AN IoT-BASED WATER QUALITY MONITORING SYSTEM FOR RECIRCULATING AQUACULTURE SYSTEMS

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ABSTRACT

The Recirculating Aquaculture System (RAS) is an advanced aquaculture model that enables water reuse within the system, thereby significantly reducing water consumption, minimizing environmental pollution, and maintaining optimal water quality parameters. In RAS, water treatment plays an important role in ensuring a stable and healthy living environment for aquatic species, especially under high stocking density conditions. To maintain effective water treatment, continuous and precise monitoring and control are essential. In this context, the Internet of Things (IoT) has emerged as a breakthrough technology, allowing real-time collection and analysis of water quality data. This facilitates automated system control while minimizing human error. This paper provides an overview of IoT applications in water treatment for RAS and focuses particularly on the observation and discussion of biofilm formation within the system. Using periodic data collected by IoT-based sensors—such as flow rates through filter—the analysis demonstrates that biofilm plays a critical role in the biological treatment process. The findings confirm that IoT not only enables effective monitoring of biofilm development but also supports the real-time optimization of water treatment operations. The study also highlights several technical challenges in IoT integration and proposes future development directions to enhance the performance and sustainability of RAS.

Keywords: Internet of Things, RAS, water treatment, mechanical filtration, water quality.

1. INTRODUCTION

Aquaculture plays an increasingly vital role in global food security. However, traditional aquaculture practices such as open ponds, earthen ponds, or floating cages are showing several limitations, including high water consumption, poor disease control, and significant environmental pollution [1]. In this context, Recirculating Aquaculture Systems (RAS) are considered a superior solution. RAS can recycle nearly all the water used in the system, with only 5–10% of the water replaced daily [2, 3]. Unlike traditional systems, RAS relies heavily on its internal water treatment systems to maintain optimal conditions for the growth and development of aquatic organisms. Therefore, water treatment in RAS is not merely about purifying water, but also maintaining key parameters such as dissolved oxygen, pH, ammonia, nitrite, nitrate, suspended solids, and harmful microorganisms within safe thresholds [4, 5].

Amid this digital transformation era, the Internet of Things (IoT) is considered a key driver for enhancing RAS operational efficiency. IoT enables real-time water quality data collection and supports the automation of water treatment systems. This reduces manual labor, increases accuracy, and ensures timely responses to environmental changes [6-10]. According to the Food and Agriculture Organization of the United Nations (FAO), the adoption of IoT in aquaculture is increasing globally, particularly in high-tech agriculture countries such as Norway, Japan, China, and more recently, Vietnam [11]. Nonetheless, integrating IoT systems into RAS still faces several challenges, including high initial investment costs, hardware and software integration, sensor accuracy, and operator technical expertise.

This paper provides a comprehensive overview of IoT-based water treatment systems designed for Recirculating Aquaculture Systems (RAS), highlighting their structure and functionality. It focuses on the mechanical filtration stage of the proposed IoT-enabled system, analyzing key factors that influence water quality at this critical phase. By exploring the interaction between smart control components and physical filtration mechanisms, the study aims to demonstrate how IoT can enhance operational efficiency, ensure real-time monitoring, and maintain optimal water conditions for aquatic organisms.

2. MATERIALS AND METHODS

2.1 Materials

2.1.1. Structure of the RAS

A typical Recirculating Aquaculture System consists of the following main components:

- Rearing tank: where aquatic species are reared.
- Mechanical filters: for removal of suspended solids such as feces and uneaten feed.
- Biofilters: for nitrification, converting ammonia into nitrate.
- Degasser: to eliminate CO_2 and toxic gases.
- Disinfection units: typically using UV light or ozone to eliminate pathogens.
- Recirculation and aeration systems: to maintain water flow and dissolved oxygen.
- Intermediate or sedimentation tanks.

The water treatment process must ensure the stability of key environmental parameters, particularly temperature, pH, dissolved oxygen, ammonia, nitrite, nitrate concentrations, and suspended solids.

2.1.2. Water recirculation process

Water in the recirculating aquaculture system (RAS) begins its journey in the fish tank, where IoT sensors are installed to monitor key environmental parameters such as temperature, pH, and dissolved oxygen. As the water becomes polluted with fish waste, it flows through a settling tank and mechanical filter to remove suspended solids. Next, it moves into the biological filter, where beneficial microorganisms break down harmful compounds like ammonia and nitrite into the less toxic nitrate. The water then passes through a disinfection unit—either UV or ozone—to eliminate pathogenic bacteria. Finally, the clean water is collected in a storage tank and pumped back into the fish tank, completing a closed-loop cycle that conserves water and maintains a stable rearing environment.

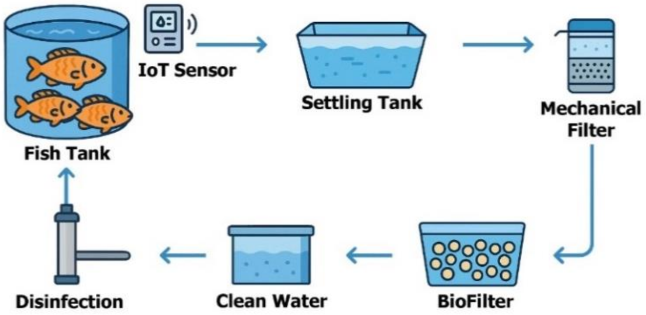

Figure 1. Flow diagram of the water recirculation process

2.1.3. Limitations of manual monitoring

Most RAS facilities in Vietnam currently rely on manual monitoring using chemical test kits or handheld devices. This approach presents several limitations:

- Low monitoring frequency, resulting in delayed detection of system failures.
- High potential for human error during manual testing.
- Inability to store and analyze long-term data trends.
- Incompatibility with automated control systems.

Therefore, implementing automated measurement and control technologies, particularly IoT-based solutions, is crucial.

2.2. Methodology

2.2.1. Automated water sample collection system

The Water Sample Collection System (WASACO) is an IoT-based solution composed of smart sensors, a central control unit, and a SepRef filter (Oslofjord Ressurspark AS, Norway). The system is designed with a high degree of flexibility, allowing its application across various aquaculture species such as tilapia (Oreochromis niloticus), snakehead fish (Channa striata), and whiteleg shrimp (Litopenaeus vannamei). However, technical parameters—including flow rate, hydraulic retention time, and the capacity of biological filtration—must be tailored to the specific physiological and environmental requirements of each species. Figure 2 illustrates a system designed in a cubic structure mounted on a circular floating base. The supporting frame is constructed from aluminum profiles connected by joints, providing structural stability and enabling easy modular assembly. The Central Processor is located at the top of the device and is responsible for controlling and monitoring the entire system's operation, including pump management, sensor input, and data processing. It features an LCD display and control buttons for configuration and system monitoring. WASACO utilizes two peristaltic pumps capable of handling water containing small solid particles. Pump 1 is positioned near the Central Processor and draws water into the larger filtration chamber (Chamber 1). Pump 2, mounted on the top of the smaller chamber (Chamber 2), transfers water from Chamber 2 back to Chamber 1. Chamber 1 and Chamber 2 are made of transparent plastic, allowing for easy visual inspection of the internal filtration processes. Silicone tubes are used to transport water between the chambers and pumps. These tubes are flexible, durable, and chemically resistant, making them ideal for water and mild chemical handling. The SepRef unit, located at the bottom in a separate compartment, plays a key role in the water treatment process. The SepRef unit functions as a mechanical filter with two output streams, designated as Permeate and Concentrate. The Concentrate outlet directs water containing larger impurities to Chamber 2. Conversely, the Permeate outlet returns most of the water, containing smaller particulate matter, back to the RAS for reuse. Due to its specially designed inlet structure, SepRef effectively filters out contaminants without causing clogging, an issue commonly associated with traditional membrane filters [12]. The floating circular structure helps keep the system buoyant, balanced, and stable on water surfaces such as ponds, lakes, or aquaculture tanks.

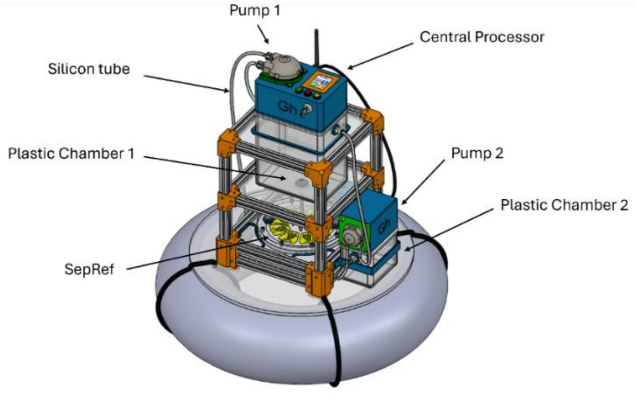

Figure 2. Automated water sample collection system

WASACO, is designed for automatic water sampling and quality monitoring, enabling high-frequency, real-time data acquisition and intelligent control in RAS operations, has four primary functional layers:

- ***Sensor Layer***: responsible for collecting real-time environmental data from the water, such as temperature, pH, dissolved oxygen (DO), ammonia (NH_3), nitrite (NO_2^-), and others.
- ***Processing and Control Layer***: utilizes an Arduino-based controller to process sensor data and manage connected devices accordingly.
- ***Network Layer***: supports wireless data transmission through technologies such as Wi-Fi, Bluetooth, and 4G/5G networks.

- ***Application Layer***: provides user interfaces via mobile and web applications, allowing remote monitoring and control of the system.

In RAS applications, WASACO performs the following core functions:

- ***Monitoring***: continuously measures water quality parameters in real time, providing accurate insights into the aquatic environment.
- ***Alerting***: automatically sends notifications when any parameter exceeds predefined thresholds. These alerts are managed by the central processor unit and are sent to the user via Mobile/Web App.
- ***Control***: automatically activates devices such as water pumps to transfer water into filtration chambers when required.

2.2.2. Workflow

When the WASACO system starts, both ultrasonic sensor 1, positioned in the larger filtration chamber (Chamber 1), and ultrasonic sensor 2, located in the smaller filtration chamber (Chamber 2), are activated at the same time. If the distance between sensor 1 and the water surface in Chamber 1 exceeds 7 cm, RAS water will be pumped into Chamber 1. This process continues until the measured distance falls below 7 cm, at which point pumping is temporarily suspended.

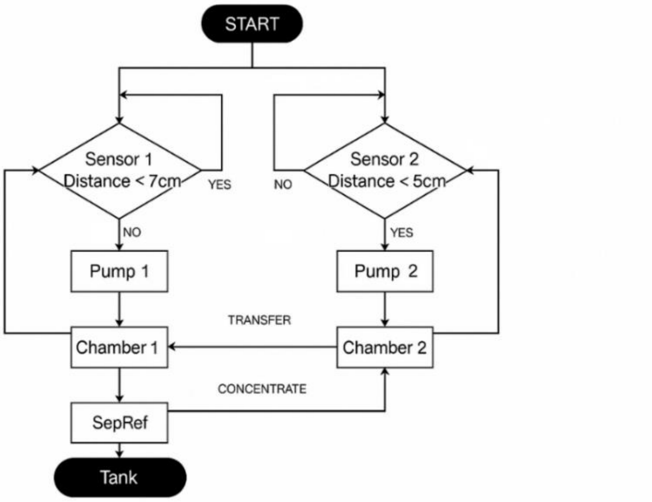

Figure 3. Workflow of WASACO

The operation of sensor 2 follows a similar procedure; however, its threshold condition is the inverse. While water flows from Chamber 1 through SepRef via a silicone tube into Chamber 2, water from Chamber 2 is transferred back to Chamber 1 via Pump 2, and subsequently flows through SepRef again. This recurring process serves to remove suspended solids while retaining the majority of water within the RAS.

Throughout operation, Chamber 1 is equipped with sensors that continuously monitor parameters such as temperature, pH, and dissolved oxygen in real time. These data are transmitted to the central processing unit and displayed as reports via a mobile application or web-based interface.

2.2.3. Experimental evaluation

Mechanical filtration is the first step in the water treatment sequence of RAS and is essential for removing suspended solids such as fish feces, uneaten feed, fish scales, and organic debris. If not removed promptly, these solids decompose, increasing biochemical oxygen demand (BOD), accumulating ammonia, fostering anaerobic bacterial growth, and ultimately degrading water quality. An effectively designed mechanical filtration system can eliminate 60–85% of total suspended solids before they break down into toxic substances like ammonia [1].

In this study, the WASACO system was investigated for its performance in automating the mechanical filtration stage of RAS water treatment. Specifically, we examined factors influencing filtration quality, including water inflow rate and biofilm formation on internal surfaces such as silicone tubes, filtration chambers, and within the SepRef unit.

a) Investigation of biofilm formation in silicone tube

Table 1 presents the technical specifications of two types of pumps used in the WASACO system. The rotational speed and flow rate increase linearly with the input voltage for both pump models, allowing precise control of flow via voltage regulation or through a Pulse-Width Modulation (PWM) circuit. The WP1100 demonstrates significantly higher performance compared to the WPX1 at equivalent voltage levels; for instance, at 12V, the WP1100 delivers a flow rate of 414 mL/min, whereas the WPX1 only reaches 166 mL/min. Maintaining stable flow at each rotational speed is essential to ensure consistent hydraulic conditions for both biofiltration and UV disinfection units. In this experiment, the inflow rate of water into WASACO was set at six different levels and monitored over a 12-day period. After this period, a 5 cm segment of silicone tube at the pump inlet was extracted for analysis. Biofilm accumulated on the inner surface of the silicone tube was scraped off using a scalpel and suspended in deionized (DI) water. The resulting suspension was placed on aluminum foil and dried in an oven at 103 °C for 18 hours. After cooling, the dried biofilm residue on the foil was weighed using an analytical balance.

Table 1. Water flow rates for investigation of WASACO

WPX1			WP1100		
6V DC 58 rpm	9V DC 98 rpm	12V DC 138 rpm	6V DC 58 rpm	9V DC 98 rpm	12V DC 138 rpm
70 mL/min	118 mL/min	166 mL/min	174 mL/min	294 mL/min	414 mL/min
FR1	FR 2	FR3	FR4	FR5	FR6

b) Investigation of biofilm formation on the surface of the filtration chamber

Plastic squares composed of the same material as the filtration chamber were positioned at the chamber’s base and left there for a duration of 12 days. Each day, one plastic sample was collected to extract the biofilm and record its corresponding weight.

3. RESULTS AND DISCUSSION

3.1. Biofilm formation in the silicone tube

Figure 4 shows that the water flow rate at the pump outlet, which also serves as the inlet flow rate of the filtration chamber, remained relatively stable over the 12-day operational period. Six distinct data series (FR1 to FR6), represented by curves with different markers and colors, are categorized into three groups for performance analysis.

Low Flow Rate Group: FR1 & FR2

- FR1 (yellow) exhibits the lowest flow rate (~60–70 mL/min), indicating that the pump operates at a minimal level, suitable for fine-tuned flow control or micro-recirculation systems.
- FR2 (orange) maintains a stable rate around 115 mL/min, reflecting high operational stability but no observable performance improvement over time.

Medium Flow Rate Group: FR3 & FR4

- FR3 (red) shows a notable increase from ~135 to 165 mL/min by day 6, followed by a slight decline—suggesting that the system may have reached an optimal flow before experiencing a performance drop possibly due to biofilm formation, partial clogging, or debris accumulation.
- FR4 (pink) exhibits a slight increase and remains stable around 160–170 mL/min, indicating that the pump may have been well-calibrated.

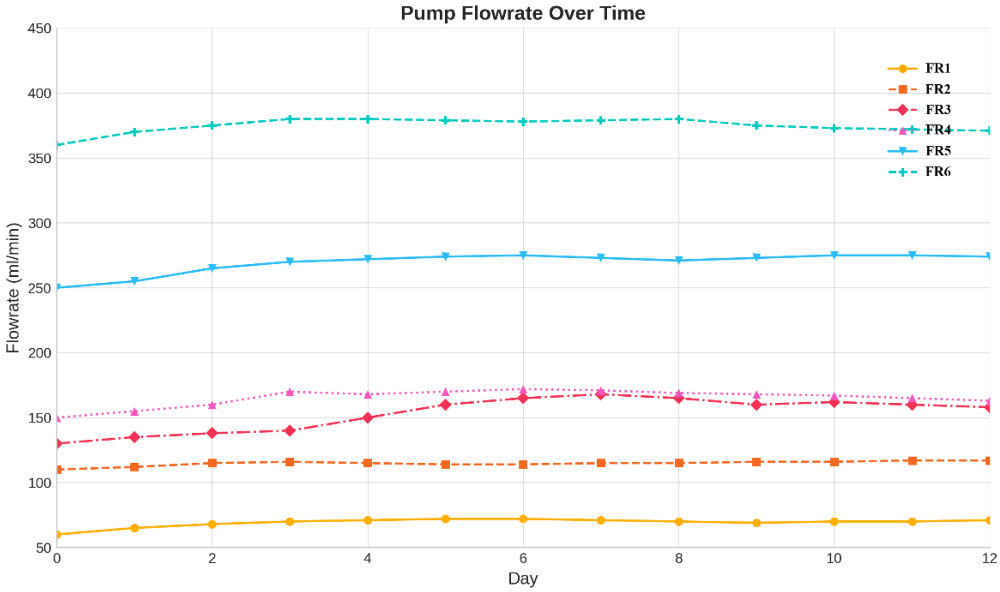

Figure 4. Flow rate at the outlet of the peristaltic pump

High Flow Rate Group: FR5 & FR6

- FR5 (blue) operates steadily at approximately 255–270 mL/min, with only minor fluctuations observed after day 6.
- FR6 (turquoise) achieves the highest flow rate, peaking near 400 mL/min on day 6, followed by a slight decrease to ~380 mL/min—suggesting that this pump may be affected by loading factors or particle accumulation within the system.

Through the analysis of the three performance groups, flow rates FR4–FR6 exhibited high discharge capacities, making them suitable for primary treatment units such as sedimentation tanks and biofilters. The slight decline observed after day 6 serves as an important indicator for scheduling regular maintenance. In contrast, FR1–FR2 functioned as auxiliary flows with high operational stability.

Based on this analysis, several recommendations are proposed: (1) inspect and clean FR3 and FR6 from day 7 onward to prevent further performance degradation; (2) maintain an IoT-based flow monitoring system to promptly detect minor variations; (3) optimize the biofilter design to minimize flow obstruction and prevent excessive biofilm formation; and (4) establish a maintenance schedule for high-flow pumps (FR5 and FR6) after every 7 days of continuous operation.

Table 2 presents the dry matter of biofilm collected from 5 cm sections of silicone tubing at six different sampling points (FR1–FR6), along with the corresponding tube weights and normalized biofilm mass (mg of biofilm per gram of tube). This dataset provides key insights into the spatial variability of biofilm formation within the water recirculation system.

With 0.50 mg of dry matter, FR2 demonstrated the highest level of biofilm accumulation, reaching 0.64 mg/g of tubing—four times that of FR1 and 32 times higher than FR6. Although the tubing weight at FR2 is only moderate (~0.78662 g), the significantly high biofilm load suggests intense microbial activity. This likely results from low flow velocity or stagnant zones at this location, which promote biofilm development.

In contrast, FR6 presents the lowest biofilm accumulation at only 0.02 mg/g, indicating negligible biofilm presence. This finding aligns with data from Figure 4, where FR6 corresponds to the highest flow rate, supporting the hypothesis that increased flow velocity—and thereby greater shear force—effectively suppresses biofilm formation.

Although FR4 has the heaviest tubing (0.93793 g), its biofilm concentration remains low at 0.11 mg/g. This discrepancy emphasizes that raw tube weight is not a reliable indicator of biofilm accumulation. Therefore, normalizing the data as mg of biofilm per gram of tubing provides a more accurate basis for comparison.

Table 2. Dry matter of biofilm collected from a 5 cm segment of silicone tube

	Dry matter (mg)	Silicone tube weight (g)	Biofilm (mg/g tube)
FR1	0.12	0.75797	0.16
FR2	0.50	0.78662	0.64 (highest)
FR3	0.12	0.78057	0.15
FR4	0.10	0.93793 (heaviest)	0.11
FR5	0.03	0.78900	0.04
FR6	0.02 (lowest)	0.89915	0.02 (lowest)

Table 2 provides empirical evidence indicating that biofilm formation across the system is highly heterogeneous and strongly influenced by localized hydrodynamic conditions. This insight helps WASACO users select an appropriate flow rate to avoid overheating the system while extending the lifespan of the silicone tube.

3.2. Biofilm on the surface of the filtration chamber

After 12 days of trial operation, the plastic samples at the bottom of the WASACO filtration chamber were collected one by one to assess biofilm development. As shown in Figure 5, biofilm formed on the surface of these plastic samples, and suspended solids settled without being carried by the water flow. This led to the progressive thickening of the biofilm over time, which may eventually clog the silicone tube and block the mechanical filter inlet of SepRef. Figure 6 illustrates the temporal dynamics of biofilm development on a 2×2 cm surface area over a 12-day period.

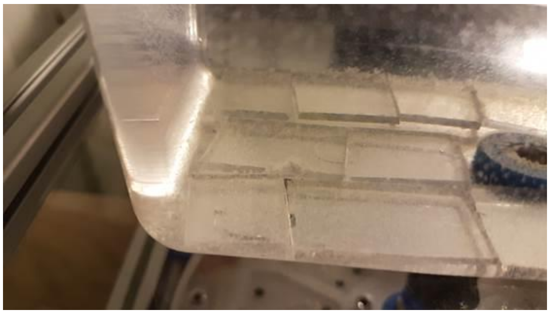

Figure 5. Plastic sample placed at the bottom of WASACO's filtration chamber

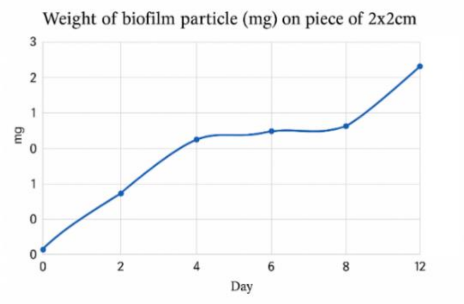

Figure 6. Biofilm formation over time

The curve exhibits a nonlinear upward trend, with three distinct phases:

- Day 0–4: Rapid Accumulation Phase

  During the initial four days, the biofilm mass increased significantly from 0 to approximately 1.8 mg. This reflects the initial microbial adhesion and exponential growth, corresponding to the lag and log phases of biofilm development.

- Day 4–8: Stabilization and Maturation Phase

  Between days 4 and 8, the rate of biofilm accumulation slowed markedly, with negligible increase. This indicates the onset of the maturation stage, where the biofilm structure becomes stable and further growth is constrained by limitations in nutrients or available space.

- Day 8–12: Secondary Growth Phase

  Notably, from day 8 onwards, biofilm mass resumed its increase, reaching over 2.5 mg by day 12. This resurgence may be attributed to microbial recolonization by different species, detachment-regrowth cycles, or environmental fluctuations (e.g., flow velocity or organic load) that promote renewed biofilm expansion.

Such a biphasic growth pattern is characteristic in recirculating systems and should be considered when designing cleaning protocols or scheduling maintenance operations.

The formation of biofilm in the WASACO system can have long-term impacts on both operational performance and the physical durability of system components. Biofilm is a biological layer formed by the accumulation of microorganisms on surfaces in contact with water, commonly found on pipe interiors, filtration chambers, sensor surfaces, and silicone tubing. Over time, the thickening of biofilm can reduce the effective diameter of pipes, resulting in increased pressure, reduced flow rates, and higher energy consumption to maintain stable circulation. Furthermore, biofilms can trap suspended solids and interfere with sensor readings (e.g., DO, pH, EC sensors), thereby compromising the accuracy of the central control system. From a materials perspective, biofilm and associated biological by-products may contribute to corrosion, aging, or damage of polymer and rubber components, ultimately shortening the system's lifespan.

To mitigate these negative effects, biofilm control strategies should be integrated from the system design and operational phases. First, selecting anti-fouling materials for tubing and sensors is essential. Second, the system should be designed for ease of disassembly and regular cleaning, accompanied by periodic flushing or clean-in-place (CIP) procedures using hot water or mild disinfectants such as H_2O_2 or diluted organic acids. Additionally, advanced technologies such as UV treatment in the recirculation loop may be employed to inhibit microbial growth. Finally, integrating sensors to monitor biofilm thickness or track flow pressure variations over time offers a proactive solution for early detection and alerts of biofilm-induced performance degradation. Effective biofilm control not only ensures water quality but also enhances the stability and operational lifespan of the WASACO system in recirculating aquaculture applications.

4. CONCLUSION

Recirculating Aquaculture Systems (RAS) represent a strategic solution for sustainable, eco-friendly, and economically efficient aquaculture. In such systems, water treatment plays an important role in determining overall performance and success. The water treatment process in RAS is a complex integration of mechanical filtration, biological filtration, disinfection, gas management, chemical stabilization, and toxic compound control. In this study, biofilm formation was identified as a factor that can influence mechanical filtration performance. Experiments were conducted over a 12-day period to provide practical data, helping WASACO users optimize operational parameters for specific scenarios. Furthermore, the study proposes the implementation of an ultrasonic cleaning module to reduce biofilm accumulation on the filtration chamber surface in future system upgrades.

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TÓM TẮT

GIÁM SÁT CHẤT LƯỢNG NƯỚC NUÔI TRỒNG THỦY SẢN TUẦN HOÀN BẰNG CÔNG NGHỆ IoT

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Hệ thống nuôi trồng thủy sản tuần hoàn (RAS) là một mô hình tiên tiến, cho phép tái sử dụng nước trong hệ thống nhằm giảm thiểu lượng nước tiêu thụ, hạn chế ô nhiễm môi trường và duy trì các thông số chất lượng nước ở mức tối ưu. Trong RAS, xử lý nước đóng vai trò cốt lõi trong việc đảm bảo môi trường sống ổn định cho thủy sản, đặc biệt trong điều kiện nuôi mật độ cao. Để duy trì hiệu quả xử lý nước, việc giám sát và điều khiển liên tục, chính xác là vô cùng cần thiết. Trong bối cảnh đó, công nghệ Internet vạn vật (IoT) được xem là giải pháp đột phá, cho phép thu thập và phân tích dữ liệu chất lượng nước theo thời gian thực, từ đó hỗ trợ điều khiển tự động và giảm thiểu sai sót do con người. Bài viết này trình bày tổng quan về ứng dụng IoT trong xử lý nước của hệ thống RAS, đồng thời tập trung quan sát và thảo luận quá trình hình thành màng vi sinh trong hệ thống. Thông qua các số liệu định kỳ được thu thập bởi cảm biến IoT như tốc độ dòng chảy qua các lớp vật liệu lọc, việc phân tích cho thấy màng vi sinh đóng vai trò trung tâm trong quá trình xử lý nước, đồng thời xác nhận rằng hệ thống IoT không chỉ giúp giám sát quá trình hình thành màng vi sinh một cách hiệu quả mà còn hỗ trợ tối ưu hóa quá trình xử lý nước theo thời gian thực. Nghiên cứu cũng chỉ ra một số thách thức kỹ thuật trong việc tích hợp IoT và đề xuất các hướng phát triển trong tương lai nhằm nâng cao hiệu suất và tính bền vững của RAS.

Từ khóa: Internet of Things, RAS, xử lý nước, lọc cơ học, chất lượng nước.