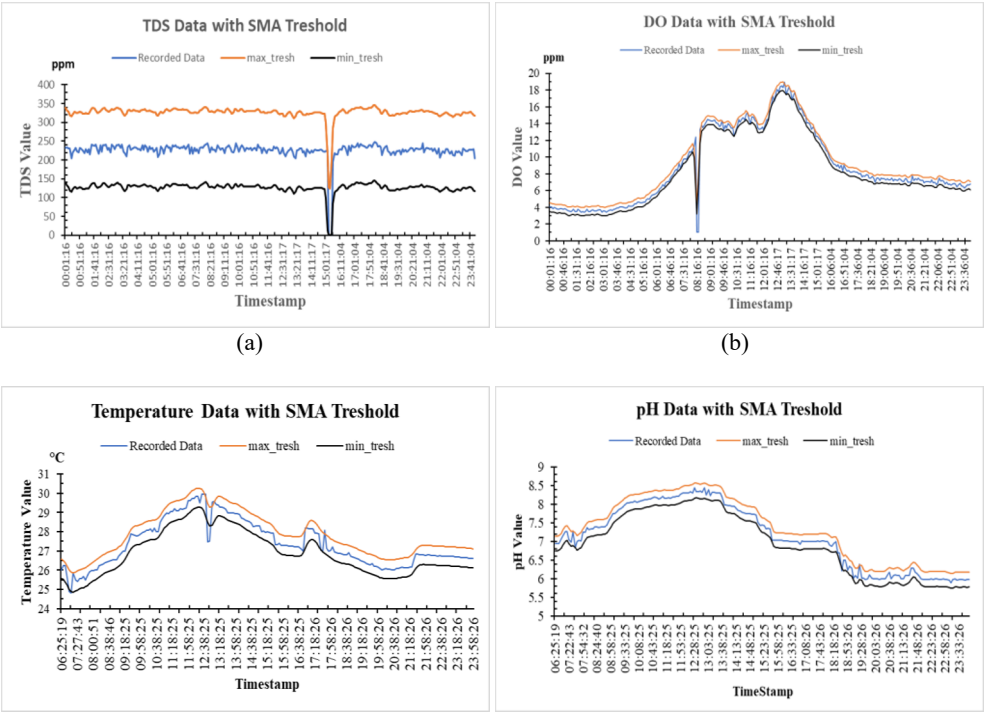


Fig. 11. Data with SMA threshold of : (a) TDS, (b) DO, (c) Temperature, and (d) pH

Laboratory testing was conducted on the water from the aquaponics pond to validate the monitored parameter values. The laboratory tests were carried out at CDU Lab Semarang. The results can be seen in Table 3.

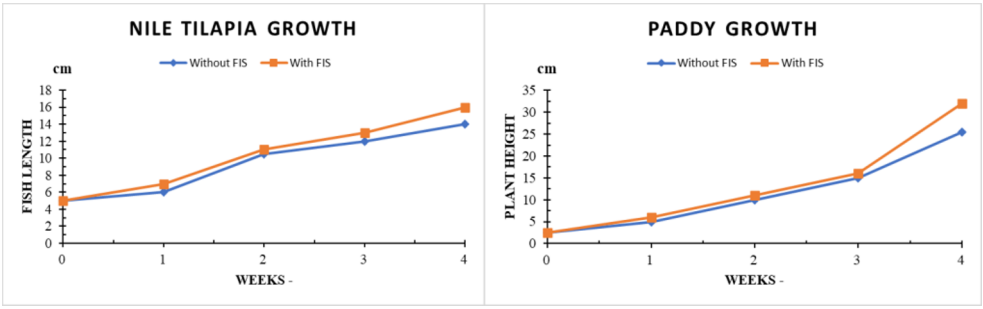
Table 3. Laboratory check result

No	Parameter	Unit	Lab Result	Result on Field (Average)
1	TDS	mg/L	433	319.8491
2	pH	-	7.9	7.1669
3	Calcium	mg/L	36.8	-
4	Bicarbonate	mg/L	34.1	-
5	Temperature	°C	-	27.2367
6	DO	mg/L	-	7.4813

The system was deemed suitable for implementation after the observations conducted from September 24th to September 30th, 2022, demonstrated reliable data and behavior consistent with the literature review. Prior to the observations, the pond was subjected to treatment by adding 120 mg/L of Calcium Carbonate ($CaCO_3$).

3.2 Control System Implementation Result

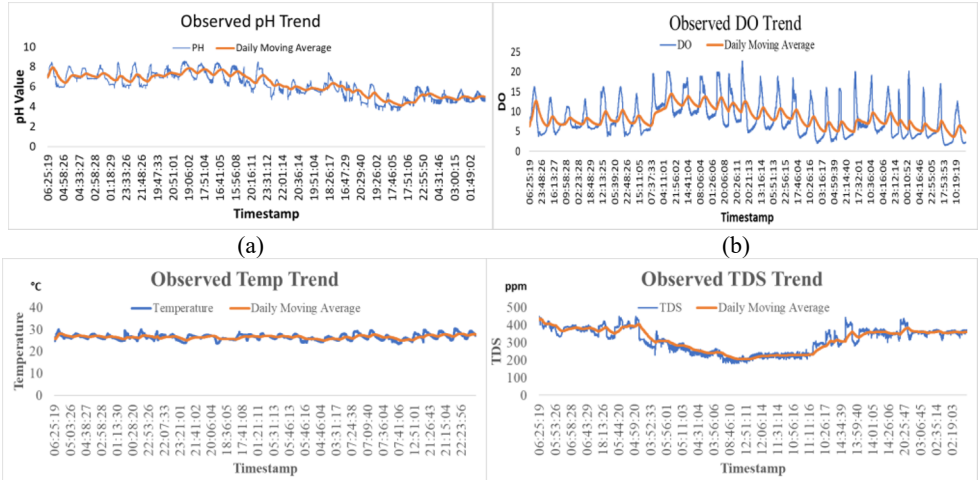
After implementing the control system for aquaponics for four weeks, from October 4th, 2022, to November 5th, 2022, data on the length of plants and fish were obtained from the cultivated samples. These data were compared with the results of cultivation without using the FIS control system.



(a) (b)

Fig. 12. Growth comparison graph : (a) Nile Tilapia, and (b) Paddy

Based on the data collected on Figure 12**.** there was an increase in the growth rate of both fish and paddy crops. It is consistent with the research conducted by Kadarani, et al. [17], where adding calcium carbonate can enhance the growth of cultured fish. Calcium carbonate stabilizes and maintains pH at a value of 6.5 – 7.5. In addition, hydrolyzed calcium ions (Ca^{2+}) entering through the fish's gills can aid in metabolism, strengthen bones, and contribute to blood clotting in fish. The increase in rice growth aligns with the findings of the study conducted by Elizabeth [18], where paddy crops experienced an increase in soil pH, it resulting in increased height and the number of tillers. This is proof that control system and good water filter resulting in a maintained optimum environment for fish and paddy to grow also contributes to increased growth shown in this study.



(a) (b)

(c) (d)

Fig. 13. Water quality data trend during implementation : (a) pH, (b) DO, (c) Temperature, and (d) TDS

Figure 13 show water quality parameters including pH, temperature, TDS, and DO exhibited daily stability conducive to the growth of both fish and rice plants in the system. The system effectively maintained water temperature within the ideal range of 26 – 28°C, kept TDS levels low at 300 – 450 ppm. The pH level maintained at optimum range, although experiencing a gradual decrease to 5 by the end of the study, the maintained pH level is within the optimal range for tilapia growth. Additionally, dissolved oxygen (DO) values showed daily variations within the range of 5 – 12 ppm, aligning with prior research indicating that dissolved oxygen tends to exhibit higher dynamism compared to other parameters due to influences from physical (temperature), biological, and chemical factors. Despite these fluctuations, DO values consistently supported the growth of both fish and rice plants. These findings highlight the system's effective management and maintenance of water quality parameters, creating an ideal environment for the organisms involved in aquaponic cultivation.

Table 4. Data noise during implementation

No	Parameter	Data Noise	Total Data	Error Rate (%)
1	TDS	14	8743	0.16
2	pH	447		5.11
3	DO	139		1.59
4	Temperature	515		5.89

Table 4 contains a summary of noise data during implementation, with the highest amount of noise occurring in the temperature data with 5.89 % error rate and the lowest being the TDS with 0.16 % of error rate. The calculation was determined using threshold value from a simple moving average of data recorded $\pm$ the given vendor accuracy value.

4 Conclusions

In conclusion, the design and implementation of the monitoring and control system utilizing fuzzy logic control on an ESP-32 microcontroller-based IoT platform for aquaponics paddy and Nile Tilapia farming have demonstrated successful performance. The system effectively regulated the parameters in line with the expected behaviour described in the literature, and it exhibited a high level of data precision, reaching up to 94.11%. Applying this control system in aquaponics improved growth rates for both fish and paddy crops. However, further research and development efforts are warranted to enhance the control system's capabilities and optimize its suitability for large-scale industrial applications. These advancements will contribute to aquaponics farming systems' overall efficiency and productivity.

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References

1. J. Wood and C. W. S. Paturi, "Vertical Farming: An Assessment of Singapore City," *eTropic: electronic journal of studies in the tropics,* vol. **19**, no. 2, pp. 228-248, 2020.
2. Butler, L. Michael and D. M. Maronek, "Urban and agricultural communities: Opportunities for common ground," CAST Task Force Report, 2002.
3. J. Chidiac, "Critical System Analysis: Deep Flow Technique (DFT) for Hydroponics," Linkedin, 23 Desember 2019. [Online]. Available: https://www.linkedin.com/pulse/critical-system-analysis-deep-flow-technique-dft-chidiac-msc-/. [Accessed 21 Maret 2022].
4. Direktorat Utama Pembinaan dan Pengembangan Hukum Pemeriksaan Keuangan Negara, "PERATURAN PEMERINTAH (PP) No.22 TAHUN 2021," 14 April 2021. [Online]. https://peraturan.bpk.go.id/Home/Details/161852/pp-no-22-tahun-2021. [Accessed 15 Januari 2023].
5. D. Megawati, K. Masykuroh and D. Kurnianto, "Rancang Bangun Sistem Monitoring PH Suhu Air Pada Akuaponik Berbasis Internet of Things," *Jurnal TELKA,* vol. **6**, no. 2, pp. 124-137, 2020.
6. M. Airlangga, A. Qurthobi and A. Suhendi, "Sistem Kontrol Nutrisi Pada Sayuran Sawi Hijau Dengan Metode Akuaponik Deep Flow Technique Berbasis Logika Fuzzy," *e-Proceeding of Engineering,* vol. **8**, no. 5, pp. 5979-5987, 2021.
7. A. R. Cahyantara, "Rancang Bangun Sistem Pengendali Kadar Oksigen Terlarut Dengan Algoritma Fuzzy Logic Controller Pada Budidaya Akuaponik," *Jurnal Teknik ITS,* vol. **6**, no. 2, pp. A707-A711, 2017.
8. D. A. Wahyudi, S. A. Wibowo and R. P. P, "Rancang Bangun Sistem Padi Aquaponik," *JATI (Jurnal Mahasiswa Teknik Informatika),* vol. **5**, no. 1, pp. 108-114, March 2021.
9. M. Rusli, Dasar Perancangan Kendali Logika Fuzzy, Malang, Jawa Timur: UB Media, 2017.
10. Y. Christin, I. W. Restu and G. R. A. Kartika, "Laju Pertumbuhan Ikan Nila (Oreochromis niloticus) Pada Tiga Sistem Resirkulasi yang Berbeda," in Proceeding of the *Current Trends in Aquatic Science,* vol. **IV**, no. 2, pp. 122-127, 2021.
11. M. K. Mustapha and S. D. Atolagbe, "Tolerance Level of Different Life Stages of Nile Tilapia Oreochromis Niloticus (Linnaeus, 1758) to Low pH and Acidified Waters," *The Journal of Basic and Applied Zoology,* vol. **79**, no. 1, pp. 1-6, 2018.
12. B. L. Querijero and A. L. Mercurio, "Water Quality in Aquaculture and Non-Aquaculture Sites in Taal Lake, Batangan, Philippines," *Journal of Experimental Biology and Agricultural Sciences,* vol. **4**, no. 1, pp. 109-115, 2016.
13. V. A. Prakoso and Y. J. Chang, "Pengaruh Hipoksia terhadap Konsumsi Oksigen pada Benih Ikan Nila," *Oseanologi dan Limnologi di Indonesia,* vol. **3**, no. 2, pp. 165-171, 2018.
14. J. N. Leonard and P. V. Skov, "Capacity for thermal adaptation in Nile tilapia (Oreochromis niloticus) : Effects on oxygen uptake and ventilation," *Journal of Thermal Biology,* vol. **105**, p. 103206, 2022.

15. N. Pandit and M. Nakamura, "Effect of High Temperature on Survival, Growth and Feed Conversion Ratio of Nile Tilapia, Oreochromis niloticus," *Our Nature,* vol. **8**, no. 1, pp. 219-224, 2010.
16. R. Minerva, A. Biru and D. Rotondi, "Towards a Definition of the Internet of Things (IoT)," *IEEE Internet Initiative,* vol. **1**, no. 1, pp. 1-86, 2015.
17. T. Kadarini, S. Z. Musthofa, S. Subandiyah and B. Priono, "Pengaruh Penambahan Kalsium Karbonat Dalam Media Pemeliharaan Ikan Rainbow Kurumoi (Melanotaenia parva) Terhadap Pertumbuhan Benih dan Produksi Larvanya," *Jurnal Riset Akuakultur,* vol. **10**, no. 2, pp. 187-197, 2015.
18. E. Kaya, "Pengaruh Pupuk Organik dan Pupuk NPK terhadap pH dan K-Tersedia Tanah serta Serapan-K, Pertumbuhan dan Hasil Padi Sawah (Oryza Sativa)," *Buana Sains ,* vol. **14**, no. 2, pp. 113-122, 2014.