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Original Research Paper

Design and Optimization of a Sustainable Automated Irrigation System for Enhanced Water Management in Small-Scale Fishpond

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ABSTRACT

Efficient water management is essential for improving productivity and sustainability in small-scale aquaculture systems. Traditional manual irrigation practices often result in inconsistent water quality, excessive water consumption, and increased labor requirements, which negatively affect fish growth and farm profitability. This study developed and evaluated a sustainable automatic irrigation system designed to optimize water management in small-scale fishponds through real-time monitoring and automated control of critical water quality parameters. The system integrates an Arduino Mega microcontroller with temperature, pH, and dissolved oxygen sensors to regulate water exchange using a water pump and solenoid valve powered by a solar-assisted energy system.

A 90-day experimental evaluation was conducted using two identical 1,000-L IBC plastic tanks stocked with African catfish (Clarias gariepinus). One tank was managed using conventional manual irrigation, while the other employed the developed automated irrigation system. Daily measurements of water temperature, pH, and dissolved oxygen were collected and analyzed using independent samples t-tests at a 5% level of significance. Water consumption, fish survival, and economic performance were likewise evaluated.

Results demonstrated that the automated irrigation system maintained significantly more stable water quality than the manual system. The automated setup achieved lower average water temperature (29.87°C), more favorable pH (7.72), and higher dissolved oxygen concentration (5.94 mg L^{-1}), all of which were significantly different from those observed under manual irrigation ($p < 0.05$). Water consumption was reduced by 40%, decreasing from 7,500 L in the manual system to 4,500 L in the automated system over the experimental period. Higher fish survival (92%) resulted in greater gross income (₱8,050), net income (₱5,050), and return on investment (16.83%) compared with conventional management.

The findings demonstrate that integrating sensor-based automation with sustainable energy provides an effective and economically viable approach for improving water management, conserving freshwater resources, and enhancing productivity in small-scale aquaculture operations.

Keywords: automatic irrigation, aquaculture, smart farming, Arduino, water quality monitoring, sustainable agriculture, fishpond management

INTRODUCTION

Aquaculture has become one of the fastest-growing food production sectors worldwide, contributing significantly to food security, rural livelihoods, and national economies. In the Philippines, small-scale fish farming plays a critical role in supplying affordable crop productivity. Vertical farming systems—where crops are cultivated in stacked or tower-based configurations—offer a strategic advantage in animal protein while providing income opportunities for farming communities. However, the sustainability and productivity of these operations remain constrained by inefficient water management practices. Most small-scale fishponds continue to rely on manual irrigation and periodic water replacement, where water exchange decisions depend largely on operator experience rather than continuous assessment of water quality. Such

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practices frequently result in unstable environmental conditions that adversely affect fish health, growth performance, and production efficiency.

Maintaining suitable water quality is fundamental to successful aquaculture production. Parameters such as water temperature, hydrogen ion concentration (pH), and dissolved oxygen directly influence fish metabolism, feed conversion efficiency, disease resistance, and survival. Variations outside the optimum range may induce physiological stress, reduce growth, increase mortality, and ultimately lower farm profitability. Conventional irrigation systems often fail to respond immediately to these fluctuations because monitoring is performed intermittently and corrective actions depend on manual intervention. Consequently, excessive water use, inconsistent pond conditions, and increased labor costs remain common problems among small-scale aquaculture enterprises.

Recent advances in precision agriculture and smart farming technologies have enabled the development of automated monitoring and control systems capable of improving resource-use efficiency. Sensor-based irrigation systems integrated with microcontrollers can continuously monitor environmental conditions and automatically regulate water exchange whenever predefined thresholds are exceeded. These intelligent systems reduce human intervention while ensuring stable production environments, minimizing resource wastage, and improving operational efficiency. Moreover, incorporating renewable energy technologies such as solar power further enhances sustainability by reducing dependence on conventional electricity sources.

Previous studies have demonstrated the effectiveness of automated monitoring systems in improving water quality management through continuous measurement of temperature, pH, and dissolved oxygen. Intelligent control systems utilizing microcontrollers, wireless communication, and sensor networks have likewise been shown to reduce labor requirements while improving environmental stability and production efficiency in agricultural and aquaculture applications. Nevertheless, most available studies focus primarily on water quality monitoring or automated feeding systems, with relatively few investigations evaluating the combined technical, environmental, and economic performance of sustainable automated irrigation systems specifically designed for small-scale fishpond operations under Philippine conditions.

Addressing this research gap, the present study developed a sustainable automatic irrigation system integrating water quality sensors, automated control mechanisms, and solar-assisted energy to improve water management in small-scale aquaculture. The developed system was evaluated by comparing its performance with that of conventional manual irrigation over a 90-day production cycle.

Specifically, the study aimed to:

1. develop a sustainable automatic irrigation system for small-scale fishponds using sensor-based monitoring and solar-assisted operation;
2. evaluate the effectiveness of the system in maintaining optimal water temperature, pH, and dissolved oxygen levels;
3. compare water consumption, fish survival, and production performance between automated and manual irrigation systems; and
4. determine the economic feasibility of implementing the developed system for sustainable small-scale aquaculture.

RELATED WORKS

Hydroponics and Controlled-Environment Agriculture

Hydroponic production has emerged as an important component of controlled-environment agriculture (CEA), particularly in locations where conventional soil-based production is constrained by limited arable land, water availability, climate variability, and soil-related production problems. In hydroponic systems, plants are cultivated without conventional agricultural soil and receive water and essential mineral nutrients through a managed nutrient solution. The approach provides greater control over the root-zone environment and allows producers to regulate important production variables such as nutrient concentration, pH, electrical conductivity, irrigation frequency, and water availability. Treftz and Omaye (2016) noted that hydroponics can complement conventional agriculture by enabling crop production in non-arable and urban environments while reducing water waste through recirculation and allowing greater control of nutrients and environmental conditions.

The advantages of hydroponics are particularly relevant to controlled-environment production because the root-zone environment can be managed independently of many of the limitations encountered in open-field agriculture. Recent reviews emphasize that hydroponic and CEA systems can improve water and nutrient-use efficiency, reduce dependence on soil, and provide opportunities for year-round crop production. However, these benefits must be considered alongside the technical requirements of nutrient management, system maintenance, energy consumption, and initial capital investment (Jyothi & Devi, 2026; Regmi et al., 2024).

For onion production, nutrient management is particularly important because bulb development depends on adequate vegetative growth followed by the accumulation of assimilates in the bulb. Kane et al. investigated the influence of nutrient solution composition and pH on onion growth under greenhouse hydroponic conditions using Allium cepa cultivars and Allium fistulous. Their study demonstrated that both nutrient formulation and solution pH can influence onion growth and mineral composition, highlighting the importance of maintaining appropriate chemical conditions in hydroponic onion production.

These findings provide a scientific basis for the nutrient-management approach used in the present study. The Red Creole onions were cultivated under controlled greenhouse conditions with nutrient solution pH maintained at 5.8–6.2 and electrical conductivity at 1.8–2.2 mS cm^{-1}. Such control is important because variations in nutrient availability and root-zone conditions can affect vegetative development, root growth, and ultimately bulb formation.

Vertical Farming and Space-Use Efficiency

Vertical farming extends the concept of hydroponics by arranging plants in vertically stacked or column-based configurations. The principal advantage of this approach is the ability to increase crop production within a limited horizontal footprint. Vertical production is therefore particularly relevant to urban and peri-urban agriculture, institutional farms, and locations where land is expensive or scarce.

RELATED WORKS

The study of (Nagothu et al., 2025), presents a fuzzy logic-based water quality monitoring system that continuously tracks parameters like temperature, pH, and dissolved oxygen, autonomously adjusting controls to maintain optimal conditions, thereby enhancing water management efficiency in aquaculture operations.
Sustainable water management (Mastrorilli & Zucaro, 2019), in agronomy focuses on efficient water use without environmental harm, emphasizing crop water use efficiency, economic sustainability, and strategies for improvement. It also discusses policy instruments to achieve efficient and sustainable water management practices.

Duan et al., (2018) this article, a small irrigation control system was designed to make the potted plants with different living habits have more suitable soil environment to live and to realize the automatic irrigation to ensure the survival conditions of Potted plants.

Mahzabin et al., (2016) this project deals with the automatic operation of the pump to supply water in the field depending on the soil moisture using solar energy or even the DC voltage converted from AC using ATMEGA328. The automatic irrigation system helps optimize power usage by using a solar tracker and automatic pump controller

Khan et al., (2017) in this paper, proposed the design of a node network based on microcontroller ESP32-Lora and Internet connection through SIGFOX network and the results obtained show the stability and robustness of the designed system.

Holzapfel et al., (2009) this paper, the authors analyze knowledge and investigations that enable to identify the principal criteria and processes that allow improving the design and managing of the irrigation systems, based on the basic concept that they facilitate to develop agriculture more efficient and sustainable.

Sunday Fidelis & Aniebiet Idim, (2020) their paper shows that the wireless communication mode of data transmission using STM32 and NB-IoT (narrow band-internet of things) technology can meet the requirements of reducing the time cost and enhancing the reliability of the system and can Meet the goal of data Transmission of intelligent irrigation system and water-saving irrigation.

Yusoff et al., 2024, Water management in aquaculture involves maintaining optimal water quality through technologies like RAS, IMTA, and aquaponics, addressing waste treatment, nutrient recycling, and environmental factors to enhance fish health, growth, and sustainability while minimizing pollution impacts on ecosystems.
This study (Roy, 2018), provides information about automatic irrigation to the plants which helps in saving money and water. The entire system is controlled using ATMEGA 328 microcontroller which gives signals to the motor. Moisture sensors and water level sensors are connected to internal ports of the microcontroller. Whenever there is a change in the moisture of the soil or reduction in water level of the reservoir, a signal is sent to the microcontroller and thus the motor gets activated, and the buzzer and the LEDs are also activated accordingly.
Small-scale tank irrigation system (UNAMI, 2005), is an effective option for sustainable agricultural water development. The management strategy for water release in such a system is considered in the framework of variational calculus. A minimum principle is deduced to characterize an optimal strategy minimizing a performance index that evaluates water content deviation in the command area and the time when the irrigation tank dries up. The optimal strategies are demonstrated in two practical example systems.
The study of C et al., (2024), focuses on an automatic smart irrigation system utilizing NodeMCU and IFTTT to manage irrigation through soil moisture, temperature, and humidity sensors. While it primarily addresses agricultural applications, the principles of water conservation and efficient management can be adapted for small-scale fishponds. By automating irrigation based on real-time soil moisture data, the system enhances water efficiency, reduces manual

labor, and promotes sustainable practices, which could be beneficial for maintaining optimal water levels in fishponds.

The paper (Azman et al., 2025), presents a solar-powered Automatic Irrigation System that optimizes water usage through real-time monitoring with capacitive soil moisture and ultrasonic distance sensors. While it focuses on agricultural applications, the principles can be adapted for small-scale fishponds by integrating similar sensors to manage water levels and prevent overwatering. This system promotes sustainable practices by operating entirely on solar energy, making it suitable for remote areas, thus enhancing water management in aquaculture settings.

The paper (Iriani et al., 2024), focuses on an automated water circulation and fish feeding system for tilapia ponds, utilizing solar panels for sustainable energy. While it does not specifically address irrigation systems, it emphasizes the importance of maintaining water quality, particularly pH levels, through automation. The integration of sensors for real-time monitoring and control can be adapted for irrigation purposes, enhancing water management in small-scale fishponds by ensuring optimal conditions for fish growth while minimizing resource waste.

The paper presents (Thillainayagi et al., 2025), a solar-powered irrigation system that optimizes water usage based on soil moisture levels, which could be adapted for small-scale fishponds. By employing a moisture sensor to monitor soil conditions, the system automates irrigation decisions, ensuring efficient water management. The integration of renewable energy allows for operation in remote areas, enhancing sustainability. Although focused on agriculture, the principles of automated moisture monitoring and solar energy utilization can be applied to improve water management in fishponds.

METHODOLOGY

This study employed a quantitative experimental research design to develop and evaluate a sustainable automatic irrigation system intended to improve water management in small-scale fishponds. The performance of the developed system was compared with that of a conventional manual irrigation method under identical production conditions. The evaluation focused on its ability to maintain optimal water quality, improve water-use efficiency, enhance fish survival, and determine its economic feasibility. Two experimental treatments were established: (1) a manually operated irrigation system representing conventional fishpond management and (2) a sensor-based automated irrigation system developed by the researchers. Both systems were operated simultaneously for ninety (90) consecutive days under comparable environmental conditions to ensure consistency throughout the experiment.

The experiment was conducted at the Smart Agriculture Center of Tarlac Agricultural University using two identical intermediate bulk container (IBC) plastic tanks with a holding capacity of 1,000 L each. One tank served as the manual irrigation treatment, while the second tank was equipped with the developed automatic irrigation system. Each experimental unit was stocked with 250 African catfish (Clarias gariepinus) juveniles of comparable size and age. Both treatments received the same feeding schedule and husbandry practices throughout the experimental period, with the irrigation method serving as the only experimental variable. The manual irrigation system relied on scheduled water replacement performed twice weekly, whereas the automated system continuously monitored water quality and initiated water exchange only when measured parameters exceeded predefined threshold values suitable for African catfish production.

The automatic irrigation system consisted of an Arduino Mega 2560 microcontroller integrated with water temperature, pH, and dissolved oxygen sensors for real-time monitoring of pond conditions. A two-channel relay module controlled a DC water pump and a solenoid valve responsible for water circulation and replacement. To enhance sustainability, the system was powered by a photovoltaic energy source composed of a 100-W solar panel, charge controller, and rechargeable sealed lead-acid battery, allowing continuous operation while reducing dependence on conventional electricity. The control program was developed using the Arduino Integrated Development Environment (IDE). Sensor readings were continuously acquired and compared with preset threshold values. Whenever water quality parameters exceeded acceptable limits, the microcontroller automatically activated the relay module to operate the pump and solenoid valve, initiating water replacement until the measured values returned within the desired range. This closed-loop control mechanism minimized unnecessary water consumption while maintaining favorable environmental conditions for fish growth.

System development followed the Agile System Development Methodology, consisting of iterative planning, design, development, testing, deployment, and evaluation phases. Initial planning involved field observations, consultations with fish farmers, and a review of related literature to establish the functional requirements of the system. Hardware and software components were subsequently designed and integrated into the prototype. Following assembly and calibration of the sensors, functional testing was conducted to verify the proper operation of the automated control system before its deployment in the experimental fishpond. The prototype was then evaluated throughout the 90-day production period to determine its technical performance and operational effectiveness.

Water quality data were collected over ninety (90) consecutive days. Water temperature (°C), pH, and dissolved oxygen (mg L^{-1}) were measured twice daily, at 8:00 AM and 2:00 PM, to account for normal diurnal variations. Daily mean values were computed for statistical analysis. Water consumption for each irrigation treatment was monitored throughout the experiment, while fish survival was determined by counting the number of surviving fish at harvest. Economic performance was evaluated by calculating gross income, net income, and return on investment (ROI) using the prevailing market price of African catfish and the corresponding production costs.

The collected data were analyzed using descriptive statistics, particularly mean values, to summarize the observed water quality parameters. Differences between the manual and automated irrigation systems in terms of water temperature, pH, and dissolved oxygen were determined using the independent samples t-test at a 5% level of significance. Water-use efficiency was calculated based on the percentage reduction in water consumption achieved by the automated system relative to manual irrigation, while economic feasibility was assessed through the computation of return on investment (ROI). These analytical procedures enabled a comprehensive evaluation of the technical, environmental, and economic performance of the developed sustainable automatic irrigation system

RESULTS AND DISCUSSIONS

The developed sustainable automatic irrigation system was evaluated over a 90-day production period by comparing water quality parameters, water-use efficiency, and economic performance with those of a conventional manual irrigation system.

The automated irrigation system consistently maintained lower water temperature than the manual irrigation system throughout the monitoring period. The automated treatment recorded a mean temperature of 29.87°C, while the manual system recorded 30.67°C. Statistical analysis showed that the difference between treatments was significant ($p < 0.05$), indicating that automated water exchange effectively regulated pond temperature within the recommended range for African catfish culture.

Table 1. Comparison of mean water temperature between manual and automated irrigation systems over the 90-day experimental period.

Parameter	Manual Irrigation	Automated Irrigation	Interpretation
Mean Water Temperature (°C)	30.67	29.87	Significant difference ($p < 0.05$)

The pH measurements also showed improved stability under automated irrigation. The automated system maintained a mean pH of 7.72, compared with 8.25 under manual irrigation. Statistical analysis confirmed that the observed difference was significant ($p < 0.05$), suggesting that the automated system provided a more balanced water environment throughout the production period.

Table 2. Comparison of mean water pH between manual and automated irrigation systems over the 90-day experimental period.

Parameter	Manual Irrigation	Automated Irrigation	Interpretation
Mean Water pH	8.25	7.72	Significant difference ($p < 0.05$)

A similar trend was observed for dissolved oxygen concentration. The automated irrigation system maintained a higher mean dissolved oxygen level (5.94 mg L^{-1}) than the manual irrigation system (5.15 mg L^{-1}). Statistical analysis revealed a significant difference ($p < 0.05$), indicating that automated irrigation improved water aeration and oxygen availability.

Table 3. Comparison of mean dissolved oxygen concentration between manual and automated irrigation systems over the 90-day experimental period.

Parameter	Manual Irrigation	Automated Irrigation	Interpretation
Dissolved Oxygen (mg L^{-1})	5.15	5.94	Significant difference ($p < 0.05$)

Water-use analysis demonstrated that the automated irrigation system substantially reduced water consumption. The conventional manual irrigation system consumed 7,500 L of water over the 90-day period, whereas the automated system used only 4,500 L, representing a savings of 3,000 L or 40%.

Table 4. Water consumption and water-use efficiency of the two irrigation systems.

Parameter	Manual Irrigation	Automated Irrigation
Total Water Consumption (L)	7,500	4,500
Water Saved (L)	—	3,000
Water Saving (%)	—	40%

The improved water quality maintained by the automated irrigation system resulted in better fish survival and higher economic returns. Of the 250 fish initially stocked, 230 fish (92%) survived under automated irrigation compared with 200 fish (80%) under manual irrigation. Consequently, the automated system produced a harvest weight of 57.5 kg, exceeding the 50.0 kg obtained under manual irrigation. At a market price of ₱140 kg^{-1}, the automated irrigation system generated a gross income of ₱8,050 and a net income of ₱5,050, whereas the manual system generated ₱7,000 gross income and ₱4,000 net income. The return on investment (ROI) was likewise higher for the automated irrigation system (16.83%) than for manual irrigation (13.33%).

Table 5. Fish survival and economic performance of manual and automated irrigation systems.

Parameter	Manual Irrigation	Automated Irrigation
Initial Stock (fish)	250	250
Fish Survival (fish)	200	230
Survival Rate (%)	80	92
Harvest Weight (kg)	50.00	57.50
Gross Income (₱)	7,000	8,050
Feed Cost (₱)	3,000	3,000
Net Income (₱)	4,000	5,050
Return on Investment (%)	13.33	16.83

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