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Building a Fish–Vegetable Coexistence System Based on a Wireless Sensor Network

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ABSTRACT The foremost purpose of this study is to use wireless sensor network (WSN) technology to build an intelligent fish–vegetable coexistence system. As a traditional fish–vegetable coexistence system lacks intelligent diagnoses, personnel and the original materials are difficult to control, and efficiency is low. We expect to remotely monitor the environmental values of the fish–vegetable coexistence system at any time through Internet of Things technology and to control the feeding time and the brightness of LED lamps. The key concept of this system is to ''let the fishes be farmers'', meaning that when the system is balanced, the nutrient supply and water purification can form a good circulation system as long as fish feed is provided and the evaporated moisture is supplemented in a timely manner. The main control board of the system is an Arduino Mega 2560, and the ZigBee communication protocol is used as a wireless transmission tool, which is combined with a temperature humidity sensor and an illuminance sensor. Thus, the performance of the traditional temperature humidity sensor is improved, and the fish yield is increased. Real-time monitoring can minimize the loss of fish. This expert system increases the success rate of culturing and planting, and the overall system efficiency is increased. Our team creates a human–computer interaction interface using the C# programming language. This interface can be used to monitor the current sensing values and store the data in an Excel data sheet, thus allowing users to query and analyze previously detected data. Users can monitor the system operation status and control the load through the designed human–machine interface to achieve smart network remote monitoring.

INDEX TERMS WSN, Internet of Things, sensor, fish–vegetable coexistence system, ZigBee.

I. INTRODUCTION

The world is confronted with problems such as environmental deterioration, continuously decreasing natural resources, and food shortages resulting from population growth as tillable fields decrease in size every year due to urbanization and industrialization. According to a crop prospect and food situation report published by the Food and Agriculture Organization (FAO) of the United Nations in 2002, global population is increasing rapidly and is estimated to exceed 9 billion by 2050. Therefore, the demand for food will increase by 1.2-1.4% annually over the next 40 years [1]. Our limited global resources must feed all people and satisfy human living standards; thus, humans have to maximize the development of natural resources while reducing the number of disasters resulting from rapid population growth [2], [3].

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While investments have been made in industry and daily life in the past, with the rise of the Internet of Things in recent years, investments in agriculture and fisheries have increased yearly. According to a report by the American farm investment platform AgFunder [4] in 2016, from 2010 to 2015, the amount of investment in the domain of agricultural technology increased to USD 4.6 billion, as shown in Fig. 1, which suggests that agricultural automation is an important research direction and trend.

As the population continuously increases, tillable lands are becoming increasingly scarce, and food supplies will become critical. To address these problems, in this study, we build an automatic fish–vegetable coexistence system for an agricultural and fishery production environment simulation based on the concept of the Internet of Things. Arduino Mega 2560 is used as the main control development board, and temperature, humidity, water level, illumination sensing modules, pH sensors, and dissolved oxygen sensors are used

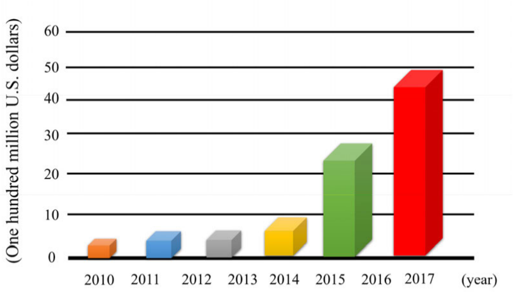

FIGURE 1. Agricultural technology tendency chart.

for monitoring. The captured physical sensing signals are processed, calculated, and transmitted to a terminal computer via ZigBee by a wireless sensor network (WSN), and the results are instantly displayed by the C# graphic control interface program on a monitoring sensing interface [5]. In this study, we use fuzzy theory for intelligent computing and a rule base to analyze the growth of plants and fishes in real time. To assess growth problems, a relay is connected, and a heating rod, aerator, and fan are controlled. When the water pH is too low or the dissolved oxygen is insufficient, the user is reminded to improve the water quality to reduce the death rate of plants and fishes resulting from the nonideal habitat. Finally, the information is stored in a computer database for the user to recall the overall culture and growing processes and thus seek the optimal culture habitat [6], [7].

The hydroponic system depends on elaborately prepared artificial nutrient solutions to meet the optimal growth conditions of plants. These nutrient solutions are prepared by mixing chemical substances, salts, and microelements according to a certain ratio. The water for hydroponics must be discharged periodically, as the chemical substances and salts will become toxins for plants when they accumulate to a certain extent in the water. The aquaculture system aims at the maximum increment of fishes in the culture tank or fishpond. The fishes are usually cultured at a high density in the culture tank; for example, 10 kg of fish is cultured in 100 L of water. Such a high density means that the water in the culture tank is likely to be contaminated, as the accumulation of fish feces releases a highly concentrated ammonia nitrogen mixture. Therefore, some cultivation farms change 10-20% of the water every day to prevent the fishes from being poisoned. If contaminated water is discharged without treatment, there may be a severe effect on nearby river courses and ecological environments. Aquaponics is combined with the two systems, and the negative points in the independent operation of the two systems are removed. Aquaponics uses fish metabolites with rich nutrients to replace chemical nutrient solutions for plant growth, and plants and root-fixing media are used to filter and purify the water in the culture tank to avoid water deterioration. Therefore, while the water in culture tanks can be reused forever, the evaporated water must be replenished periodically [8].

To increase the success rate of culture and planting to enhance user confidence, an expert system is built and integrated with the richness of the parameters correlated with hydroponic plants and cultured fishes, which can act as a powerful resource for users. By analyzing the data uploaded to the cloud from the sensors, this expert system can set the optimal operating parameters according to the fish fry and vegetable seedlings selected by the user, including the water level and illuminance. This expert system can also recommend fit fish fry and vegetable seedling species. This "fish–vegetable coexistence system" without chemical agents can enhance common acceptance of plant factories, as existing plant factories typically require additional nutrient solutions, which is likely to make consumers worry about food safety. A plant factory combined with a "fish–vegetable coexistence system" can guarantee food safety, and this innovative model can initiate more business opportunities in the future.

The traditional fish–vegetable symbiosis system lacks efficient and intelligent decision-making. This situation often makes it difficult to adjust and control personnel and raw materials. The proposed research uses Internet of Things technology to monitor and control the environmental values of the fish and vegetable symbiosis system from a remote center at any time. The system can effectively control the motor pumping, feeding time, and LED light brightness. The most important goal of this system is to "make fish a farmer". When the proposed system reaches an ecological balance, the nutrient supply and water purification of the system can form a virtuous cycle. Therefore, as long as the system provides fish feed and the timely replenishment of evaporated water, the entire fish–vegetable symbiosis system can circulate continuously.

The distribution of farms proposed by our research is shown in Figure 2. The upper part of the fish–vegetable symbiosis system is the plant growth platform. The lower half of the system is the fishpond. The size of each aquaponic unit is shown in Figure 3. The width of the unit is 3 meters, the length is 4 meters, and the height is 2 meters. The whole fish–vegetable symbiosis system has 10 independent units, as shown in Figure 4.

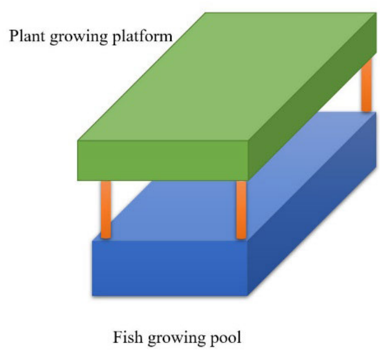

FIGURE 2. Fish and vegetable farm and fishpond.

II. LITERATURE REVIEW

The symbiosis of fish and vegetables can be traced historically, but there was initially some controversy. The Aztecs

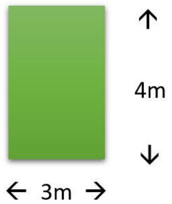

FIGURE 3. Fish and vegetable symbiosis platform unit.

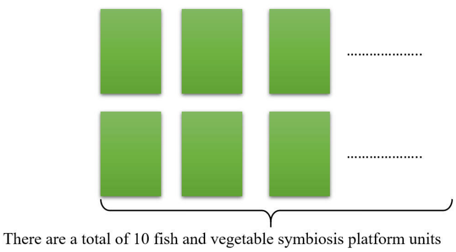

FIGURE 4. There are a total of 10 fish and vegetable symbiosis platform units.

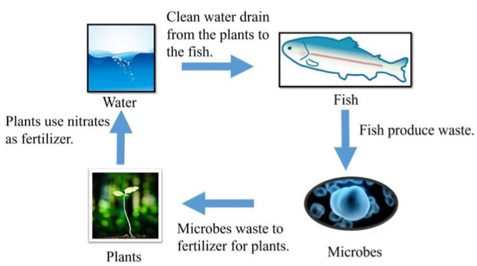

FIGURE 5. Principle of fish–vegetable coexistence circulation.

grew plants in shallow waters of a lake in 1150 and used rafts on the water. These islands, made of other materials, used the method of artificial floating islands to develop agriculture. Articles published by Dr. Mark McMurtry in the 1970s and Dr. James Rakocy [9] in 1997 pioneered the modern fish–vegetable coexistence system, and many papers regarding fish–vegetable coexistence have been subsequently published. The fish–vegetable coexistence system features closed water circulation, as shown in Fig. 5 [10], where fish feces produce ammonia in the water; the ammonia combines with the nitrifier in the water to form nitrite, which changes into nitrate; the water is pumped by a motor to the upper plant roots; the plants absorb the nutrients and purify the water. Finally, the purified water flows to the lower pond. After this series of processes, a ''fishes help vegetables and vegetables help fishes'' mutually beneficial system is built.

Wanda Vernandhes *et al.* noted that the fish–vegetable symbiosis system is highly suitable for indoor systems with some manipulations of light, temperature, and humidity for plants. Agricultural technology designs with fish and vegetable symbiosis are also beginning to use the Internet of Things because numerical information within the sensors and controllers of the system can be connected by the Internet. Operators can use smart phones for remote monitoring and control [11]. A. Zaini *et al.* also proposed monitoring and controlling the nutrient film technique (NFT) in a fish and vegetable symbiosis Internet of Things system [12]. As early as 1974, someone tried to combine a NFT with vegetable planting, and the results were promising [13]. After that, the technology continued to mature and develop [14]–[16] and was applied to the fish–vegetable symbiosis system [17]–[19]. Yaoguang Wei *et al.* noted that traditional planting and aquaculture consume massive amounts of water and land resources. In addition, water pollution is a human problem. Therefore, fish and vegetable symbiosis systems have been used to effectively solve these problems [20]. In addition, Wei Wang *et al.* designed an innovative fish and vegetable symbiosis system and used this system as an educational project [21].

Traditional fish and vegetable symbiosis systems have existed globally for some time. Our research uses a smart control system to improve the traditional fish and vegetable symbiosis system. We offer a framework for the wireless sensor network, and the integrated system is an intelligent control system. Therefore, in the development of the current fish and vegetable symbiosis systems, innovative technologies are integrated into the system architecture. At present, the development of aquaponic systems is almost always improved by using general electronic devices, but wireless sensor networks have been rarely studied. Our research aims to improve the traditional fish–vegetable symbiosis system into an intelligent fish–vegetable symbiosis automatic monitoring and control system. This is an innovative way to implement and improve traditional systems.

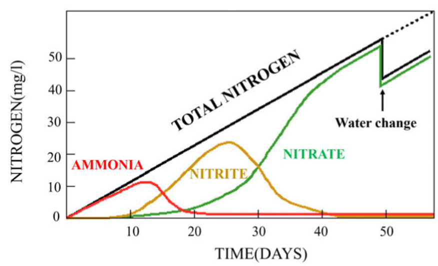

FIGURE 6. Nitrogen cycle and schedule.

A. FISH–VEGETABLE COEXISTENCE GROWTH ELEMENTS

The nitrogen cycle, which is the biological process of converting ammonia into a relatively harmless nitrogen compound, is the most important part of the fish–vegetable coexistence system [22], as shown in Fig. 6. In the cyclic process, the ammonia content increases, and after the nitrite-forming bacteria are stabilized, the ammonia content decreases suddenly. The bacteria that form nitrite will not occur until the amount of nitrite is considerable; thus, the nitrite content increases suddenly (when the accumulated ammonia is converted). When the continuously generated ammonia is turned into nitrite, the content of nitrite increases continuously. When the nitrate-forming bacteria are stabilized, the nitrite content decreases, the nitrate content increases, and the fish culture barrel finishes a full cycle.

The water temperature affects the overall system effectiveness. Generally, the optimal temperature for fish growth is 18-30 °C, and this temperature is acceptable for both nitrifiers and crops. If the water temperature is too high, the dissolved oxygen in water decreases. If the water temperature is too low, the mobility of fishes is reduced, their metabolism is slowed, and the growth of fishes is affected, leading to lower mobility or death of the nitrifier, and the nutrients for plant growth are affected [10].

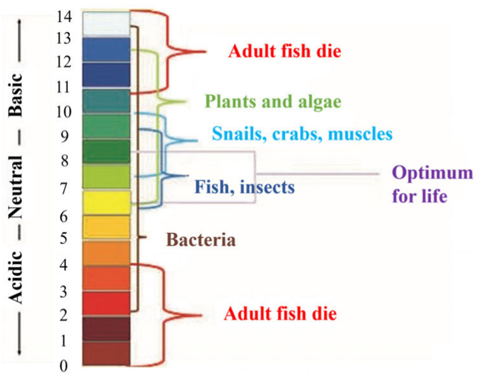

FIGURE 7. Optimal pH for biological growth.

The pH of water has a significant effect on the fish–vegetable coexistence system, especially on plants and nitrobacteria. pH affects the ability of plants to absorb nutrients. In the fish–vegetable coexistence system, to obtain plant growth, fish growth, and nitrifier growth equilibrium, the optimal pH is 6.8–7.2 [23], [24], as shown in Fig. 7 [25], [26]; however, if the pH is higher or lower than this range, the utilization rate of nutrients in the water by crops will decrease rapidly. When the pH is high, some very important elements are isolated and cannot be used by plants. Iron deficiency can be diagnosed visually according to leaf yellowing, especially at the tips. Some plants require more iron than others, and they are more likely to be affected by this condition. Nitrification is the biological process implemented by beneficial bacteria converting ammonia into nitrate, which is of vital importance and is most effective at an alkaline pH. When the pH decreases, the nitrification rate decreases, and when the pH is 5.5 or lower, this process is severely suppressed. As these levels create compressive conditions for fishes, they often cause diseases and eventually result in the death of fishes.

Figure 8 shows the tolerance of fishes to dissolved oxygen in water [23]. Most fishes need 4–5 ppm of dissolved oxygen; when the fishes float on the water surface to breathe, this means that the dissolved oxygen in the water is insufficient. This is an emergency that must be noticed immediately

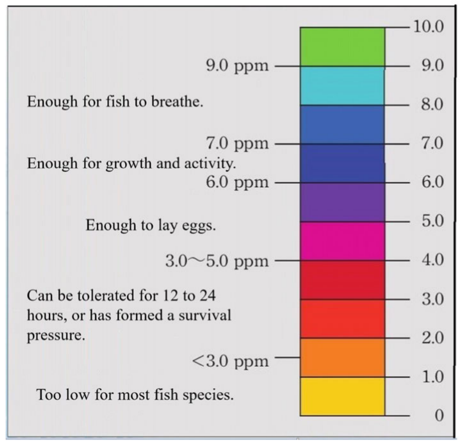

FIGURE 8. Tolerance of fishes to dissolved oxygen.

because when the dissolved oxygen is lower than 3 ppm, even strong fishes will die. The consumption of dissolved oxygen will induce significant changes in aquatic species in water [26].

TABLE 1. Photosynthesis absorption curves.

Class	Wavelength	Effect
UV	315 ~400 nm	No direct effect on plant growth, low chlorophyll absorption, influencing photoperiodic effect, preventing stems from stretching.
Blue light	400 ~ 520 nm	Directly contributing to the development of plant root and stem parts, maximum absorption ratio for chlorophyll and carotenoid, greatest effect on photosynthesis.
Green light	520~610 nm	Green plant repulsion, low marennin absorptivity.
Red light	610 ~ 720 nm	Lower plant chlorophyll absorptivity than blue light, significant effect on photosynthesis and plant growth rate.
Infrared ray	720 ~ 1000 nm	Low absorptivity of plants, directly stimulating the growth of vegetable cells, influencing blooming and germination.

Light is the most fundamental element for plant growth, and in the absence of sunlight, lights of different wavelengths and intensities have different effects on plant absorption. The UV wavelengths (300~400 nm) and near infrared light (700~800 nm) can affect crop growth response and appearance. The light rays within 400~700 nm are related to photosynthesis; the light in this band is called photosynthetically active radiation (PAR). Different plants or different organisms need lights of different wavelengths [27], [28], as shown in Table 1. In the photosynthesis of plants, blue light of 400~520 nm wavelength and red light of 610~720 nm wavelength have maximum contributions, as shown in Fig. 9. The energy distribution of a white light LED lamp has two peaks in the blue region of 445 nm and the greenish yellow region of 550 nm, and the (610~720 nm) red light for plants

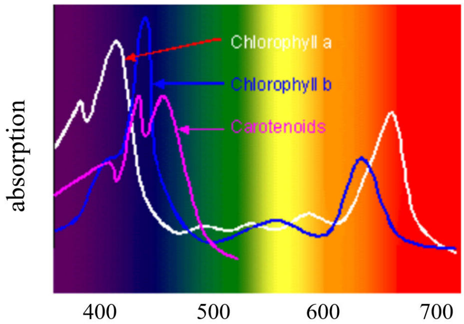

FIGURE 9. Plant photosynthesis absorption curves.

is very deficient. Therefore, the white light from LEDs is unfavorable for plant growth.

B. AUTOMATED ENVIRONMENTAL CONTROL FOR FISH–VEGETABLE COEXISTENCE

Among the studies of wireless monitoring systems for fish–vegetable coexistence, Nagayo *et al.* used the Global System for Mobile Communications (GSM) as a WSN in Oman, where there is water deficiency, to send information through mobile phone short messages, which was combined with the LabVIEW human-machine interface to receive values and control the system and then combined with solar power generation, thus forming a complete system [29].

Kumar *et al.* used 6LoWPAN as a wireless sensor interface to test nitrogen content, pH value, and temperature and built a self-regulating system able to collect messages about water quality and store them in a cloud database. They also implemented "connected aquaponics" involving a WSN and Next-Gen Telco to increase crop yield and provide sustainable organic food for international communities [30].

Shaout *et al.* used a low-cost monitoring and control system [31], [32], with Arduino Uno R3 as the development board, and proposed fuzzy control. The system monitored water temperature, pH, air temperature, and brightness, and a MATLAB human–machine interface was used for equipment control and monitoring. The warnings were finished by the free Things peak server tool; effective work was proven, and there were responses to instabilities in the fish–vegetable coexistence system.

C. WIRELESS COMMUNICATION TECHNOLOGIES

The wireless communication technologies used in the literature include ZigBee Bluetooth, infrared and Wi-Fi. Since the network in this paper uses a wireless sensing network architecture, it is more suitable to use ZigBee for wireless sensing signal transmission. We have discussed the advantages of using ZigBee wireless transmission in a related paper [5]. The ZigBee wireless communication protocol has excellent performance in low SNR environments. In the ZigBee Alliance literature, ZigBee network noise and interference are minimal compared to other wireless networks. Please refer to Figure 10.

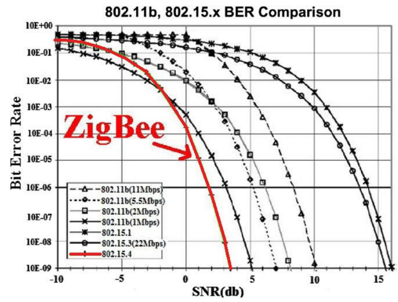

FIGURE 10. A BER of 802.15.4 has excellent performance in low SNR environments.

III. SYSTEM ARCHITECTURE DESIGN

The system in this study is divided into four major parts: environmental sensing, load control, terminal computers, and data storage. Environmental sensing is divided into plant growth sensing and fish growing environment sensing. There are three sensors used for plant growth sensing: temperature and humidity sensors and an illuminance sensor. There are water temperature, water level, pH, and dissolved oxygen sensors in the fish growing environment. The load control includes the control heater, LED lighting, a pumping motor, a fan, and an aerator. The data detected by the aforementioned sensors are sent by the ZigBee end device to the ZigBee coordinator, and the ZigBee reading module is connected to the terminal computer for monitoring and control. The terminal computer uses C# to design a graphical user interface for user control. The graphic control interface displays the environmental data sent from the sensors, as well as the appropriate default environmental parameters, through the fish–vegetable coexistence system to adjust the operating load control of the overall system, and Microsoft Excel is used in the terminal computer to store the sensing data so that users can perform subsequent analyses according to the stored data. The system architecture is shown in Fig. 11.

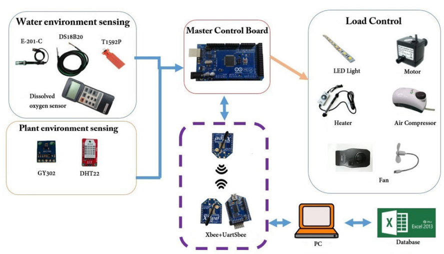

FIGURE 11. System architecture.

Figure 12 shows the system monitoring flowchart. First, the physical quantities detected by the sensors are converted by the Arduino Mega 2560 into digital signals and sent by the terminal ZigBee to the coordinator ZigBee end. Afterwards, the received data are transmitted via RS232 or USB to the terminal computer to display the current environmental conditions, and the data are stored in Excel for subsequent research analysis.

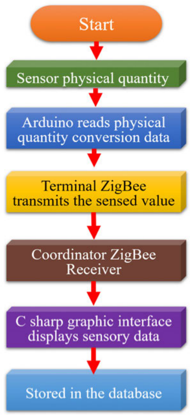

FIGURE 12. Environmental surveillance flowchart.

Number	Sensor and Load device
1	Water sensor, Fan1, Pump
2	Load control board, Fan2
3	Suction Pump
4	Main control board, XBee communicator module
5	Automatic feeder
6	pH detection sensor probe, Dissolved oxygen probe
7	Temperature, Humidity sensor
8	Illuminance sensor
9	LED strip

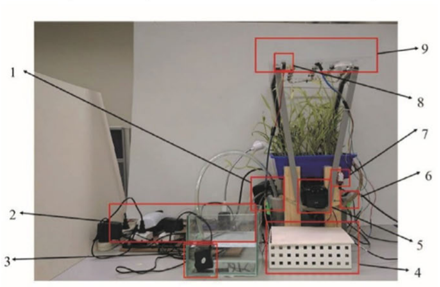

FIGURE 13. System end product.

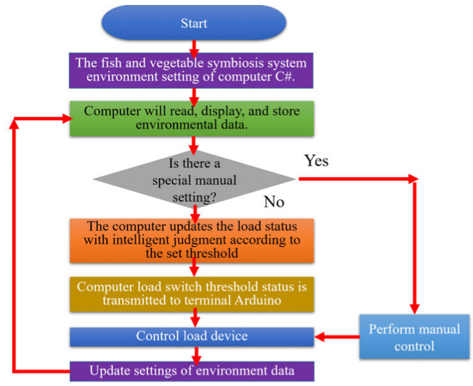

FIGURE 14. System environment control flow chart.

The system end product is shown in Fig. 13. Figure 14 shows the system environment control flow chart, where the threshold in the fish–vegetable coexistence system environment is set up on the terminal computer C# graphic control interface, the receiving system receives the environmental values, and then, whether or not they meet the threshold setting requirement is judged on the basis of fuzzy theory. If the environmental sensing mismatches the preset threshold, the system platform transmits control signals, which are transmitted to the end device over radio by the ZigBee coordinator, the signals are received and read by the Arduino board, and the relay switch is activated. In the case of emergency, the equipment can be controlled in manual mode, where the program interface directly controls the terminal loading equipment.

The WSN, as the main architecture, is divided into three parts. Part 1 is the development substrate and sensor measurement. The hardware of the development substrate is the Arduino Mega 2560 embedded microcomputer controller combined with a ZigBee module for data transmission, and the physical data in the environment are captured by the temperature humidity sensor, illuminance sensor, water temperature sensor, pH sensor, and dissolved oxygen sensor to master the plant growth and fish culture habitat. Part 2 is the software design. In this study, we use Microsoft Visual C# to design the terminal interface, where the ZigBee received data are displayed on the interface, and the interface can be used for wireless control of the loading equipment. The fuzzy theory is used in the interface, the loading equipment is controlled according to the habitat requirements for plants and fishes, and the user is informed to use intelligent networking. Part 3 uses Excel to store the received sensor physical data in the computer for future research on plant growth and fish growth, providing reliable empirical data for analysis.

A. HARDWARE ARCHITECTURE DESIGN

In this study, we use the Arduino Mega 2560 as the main development board, which uses an ATmega2560 as the processing chip. There are 54 sets of digital I/O ends (14 sets can be PWM output), 16 sets of analog input ends, 4 sets of UART (hardware serial ports), and an instruction cycle of 16 MHz.

As there is a boot loader, the programs can be directly downloaded via USB without other external programmers. The power can be supplied directly from a USB, or an AC-to-DC adapter and battery can be used as an external power supply.

During our experiment, the computer uses USB to connect to the hardware module of UartSBee, and this UartSBee hardware module is combined with the XBee hardware module to act as a coordinator node in the ZigBee network architecture. Therefore, the connection between the computer and UartSBee requires steps to set the COM port. The hardware module of the Arduino Mega 2560 uses the wireless hardware module of XBee to transmit the data measured by each sensing device. The system will send the sensor node data to the coordinator node for data analysis and integration. After the computer system is analyzed, the control command signal will be sent to the remote Arduino Mega 2560 hardware module via the ZigBee network. Then, the Arduino Mega 2560 will start each controller device to perform control and adjustment actions.

1) XBee

XBee, which is produced by the MaxStream Company, is a wireless communication module with a data acquisition function. Different models of XBee have different antenna types and functions; the common ones are S1 and S2 modules. The S2 module is used in this study. The XBee communication protocol uses the IEEE 802.15.4 standard, which works on the 2.4 GHz frequency band; the transmission distance is 30 m indoors and 100 m outdoors, and the working voltage is 2.8 to 3.4 V. The special expansion board for XBee can perform communication links via USB or RS-232.

2) TEMPERATURE HUMIDITY SENSING MODULE

In this study, we use the AM2302 digital temperature humidity module, which is a temperature humidity compound sensor with calibrated digital signal output and special digital module acquisition technology and temperature humidity sensing technology and features very high reliability and excellent long-term stability. The sensor comprises a capacitive humidity sensing element and an NTC temperature measuring element. Therefore, the product has excellent quality, ultrafast response, and strong interference resistance. The working voltage is 3 to 6 V, the measurable temperature range is −40 to 80°C, and the error is 0.5°C. The humidity measurement range is 0 to 100% RH (relative humidity), and the measurement error is within ±0.5%.

3) WATER TEMPERATURE SENSING MODULE

As the water temperature for plant and fish growth is specified to a certain extent, water temperature measurement is an important part. In this research, we use a DS18B20 waterproof temperature sensor cable module to measure the water temperature. The DS18B20 working voltage is 3.0 V to 5.5 V, with single line transmission; thus, data can be received with only one line. The temperature sensing range is −55 to 125°C, and the precision is ±0.5°C when the temperature is −10 to 85°C.

4) ILLUMINANCE SENSING MODULE

Illuminance intensity is also important for plant growth. In this study, we use the GY 302 illuminance sensing module, which contains a ROHM BH1750FVI chip. BH1750FVI is a digital environment light sensor IC for the I2C interface, which can analyze light intensity changes in the detection range according to the collected light intensity data. The working voltage is 4.5 V, and illuminance of 1∼65535 lux can be measured.

5) WATER LEVEL SENSING MODULE

The water level sensor module used in this study is the T1592 P water level sensing module, which is a water level sensing module that exports voltage according to water level. The higher the water level, the higher the voltage. Therefore, the present water level height can be known according to the voltage to exert control.

6) pH SENSOR

In this research, we use the Lei-ci E-201-C pH test rod and pH sensor module, which provide the output proportional to pH, and they can be connected directly to any microcontroller. The working voltage is 5 V, and the detectable concentration range is pH 0-14.

7) DISSOLVED OXYGEN METER

The dissolved oxygen meter used in this study is a Lutron DO-5510, and the measurable range of dissolved oxygen in water is 0-20 mg/L. The dissolved oxygen electrode probe is placed in the test liquid to measure the dissolved oxygen in the liquid, and the data are transferred to the PC or MCU via the RS232 output of the machine.

FIGURE 15. Loading equipment.

8) LOADING EQUIPMENT

The terminal loading equipment is shown in Fig. 15 and includes the pumping motor, fan, heater, aerator, LED lamp, and feeder. The heater and fan adjust the water and ambient temperatures to optimize the ambient temperature. The pumping motor adds water automatically, complementing the evaporated water quantity to reach the required volume. The LED lamp can adjust the light color, thus providing an optimal habitat for plants. The aerator increases the oxygen content in water. The feeder automatically supplies feed. The pumping motor, fan, and aerator are controlled by relay modules for load control; the relay modules are shown in Fig. 16.

9) SENSOR AND WIRELESS NETWORK ARCHITECTURE DIAGRAM

Our microcontroller is connected to multiple water environment sensors and plant environment sensors, and the microcontroller also receives data from each sensor at the same time. At the same time, it also sends data to the coordinator node through the XBee hardware module through the ZigBee protocol. These microcontrollers are connected to

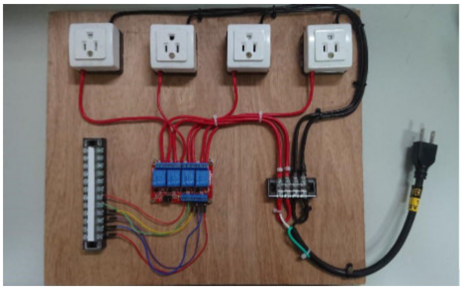

FIGURE 16. Load control relay modules.

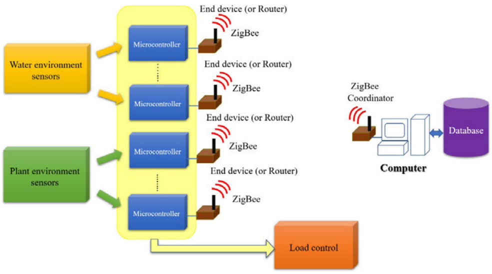

FIGURE 17. Sensor and wireless network architecture diagram.

XBee hardware modules and can be used as router nodes or end device nodes in the network architecture. These microcontrollers are contained in the Arduino Mega 2560. In addition to connecting sensors, they are also connected to load regulation control devices, such as motors, air compressors, fans, heaters, and LED lights. The coordinator node of the system is connected to the computer via USB. When the sensing data are analyzed and processed, they will be stored in the database, and the system will also send control commands to the remote microcontroller. Then, the microcontroller will perform adjustments to control each device until the sensor returns the data we expect. Please refer to the ZigBee node in Figure 17.

B. SOFTWARE ARCHITECTURE DESIGN

The software written by Arduino in this study is called Sketch (script). These scripts are written in the text editor, and the script name is the filename. In our system, there will be a login screen at the beginning; please refer to Figure 18. Our most powerful administrator account is Admin, and the rest are the login accounts of general operators. Each operator account has its own authority control. Therefore, system security is protected.

1) ZigBee

In this study, we use the ZigBee wireless network to display the environmental data of sensors on the C# graphic control interface; thus, the user can know the current growth data from the terminal computer. Figure 19 shows the main interface of the monitoring system.

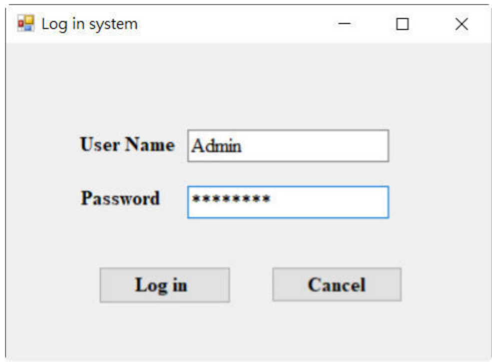

FIGURE 18. System login screen.

Figure 20 shows the communication port connection in the monitoring interface, which is located in the upper left corner of the monitoring interface. When the computer is linked, the computer port location shall be known; thus, all communication ports in the computer are displayed for the user, and the communication port for connecting ZigBee to the computer is selected. If there is no port selected, an error is displayed to remind the user to connect the correct communication port, as shown in Fig. 21.

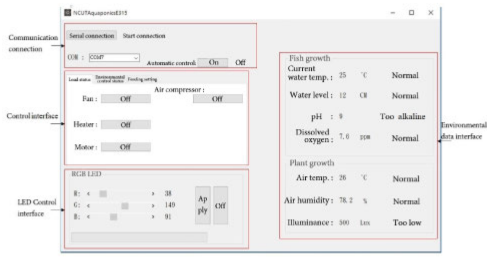

FIGURE 19. Main interface of the monitoring system.

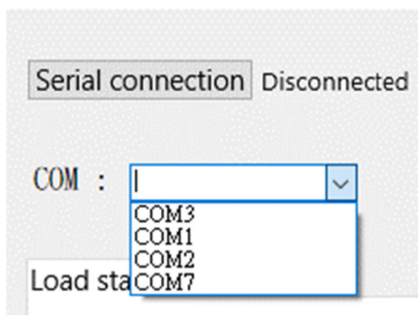

FIGURE 20. Communication port connection in monitoring interface.

Afterwards, the sensor values received by the display interface, as shown in Fig. 22, are divided into fish growth and plant growth parts. The fish growth part displays values including current water temperature, fishbowl water level, water pH, and dissolved oxygen in the water. The plant growth display values include air temperature, air humidity,

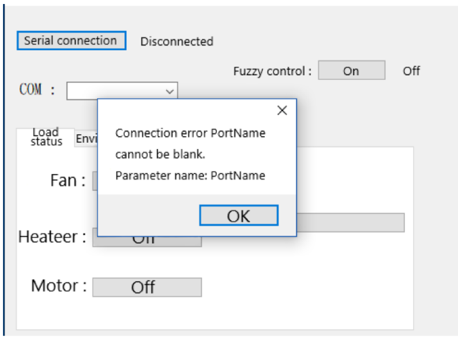

FIGURE 21. Error message of communication port not selected.

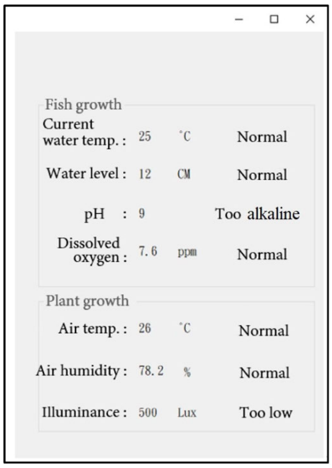

FIGURE 22. Fish–vegetable coexistence environment value display.

and illuminance. The values are fed back every half hour, and the figure shows whether the current environment sensing result is normal.

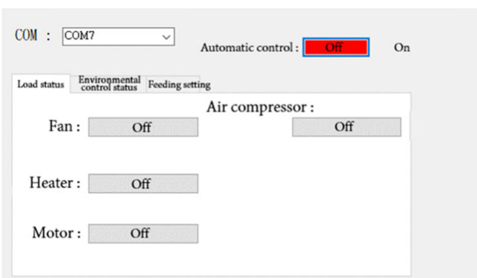

FIGURE 23. Load control menu.

Figure 23 shows the load control interface, where the control button can be pressed to control the loading equipment. When automatic control is activated, the system automatically controls the overall system loading equipment according to the thresholds set by the user. The equipment can be switched off manually if problems occur.

The ''environmental control status'' by the ''load status'' tab on the main interface of the monitoring system enables the user to determine the optimal habitat for different fishes

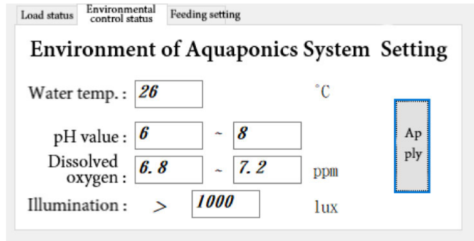

FIGURE 24. Environmental threshold setting.

and plants, as shown in Fig. 24. The corresponding thresholds are entered, ''Apply'' is clicked, the system judges whether or not the environment sensing values are normal according to the data, and then the ''automatic control'' button is clicked to execute control according to the thresholds.

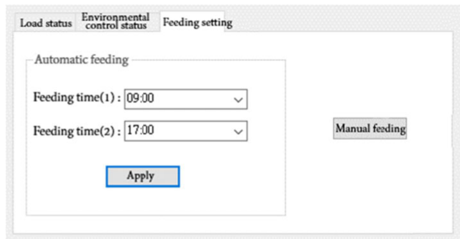

FIGURE 25. Feeding setting interface.

The ''feeding setting'' page is shown in Fig. 25; the feeding time can be determined according to the present time; when the time comes, the automatic feeder is controlled to feed. Manual control is available, where the manual feeding button is clicked to perform manual feeding.

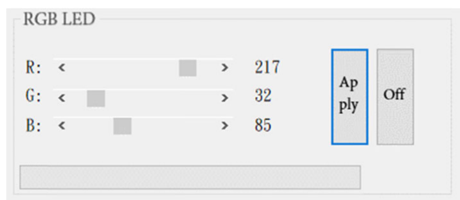

FIGURE 26. RGB LED lamp adjustment interface.

The RGB LED lamp adjustment control block is under the load position in the main interface of the monitoring system, as shown in Fig. 26. The user can adjust the light according to the optimum light color for plants, the pull bar is adjusted, and ''Apply'' is clicked to adjust the lighting. All lighting can be turned off by clicking the ''Off'' button.

The environmental sensing values are stored in the Excel datasheet of the computer; as we cannot continuously monitor the computer, this point can be remedied by Excel. When the operator is absent, the stored data can be checked and analyzed in the future. Figure 27 shows the data collected in the Excel sheet.

FIGURE 27. The data measured by the sensor every half hour.

2) FUZZY CONTROL SETTING

The proposed fish–vegetable symbiosis system is an architecture that uses a sensor network to integrate with the Internet of Things. This is different from the fish and vegetable symbiosis method of traditional agriculture. We use fuzzy methods to calculate and analyze various environmental variables and then to control and adjust various environmental controllers of the fish and vegetable symbiosis system. Our research assesses the contribution of innovative sensing applications and smart regulation to the traditional fish–vegetable symbiosis system. These innovative methods are all advantages of our research. Although our research introduces the fish–vegetable symbiosis system into intelligent automatic adjustment, some parts still require human judgment and adjustment, such as water supplementation and fishing bait supplementation. These are the disadvantages of our current system, which will be improved in the next stage of research. The nitrifier is foremost in the fish–vegetable coexistence system. To create a good living environment for the nitrifier in the important engineering process of converting ammonia into nitrate, the load is controlled by fuzzy control to improve the temperature, dissolved oxygen, and pH in the system to optimize the habitat. The fuzzy control flow chart is shown in Fig. 28.

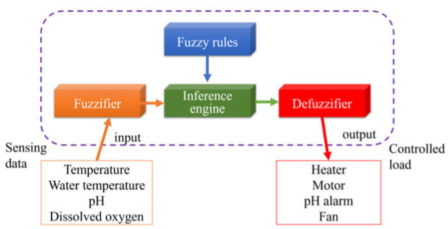

FIGURE 28. Fuzzy control flow chart.

The input and output variables of fuzzy control must be specified, and the variable elements are set according to the optimal range of growth. The fuzzy set is shown in Table 2. Table 3 shows the relevant description of the input attribute function affecting the output attribute function. Table 4 shows the range of input membership functions. Figure 29 shows the operating range of the output membership functions.

The membership function and rule base are made and displayed by using the membership function editor of the fuzzy logic designer in MATLAB. Then, fuzzy inference is performed, and the rule list is converted into the descriptive statements of IFTHEN of the Mamdani inference method to implement the fuzzy rules. Figure 30 shows the MATLAB semantic rule base.

When the semantic rule base of the previous step is completed, MATLAB creates a rule viewer, as shown in Fig. 31, where each row represents the I/O corresponding to the fuzzy rule base, and the grids with red lines in the lower right corner are the output results of fuzzification. The center of gravity is used for defuzzification.

TABLE 2. Fuzzy set.

Fuzzy set		
Input	Air temperature	colder, normal, hotter
	Water temperature	cold, normal, hot
	pH	low, normal, high
	Dissolved oxygen in water	low, normal, high
Output	Heater	on, off
	Aerator	on, off
	pH alarm	on, off
	Fan 1	on, off
	Fan 2	on, off

TABLE 3. Input attribute function and output attribute function.

	Input membership functions	output membership functions
1.	pH value	pH alarm
2.	Air temperature	Heater, Fan 1, Fan 2
3.	Water temperature	Heater, Fan 1, Fan 2
4.	Dissolved oxygen in water	Aerator

IV. RESULTS

This control system is built to provide a stable growth environment for the nitrifier so that the ammonia can be smoothly converted into nitrate. Natural growth is performed in an indoor laboratory environment, and the

TABLE 4. The range of input membership functions.

	Input membership functions	The range of input membership functions	
1	Air temperature	colder	<26.2°C
		normal	26°C~27°C
		hotter	>26.8°C
2.	Water temperature	cold	<25.2°C
		normal	25°C~26°C
		hot	>25.8°C
3	pH	low	<6.8
		normal	6.6~7.4
		high	>7.2
4	Dissolved oxygen	low	<7.8
		normal	7.6~8.4
		high	>8.2

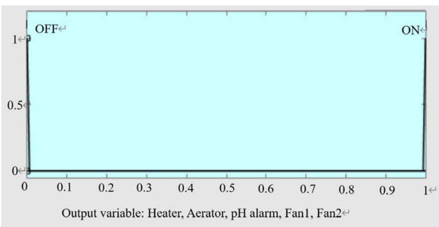

FIGURE 29. Operating range of output membership functions.

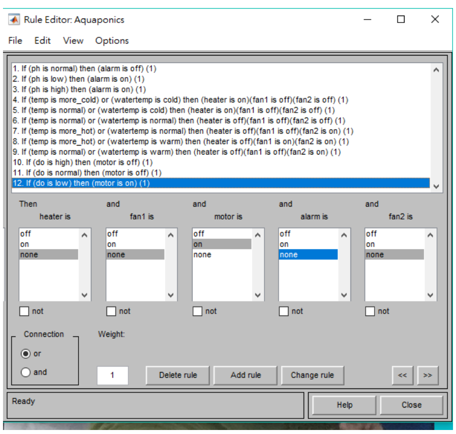

FIGURE 30. MATLAB semantic rule base.

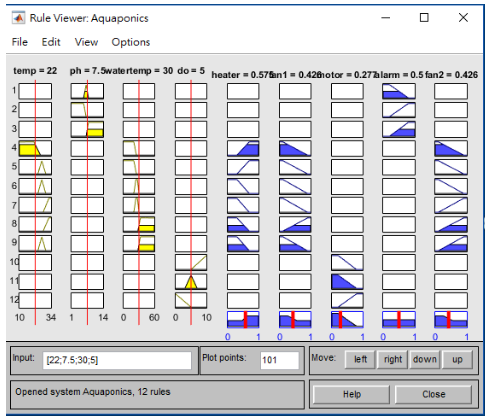

FIGURE 31. MATLAB Fuzzy rule viewer.

Time	Air temp.	Current water temp.	pH value	Dissolved oxygen
2018/4/25 12:00	27.4	25.4	6	7.3
2018/4/25 12:30	26.9	24.9	6	8.5
2018/4/25 13:00	28.0	27.0	6	7.9
2018/4/25 13:30	26.3	25.3	6	8
2018/4/25 14:00	27.9	26.9	6	7.3
2018/4/25 14:30	27.3	26.3	6	7.8
2018/4/25 15:00	26.6	25.6	6	7.2
2018/4/25 15:30	26.3	25.3	6	7.8
2018/4/25 16:00	26.0	25.0	6	7.6
2018/4/25 16:30	26.1	25.1	7	7.7
2018/4/25 17:00	27.9	26.9	7	8.4
2018/4/26 17:30	27.8	26.8	7	8.1
2018/4/25 18:00	26.7	25.7	7	7.8

Save data every half hour
Sensing data

FIGURE 32. Natural growth data.

Time	Air temp.	Current water temp.	pH value	Dissolved oxygen
2018/4/25 18:00	26.7	25.7	7	7.8
2018/4/25 18:30	27.2	25.1	7	8
2018/4/25 19:00	26.9	25.7	7	7.6
2018/4/25 19:30	27.0	25.7	7	7.4
2018/4/25 20:00	27.0	25.3	7	7.8
2018/4/25 20:30	26.5	25.1	7	7.9
2018/4/25 21:00	26.3	25.6	7	7.1
2018/4/25 21:30	26.6	25.2	7	7
2018/4/25 22:00	26.3	25.7	8	8.1
2018/4/25 22:30	26.0	25.6	8	7.9
2018/4/25 23:00	26.1	25.7	8	8.2
2018/4/25 23:30	27.5	25	8	8.4
2018/4/26 00:00	27.3	25	9	7.7
2018/4/26 00:30	26.5	25.2	9	7.7
2018/4/26 01:00	26.6	25.5	9	8.5

Save data every half hour
Sensing data

FIGURE 33. Fuzzy monitoring data.

detected values are shown in Fig. 32. Fuzzy control is performed in the same indoor laboratory environment six hours later, and the obtained monitoring system data are shown in Fig. 33. The data in the aforementioned two data sheets are recorded once per half hour.

According to the data, in a natural growing environment, the maximum value of the current water temperature is 27.0°C, the minimum temperature is 24.9°C, the difference between the maximum temperature and minimum temperature is 2°C, and the mean temperature is 25.8°C. In the fuzzy control environment, the maximum water temperature is 25.7°C, the minimum temperature is 25°C, the difference is 0.7°C, and the mean temperature is 25.3°C. In terms of water temperature, to provide a comfortable and stable habitat for plants and fishes, the ideal water temperature shall be 25 to 26°C. Figure 32 shows the uncontrolled natural growth environment temperature profile. Figure 35 shows the curve diagram of the fuzzy control environment. It is observed that after fuzzy control, the water temperature is relatively stable and is applicable to the stable growth of the nitrifier. According to Figs. 34 and 35, the ambient air temperature changes slightly in the fuzzy control environment.

In terms of pH, the optimal value for the growth of the nitrifier is 6~8, and the threshold is set in the system so that

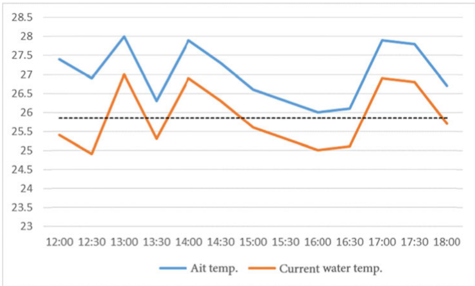

FIGURE 34. Temperature curves without fuzzy control.

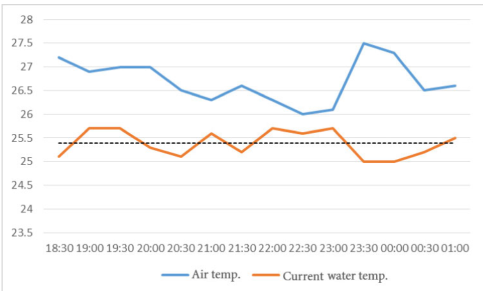

FIGURE 35. Temperature curves after fuzzy control.

a warning window will pop up when the system pH is higher or lower than the standard value, as shown in Fig. 36.

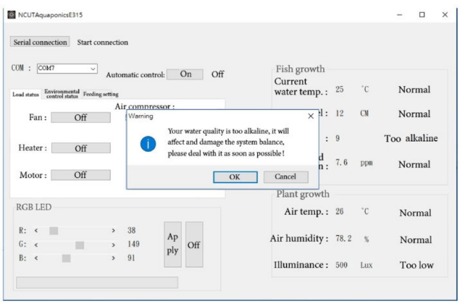

FIGURE 36. Schematic diagram of warning activation.

When the pH is lower than the standard value, some corallite can be placed in the pond to increase the pH. When the pH is higher than the preset standard value, Indian almond leaves can be placed in the pond, as Indian almond leaves are acidic, and the pH can be adjusted to the standard value. In terms of dissolved oxygen, the optimal value for the growth of the nitrifier is higher than 3 ppm. This threshold is set in the system, and when the dissolved oxygen is lower than the standard value, the aerator is actuated to control the amount of dissolved oxygen in water.

Many technologies are required to reach system balance. This system guarantees the water culture and aquatic environment conditions by sensor monitoring using the Internet of Things and the integrated analysis of cloud data. This system uses an open Internet of Things development board and sensor modules to monitor light, temperature, power supply, humidity, water level, and pH. In addition, as the conductivity of the water is one of the important indices of water quality, a water conductivity sensor is designed.

This module is provided with GSP positioning and web cam functions, and the environmental and water quality parameters, as measured by sensors and real-time video, can be sent to the cloud and smart phones via Wi-Fi so that the user can instantly monitor the changes in culture and plants and directly control the environmental conditions via the cloud, e.g., controlling the LED lighting to adjust ambient temperature.

V. CONCLUSION

In this study, we use the concept of the Internet of Things in a fish–vegetable coexistence system, where the sensing layer uses the Arduino Mega 2560 microcontroller as the master control board, and the wire layout is reduced by ZigBee low-power-consumption wireless transmission. Thus, various sensor data can be integrated to monitor the water temperature, pH, air temperature, brightness, water level, air humidity, and dissolved oxygen in the system. The C# human–machine interface is used in the computer terminal to monitor current values, and the data are stored in an Excel datasheet for the user to check and analyze previous data. The user can monitor the system operating conditions and instantly control the load through the designed human–machine interface to implement the remote monitoring of intelligent networking.

In this research, we use fuzzy control for pH, water temperature, and dissolved oxygen and consider various data. Thus, the fish–vegetable habitat is instantly corrected in the data and fed back every half hour to avoid nitrifier weakening due to a poor environment. In the fuzzy control environment, the maximum water temperature is 25.7°C, the minimum temperature is 25°C, the difference is 0.7°C, and the mean temperature is 25.3°C. Thus, the growth conditions are better than those in natural growing environments. In terms of pH, the threshold is set in the system, and a warning window pops up when the pH is higher or lower than the standard value. Thus, there will be no deaths resulting from an abnormal pH. In terms of dissolved oxygen, the optimal value for the growth of the nitrifier is higher than 3 ppm. The threshold is set in the system so that the aerator is actuated to control the dissolved oxygen content when the dissolved oxygen is lower than the standard value. The environmental values are controlled to meet the optimal habitat of the nitrifier.

In this study, we use a home fish–vegetable coexistence culture system, where the data can be built into a culture cloud database in the future. Because the data can be observed more efficiently by cloud computing and combined with agricultural data, the plant and fish growth data can be directly known; thus, any deficiencies can be improved within a short timeframe. The system can be used in large fish–vegetable coexistence systems in the future, and because there are different sensor data for different plants and fishes, the benefits of the Internet of Things for fish–vegetable coexistence can be maximized.

Our research hopes to use increasingly innovative artificial intelligence IoT technology to build a home fish–vegetable symbiosis farming system. Finally, our research focuses on applying innovative and efficient systems in everyday life.

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