SEMARAK ILMU PUBLISHING

Semarak International Journal of Machine Learning

Journal homepage:
https://sijml.com/index.php/journal/index
ISSN: 3030-5241



Smart Urban Farming: Integrating Greenhouse, Aquaponics and IoT for Sustainable Agriculture

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ARTICLE INFO

Article history:
Received 18 June 2026
Received in revised form 4 July 2026
Accepted 13 August 2026
Available online 20 September 2026

Keywords:
Aquaponics; greenhouse automation; Internet of Things (IoT); smart farming; sustainable agriculture

ABSTRACT

This project presents the development of a smart urban farming system that integrates greenhouse, aquaponics, and Internet of Things (IoT) technologies to promote sustainable agriculture. The system leverages IoT-enabled sensors to monitor critical environmental parameters, specifically temperature and water pH, with automated control mechanisms such as exhaust fan activation and solenoid valve response to maintain optimal growing conditions. Over a 31-day period, the system-maintained temperature stability during low-light hours but faced thermal challenges during midday, with peak values reaching 40.32 °C—exceeding the recommended threshold for aquatic life. Despite this, real-time control strategies reduced energy consumption to approximately 2.02 kWh/day, achieving a reduction of 8.5 to 12.8 times in energy usage per square foot compared to conventional greenhouses. Water pH remained mostly within tolerable levels, with values ranging from 6.82 to 8.41, and the solenoid valve system enabled responsive correction during deviations. Tilapia growth data over 9 weeks showed strong performance, with a percent weight gain of 1083.69%, a specific growth rate (SGR) of 3.92%/day, and a feed conversion ratio (FCR) of 1.12, indicating efficient biomass conversion and robust system support. These results demonstrate the system's capability to improve productivity while reducing energy consumption and manual labour. The integration of automation and environmental monitoring validates the potential of smart farming systems to address urban sustainability goals and contribute to global targets such as food security, clean energy, and climate action.

1. Introduction

Urban farming has emerged as a promising solution to address food security and sustainability challenges in cities. However, conventional urban farming practices often lack automation and efficient resources management, making it difficult to maintain optimal conditions for plant and fish growth particularly in aquaponic systems. These limitations hinder scalability, productivity, and the

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ability to operate in space-constrained urban environments. To overcome these challenges, this project proposes a smart urban farming system that integrates greenhouse, aquaponics, and Internet of Things (IoT) technologies. The system uses IoT sensors for real-time monitoring and automated control of environmental parameters such as temperature and water pH, enabling year-round production with reduced labor and resource consumption.

Urban farming systems are evolving rapidly through the adoption of smart technologies, particularly IoT and automation. IoT technologies enable real-time monitoring and control of environmental conditions in agriculture, helping optimize resource usage and improve yield efficiency [1]. In greenhouse applications, sensors for temperature, humidity, and light have been shown to significantly enhance plant growth by maintaining stable growing condition [2]. Aquaponics, a sustainable method combining hydroponics and aquaculture, benefit greatly from environmental control. A Cyber-Physical Aquaponic System (CyPhA) that used IoT-based sensors for pH and temperature monitoring was introduced in Mat *et al*., [4]. However, it lacked greenhouse climate integration, limiting its effectiveness in addressing external environmental factors.

Other studies have demonstrated the feasibility of IoT-enabled monitoring in hydroponic and aquaponic systems, focusing on automation but not modular scalability or long-term energy efficiency [4,5]. Further research Luckring [6] explored low-power IoT networks and suggested the use of solar energy to reduce operational costs. Many works validate individual components (e.g., sensors or automation), few combine IoT, aquaponics, and greenhouse control into a single, scalable system. This project addresses that gap by developing a fully integrated, automated smart farming model designed for resource-constrained urban environments.

The proposed smart urban farming system is based on the integration of control systems engineering, sensor technology, and aquaponic principles within a greenhouse environment to maintain optimal conditions for plant and aquatic life. IoT enables real-time data acquisition and automation through a network of interconnected sensors and devices [7]. Key sensors used in this project include temperature sensors to monitor air and water temperature and pH sensors to maintain water quality for fish and plant health. These sensors transmit data to a microcontroller, which automate system responses through actuators such as fans, pumps, or valves.

The project uses closed-loop control systems to maintain environmental stability [8]. When sensor data deviates from preset thresholds, actuators are triggered to correct conditions. For example, if the temperature exceeds optimal limits, exhaust fans activate automatically. This is a basic implementation of Proportional-Integral-Derivative (PID) control principles used in automated environments [9]. Aquaponics combines hydroponics (soilless plant cultivation) and aquaculture (fish farming) in a symbiotic system [10]. Fish waste provides nutrients for plants, while plants help filter water for the fish. Maintaining proper water pH (6.8–7.2) and temperature (22–30°C) is crucial for biological balance. The greenhouse supports this by creating a controlled microclimate that reduces external variability and enhances growth efficiency.

2. Methodology

The IoT-enabled temperature control system is designed to regulate the greenhouse environment efficiently and automatically. It uses an ITC-308 temperature Controller, which continuously monitors the ambient temperature inside the greenhouse. This sensor transmits real-time data to the INKBIRD mobile application, allowing for remote monitoring and trend analysis. When the temperature exceeds a predefined threshold of 27°C, the ITC-308 controller automatically activates the connected exhaust fan to expel excess heat from the greenhouse. Once the temperature drops to 27°C or below, the fan is turned off. This forms a closed-loop control system:

real-time temperature data is evaluated continuously, and automatic action is taken to maintain optimal thermal conditions for plant and aquatic life. The temperature threshold can also be adjusted via the INKBIRD app, providing flexibility and reducing the need for manual intervention.

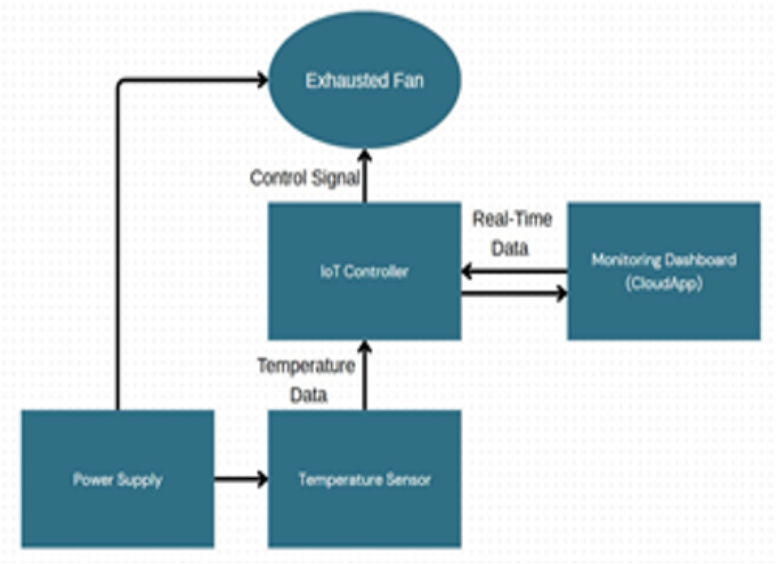


Fig. 1. Block diagram of IoT-enabled temperature sensor

The IoT-enabled pH regulation system is designed to maintain optimal water conditions for aquatic life and plant health within the aquaponics setup. A digital pH sensor continuously monitors the water's acidity level, with real-time data accessible via the Tuya Smart app. When the pH level drops below 6.8, the system automatically triggers a Two-Way Electric Solenoid Valve, which releases a buffer solution into the water to neutralize the acidity. This automated response helps maintain a stable and safe environment, reducing the need for manual pH adjustments and ensuring system efficiency. To manage water flow effectively during this process, the system uses a three-pipe configuration. Pipe 1 handles overflow management, allowing water to exit automatically when it surpasses the tank's capacity. Pipe 2 is connected to both the solenoid valve and a manual valve, enabling controlled discharge when pH correction is necessary. Pipe 3 is designated for manual draining during maintenance. This combination of automated pH monitoring and responsive control, supported by real-time mobile app integration, enhances the system’s functionality, flexibility, and sustainability.

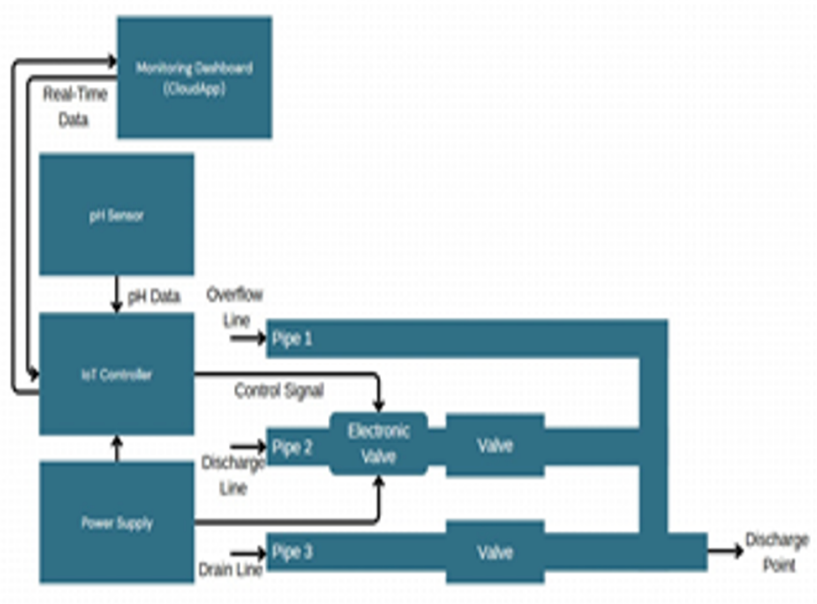


Fig. 2. Block diagram of IoT-enabled pH sensor

The system was developed to create a controlled greenhouse environment with integrated aquaponics. Two key environmental parameters were selected for monitoring and control. The air temperature to maintain a stable environment for plant growth and fish well-being while water pH level to ensure proper nutrient uptake by plants and health of aquatic species. Automation was achieved without microcontrollers, relying instead on intelligent commercial controllers capable of real-time monitoring and actuation. For description of specimens and samples, two types of biological specimens were used during the experiment. Fast-growing leafy vegetables such as kangkong and lettuce were selected due to their sensitivity to environmental conditions and short cultivation cycles and Tilapia, approximately 3 inches in length, were chosen for their compatibility with aquaponic systems and tolerance to varying water parameters. These specimens were housed in a controlled aquaponic setup inside a greenhouse to simulate an ideal urban farming environment. Manual observations of growth (e.g., plant height, leaf count, and fish length) were made weekly.

The ITC-308 temperature controller, a plug-and-play digital thermostat was connected to an exhaust fan to control air temperature. When the temperature exceeded a set threshold, the controller automatically activated the fan. When the temperature normalized, the fan turned off. The system status and real-time temperature data were monitored via the INKBIRD mobile app, allowing wireless configuration and oversight. An exhaust fan installed on the greenhouse wall, the exhaust fan functioned as the main cooling mechanism. It was directly powered and triggered by the ITC-308 controller. The fan provided consistent airflow to lower the internal temperature during heat buildup, especially during midday testing periods.

The PH/EC-W2823 wi-fi EC control detector device continuously monitored the water's pH and electrical conductivity (EC). The sensor provided real-time data through the Tuya Smart app, which also triggered alerts when values moved outside the optimal range. The sensor was not connected to other automation components but served as the central monitoring tool for water quality. A two-way electric solenoid valve was integrated into the fish tank drainage line and operated as a corrective actuator for pH control. When the pH exceeded the target range, the user could remotely or manually activate the valve to drain part of the water. The system was then replenished with clean water to help rebalance the pH naturally, reducing the need for chemical additives.

3. Results

3.1 Temperature Monitoring and Variation

The greenhouse temperature was monitored over a period of 30 days using the ITC-308 Wi-Fi-enabled temperature controller. Figure 3 shows the hourly average temperature trend over the monitoring period, with error bars representing the standard deviation at each time point. During the night and early morning hours (12:00 AM – 8:00 AM), the temperature remained relatively stable, ranging between 25.55°C and 26.29°C. The low standard deviation (< 0.5°C) during this period indicates consistent thermal conditions due to minimal external heating and effective insulation from the greenhouse structure.

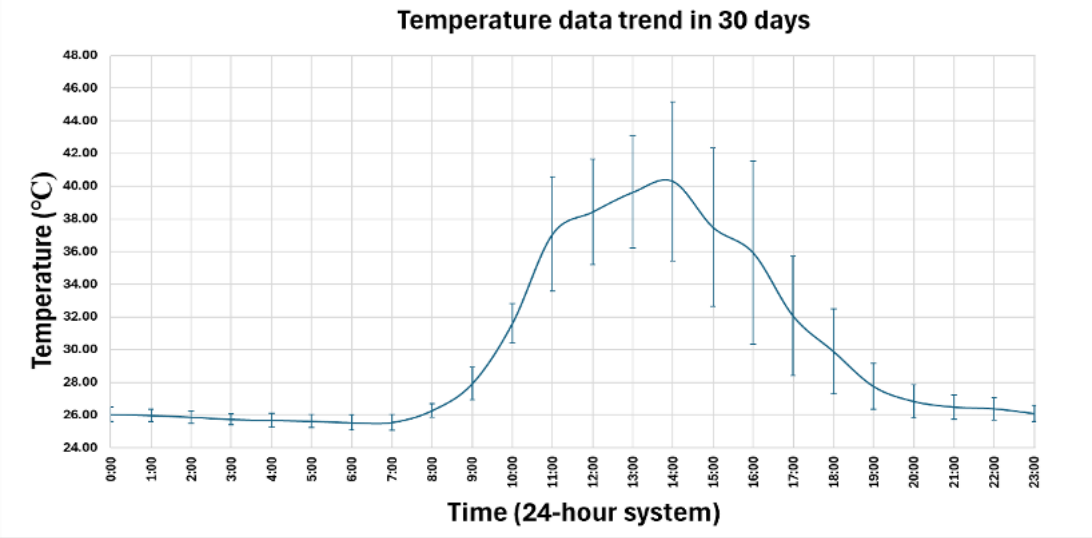


Fig. 1. Temperature variation trend in the greenhouse over 30 days, with error bars representing standard deviation

As the sun rose, the internal temperature began increasing sharply from 9:00 AM onwards, peaking between 1:00 PM and 2:00 PM at approximately 40.32°C. The highest variability occurred during this window (standard deviation ~4.8–5.6°C), driven by fluctuating sunlight intensity and ambient heat. To regulate internal temperature, the exhaust fan was programmed to activate when temperature exceeded 27°C and deactivate when it dropped back to or below 27°C. This simple control logic contributed to thermal stability during the hottest parts of the day. The effectiveness of the exhaust system is evident in how the temperature gradually declined after peaking in the early afternoon. The fan remained active from late morning until around 8:00 PM, successfully preventing excessive heat accumulation.

3.2 Water pH Analysis and Variation

The water pH levels in the aquaponic system were monitored daily over a 31-day period using the PH/EC-W2823 Wi-Fi-enabled pH detector. Figure 4 displays the daily average pH values with error bars representing the standard deviation, reflecting the variability in each day's measurements. Throughout the monitoring period, pH values ranged from 6.82 (Day 23) to 8.41 (Day 10), showing natural fluctuations associated with environmental factors and biological activity within the system. The standard deviation on most days remained below ±0.2, indicating consistent and stable pH conditions. Slightly elevated variability was observed on Day 9 (±0.28) and Day 10 (±0.30), coinciding

with the peak pH levels potentially due to increased microbial activity, nutrient cycling, or system maintenance events.

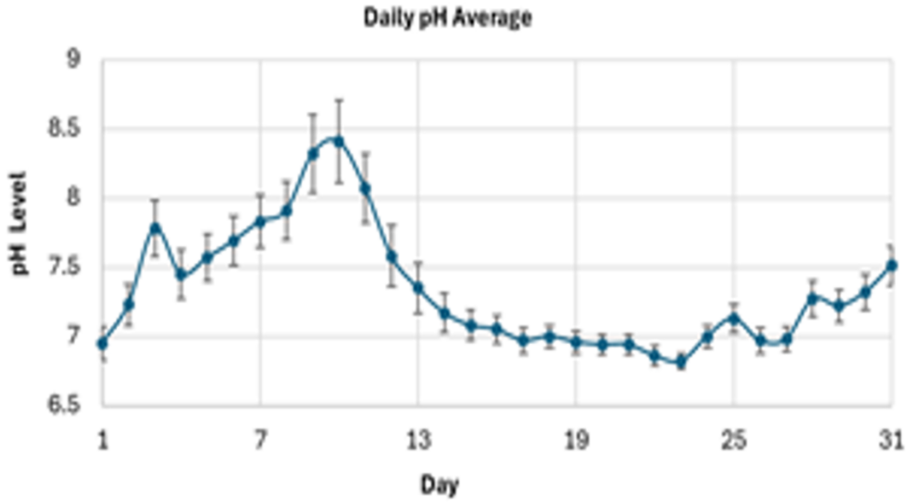


Fig. 4. Daily average water pH levels in the aquaponics system over 30 days, with error bars representing standard deviation

The pH values largely stayed within the optimal range for tilapia culture (6.5–8.5), although manual intervention was occasionally necessary. When values reach below 6.5, the electric solenoid valve was automatically activated to partially drain and replace the water, helping to rebalance the system without the use of chemical buffers. Overall, the system exhibited good pH stability with minimal intervention, demonstrating the effectiveness of the monitoring setup in supporting timely, data-informed maintenance decisions. The error bars emphasize both the natural variability of aquaponic ecosystems and the responsiveness of the management strategy in place.

3.3 Fish Weight Trend Over 9 Weeks

The average weight of tilapia was recorded weekly over a 9-week period. As shown in Figure 5, the fish exhibited a steady increase in weight from 5.09 g in Week 1 to 60.245 g in Week 9, reflecting a consistent upward growth trend supported by stable environmental conditions in the aquaponic system. Weight gain was relatively gradual during the first three weeks, rising from 5.09 g to 26.235 g. Between Weeks 3 and 4, the fish experienced a significant increase, reaching 34.51 g, followed by another sharp gain between Week 7 and Week 8, where average weight jumped from 49.60 g to 59.12 g. These periods represent phases of rapid growth, typical of juvenile tilapia in optimal conditions. The standard deviation in weight, indicated by error bars, remained low in the early weeks (e.g., ±0.18 g in Week 1), suggesting uniform fish size.

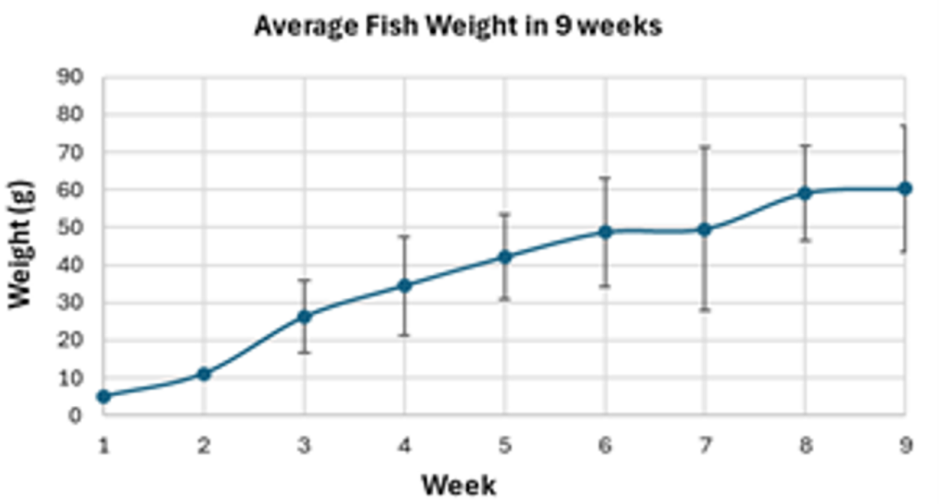


Fig. 2. Average fish weight trend over 9 weeks, with error bars representing standard deviation of weekly measurements

As the fish matured, variability increased, with the highest spread observed in Week 7 (±21.79 g) and Week 9 (±16.85 g). This variation indicates divergence in growth rates, likely due to factors such as feeding competition, genetic differences, and individual health status. Overall, the data confirms that the system effectively supported strong, healthy weight gain in tilapia, with expected natural variation emerging over time.

3.4 Fish Length Trend Over 9 Weeks

Figure 6 shows the average weekly length of tilapia measured over a 9-week period. The fish displayed a clear and consistent increase in length, starting at 7.5 cm in Week 1 and reaching 15.63 cm in Week 9, indicating steady physical development under stable environmental conditions. Initial growth occurred gradually, with the fish growing to 9.08 cm by Week 2 and 11.6 cm by Week 3. Rapid length gain continued until Week 5, reaching 13.18 cm, after which the growth rate began to taper. This plateau is typical in tilapia growth as energy is increasingly allocated to weight gain over linear body extension in later stages.

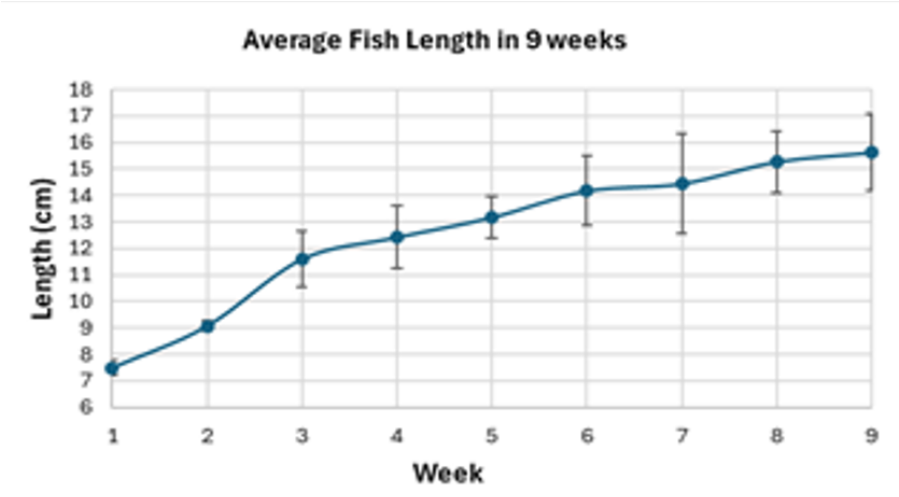


Fig. 3. Average fish length trend over 9 weeks, with error bars representing standard deviation of weekly measurements

Standard deviation, shown as vertical error bars, was low in early weeks (e.g., ±0.28 cm in Week 1, ±0.18 cm in Week 2), indicating uniform fish size. From Week 4 onward, variability increased gradually, peaking in Week 7 (±1.90 cm), suggesting differing individual growth rates a common biological trend as fish mature. Overall, the consistent increase in average length, combined with expected variability, reflects a healthy growth environment and the effectiveness of the system in supporting tilapia development.

3.5 Weight Versus Length Relationship of Tilapia

Figure 7 shows the relationship between average fish weight and length over nine weeks. Both horizontal and vertical error bars represent the standard deviations of length and weight, respectively. The graph reveals a strong positive correlation. As the fish grew longer, their weight increased more rapidly, reflecting typical growth behaviour in tilapia. During the early weeks, such as Week 1 to Week 3, growth was gradual in both length and weight. However, from around 14 centimetres onward, the fish began to accumulate weight more significantly. For instance, between Week 7 and Week 9, the length increased by only about 1.2 centimetres, while the weight rose by nearly 11 grams.

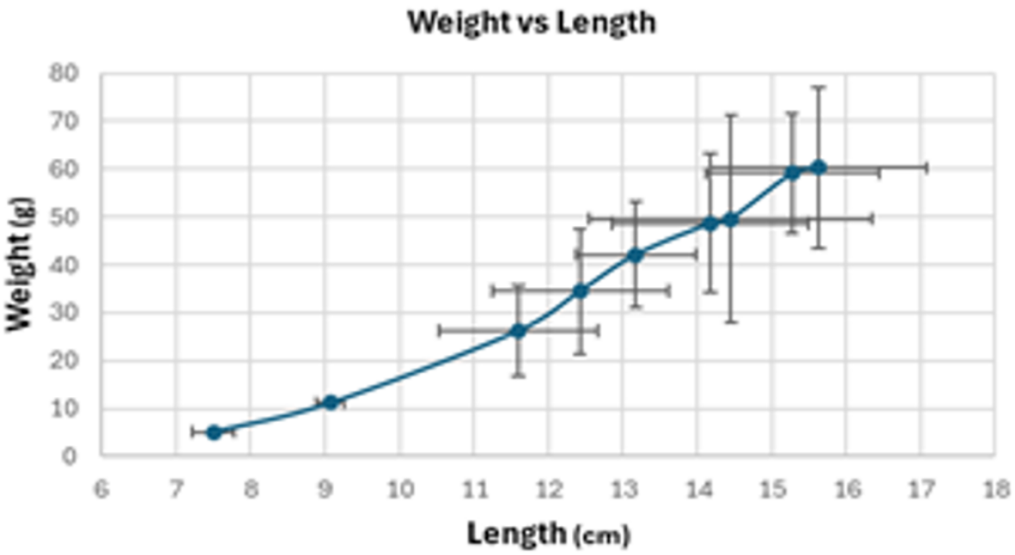


Fig. 4. Relationship between fish weight and length over 9 weeks, with horizontal and vertical error bars representing standard deviations of length and weight, respectively

The shape of the curve suggests allometric growth, where weight increases faster than length as the fish mature. This pattern is common in many fish species and indicates a shift in energy use from structural development to mass gain. Larger standard deviations in the later weeks also suggest growing differences among individual fish. This variation highlights the importance of real-time monitoring to manage growth consistency in aquaponic systems.

Table 1
Total electrical load of smart-greenhouse system

No.	Device / Component	Quantity	Estimated Power (W)	Total Power (W) (Average)
1	ITC-308 Temperature Controller	1	3-5	4
2	Exhaust Fan	1	50-100	80
3	PH/EC-W2823 Wi-Fi Detector	1	5-10	7
4	Solenoid Valve (220V, Normally Closed)	1	6-10	10
5	Water Pump	1	25-60	40
	Total Estimated Load			89-185

All devices operated independently and required no microcontrollers, manual sensors, or local data logging. The testing phase lasted several weeks, during which environmental data was tracked via mobile apps, and biological outcomes were manually recorded.

4. Discussions

4.1 Temperature Trends and Implications

Hourly temperature measurements across the 31-day period revealed significant daily fluctuations, with average temperatures ranging from a low of 25.55 °C at 6:00 AM to a peak of 40.32 °C at 2:00 PM. This aligns with expected diurnal patterns in a tropical climate, where nighttime and early morning temperatures remain relatively cool, while midday and afternoon hours show sharp increases due to solar radiation. The standard deviation values confirm that temperatures are stable during early hours (e.g., ~0.3–0.5 °C between 12:00 AM and 8:00 AM) but become increasingly volatile during the afternoon. The highest variability occurred between 2:00 PM and 5:00 PM, with standard deviations exceeding 4 °C, peaking at 5.61 °C at 4:00 PM. This suggests that not only do temperatures climb above optimal thresholds, but they also fluctuate rapidly, which can induce stress in aquatic organisms.

While the lowest recorded temperatures fall within the ideal range for tilapia (22–30 °C), conditions from 10:00 AM onward exceed 30 °C, with average values above 35 °C from 11:00 AM to 4:00 PM. This thermal profile indicates a daily exposure to suboptimal or potentially harmful temperatures for at least 6 hours, which may impair fish metabolism, reduce dissolved oxygen levels, and increase ammonia toxicity. Although shading measures were implemented, these results highlight that passive heat mitigation was insufficient under current Malaysian climate conditions, especially during midday. As climate trends push ambient temperatures higher, additional cooling strategies (e.g., improved ventilation, misting systems, or thermal insulation) may be necessary to protect aquatic life and sustain optimal system performance. Despite these challenges, the overall temperature regulation remained relatively stable during critical low-light hours, suggesting that the system design at least provides partial thermal buffering. However, given the extended periods above tolerance thresholds, further environmental control should be a priority for long-term system sustainability.

4.2 Stability and Regulation of Water pH in the Aquaponic System

The pH levels in the aquaponic system ranged from 6.82 on Day 23 to 8.41 on Day 10 throughout the 31-day monitoring period. Based on the literature, the recommended pH range for tilapia culture is 6.8 to 7.2. Within this range, nutrient availability, microbial activity, and fish health are generally optimized. However, the data shows that only a limited number of days fell within this ideal range. A significant upward trend in pH was observed between Day 7 and Day 11, with the highest value

recorded on Day 10 at 8.41. This period also showed elevated standard deviation values, such as 0.30 on Day 10 and 0.28 on Day 9, indicating greater fluctuation in water chemistry. These variations may be attributed to increased fish waste, microbial shifts, or a temporary imbalance in the buffering capacity of the system.

On days when the pH dropped below 6.5, the system's electric solenoid valve was automatically triggered. This safety feature allowed for partial drainage and replenishment of the fish tank with fresh water, helping to correct low pH levels without the use of chemical additives. Although this mechanism was not activated during the recorded period, its presence ensured readiness for critical interventions. The second half of the monitoring period, especially from Day 16 to Day 26, displayed more stable pH values with lower standard deviations, typically under 0.10. This stability was likely supported by the continuous inflow of fresh hill-sourced water and the installed filtration system, both of which helped dilute excess nutrients and maintain water quality. Despite some fluctuations, the pH remained mostly within tolerable limits for tilapia. However, consistent deviations above the recommended range suggest a need for better passive pH control measures, such as improved shading or increased buffering capacity, especially under prolonged high-temperature conditions.

4.3 Fish Biomass Development and Growth Performance

Throughout the 9-week culture period, tilapia in the aquaponic system demonstrated consistent growth. The mean initial weight was 5.09 g in Week 1, and by Week 9, the mean final weight reached 60.25 g, resulting in a total weight gain of:

$$\begin{aligned} Weight\ Gain\ (g) &= Final\ Mean\ Weight - Initial\ Mean\ Weight \\ &= 60.25\ g - 5.09\ g \\ &= 55.16g \end{aligned}$$

This steady increase indicates that the fish adapted well to the system, especially after the early acclimation phase. Notably, a sharp rise occurred between Week 2 and Week 3, where the average weight more than doubled, suggesting rapid metabolic adjustment and feed acceptance. To evaluate growth efficiency relative to initial weight, the Percent Weight Gain (%) was calculated as:

$$\begin{aligned} Percent\ Weight\ Gain\ (\%) &= \left(\frac{60.25 - 5.09}{5.09}\right) * 100\% \\ &= 1083.69\% \end{aligned}$$

This high percentage reflects excellent growth under the given conditions, despite environmental stressors such as high temperature and variable pH levels, as discussed earlier. For quantifying the daily growth rate, the Specific Growth Rate (SGR) was used:

$$SGR\ \left(\%—day\right) = \frac{[\ln(W_2) - \ln(W_1)]}{T} * 100\%$$

$$= \frac{[\ln(60.25) - \ln(5.09)]}{63} * 100\%$$

$$= 3.92\ \%\ /\ day$$

where W_2 and W_1 are the final and initial weights(g), and T is the time in days. This formula is well established in aquaculture research [11].

An SGR of nearly 4% per day is considered very good for tilapia, especially under naturally fluctuating water conditions. It confirms that the system provided adequate nutrition and water quality to support healthy biomass accumulation. The weight standard deviations ranged significantly, peaking in Week 7 at 21.79 g, which indicates some inconsistency in growth among individuals. This could be due to several factors, including competition for feed, unequal access to nutrients, or dominance hierarchy behaviour commonly observed in tilapia populations. Addressing these discrepancies may involve adjusting stocking density or feed distribution practices.

4.4 Fish Length Progression

Fish length is a key biometric parameter reflecting skeletal development and overall health. Over the 9-week culture period, the average fish length increased from 7.5 cm in Week 1 to 15.63 cm in Week 9, indicating a total length increment of:

$$Length\ Gain = 15.63\ cm - 7.5cm$$

$$= 8.13\ cm$$

The growth pattern followed a steady upward trajectory, with notable acceleration during the early phase (Weeks 1–3), where the average length grew by over 4 cm. This early spike suggests good adaptation to the aquaponic environment and effective feed utilization during initial weeks. From Week 4 onward, the rate of length gains gradually tapered, which is common as fish shift more energy toward mass accumulation rather than linear growth. By Week 7, growth appeared to plateau slightly, with only 0.275 cm increase observed between Weeks 6 and 7. However, growth resumed moderately through Week 9.

Length standard deviations generally increased as the fish matured, peaking in Week 7 at 1.91 cm, then stabilizing. This variation could be due to biological differences in individual growth rates, hierarchy formation, or uneven access to resources like feed or space. Overall, the consistent increase in length, despite environmental fluctuations, highlights the suitability of the system to support tilapia development. However, the relatively high variation suggests the potential benefit of better feed distribution strategies or grading practices in future operations.

4.5 Relationship between Fish Weight and Length

The observed relationship between fish weight and length across the 9-week study indicates a strong positive correlation: as the length of the tilapia increased, so did its weight. This pattern is consistent with the allometric growth model commonly found in fish were body mass increases exponentially relative to linear growth. To assess the efficiency of feed utilization in this context, the Feed Conversion Ratio (FCR) was calculated using the following formula:

$$FCR = \frac{Feed\ Intake\ (g)}{Weight\ Gain\ (g)} * 100\%$$

This metric evaluates how efficiently the fish convert feed into biomass. A lower FCR indicates better feed efficiency [12].

1. Feed Intake Estimation
   According to guidance from the supervisor, the fish were fed daily at a rate of 3% of their body weight. To estimate feed intake:

   $$Initial\ weight = 5.09\ g$$

   $$Final\ weight = 60.25\ g$$

   $$Average\ weight \approx \frac{(5.09 + 60.25)}{2} = 32.67\ g$$

   $$Daily\ feed = 3\ \%\ of\ 32.67\ g = 0.9801\ g/day$$

   $$Duration = 9\ weeks * 7 = 63\ days$$

   $$Estimated\ total\ feed\ intake = 0.9801 * 63 = 61.75\ g\ per\ fish$$

2. FCR
   With a weight gain of:

   $$60.25 - 5.09 = 55.16\ g$$

and estimated feed intake of 61.15 g, the FCR is:

$$FCR = \frac{61.75}{55.16} = 1.12$$

This value suggests efficient feed utilization. For comparison, typical FCR values for tilapia range from 1.6 to 1.8 under standard aquaculture conditions [12,13]. A value close to 1.0, like 1.11, indicates very good efficiency. The interpretation of FCR as:

FCR < 1.0: Extremely efficient feed use (rare in practice)
FCR = 1.0: 1 kg of feed yields 1 kg of fish
FCR > 1.0: Lower efficiency; more feed required for equivalent weight gain

5.6 Power Consumption Analysis

Based on industry data, a conventional greenhouse without IoT-driven systems relies heavily on mechanical ventilation. Exhaust fans designed to circulate 8–10 cubic feet per minute per square foot typically consume 0.5 to 1 kWh per ft² annually, operating roughly 2,000 hours per year [14]. For a 10,000 ft² facility running fans for 16 hours each day, this translates to approximately 64–96 kWh per day. Adding horizontal airflow fans (HAF) further increases energy usage by an estimated 17–48 kWh daily. Even greenhouses equipped with passive or natural ventilation systems typically use between 0.5 and 1 kWh per ft² annually. In contrast, the IoT-enhanced aquaponic greenhouse designed in this project operates with significantly lower energy consumption [15]. The total estimated electrical load ranges between 89 W and 185 W, depending on which components are active. The exhaust fan, rated at 80 W, is triggered only when the temperature exceeds 27 °C. Data recorded shows that this condition typically occurs from 9:00 AM to 7:00 PM (10 hours daily), resulting in approximately

800 Wh (0.8 kWh) per day. The water pump operates continuously at 40 W, contributing 960 Wh (0.96 kWh) per day. The ITC-308 temperature controller consumes an average of 4 W, totalling 96 Wh daily, and the PH/EC-W2823 Wi-Fi pH sensor uses 7 W or around 168 Wh daily. The two-way electric solenoid valve (10 W) is only activated for short durations during pH correction events—estimated to use just 10 Wh over 31 days, averaging only 0.32 Wh/day.

Altogether, the total daily power usage of the system is approximately 2.02 kWh. When normalized over the greenhouse area of 2,688.625 ft², this equates to approximately 0.00075 kWh/ft²/day. This figure is significantly lower than conventional systems, which consume between 0.0081 and 0.0144 kWh/ft²/day, demonstrating a 10.8 to 19.2 times reduction in energy use per square foot. This efficiency is achieved through real-time, sensor-driven control, where energy is only consumed when needed, avoiding the constant operation typical in traditional systems. This targeted, demand-based automation not only reduces energy waste but also aligns with sustainability objectives such as SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). It validates the role of IoT technology in creating cost-effective, energy-efficient, and environmentally responsible solutions in urban farming.

4. Conclusions

This study successfully demonstrated a smart urban aquaponics system that meets its initial objectives by combining automated environmental control, efficient resource use, and robust tilapia growth. Over nine weeks, average fish weight rose from 5.09 g to 60.25 g, and length increased from 7.50 cm to 15.63 cm. Performance metrics such as a feed conversion ratio of 1.12 and a specific growth rate of 3.93 percent per day further underscore the system's productivity and biological efficiency. The greenhouse operates with a notably low energy demand, averaging around 2 kWh per day. This includes roughly 800 Wh for a daily 10-hour exhaust fan run, 960 Wh for continuous water pump operation, and minimal draw from pH/EC sensors and auxiliary components. In contrast to conventional greenhouses, which may consume over 80 kWh daily for ventilation and climate control, this system achieves similar growth outcomes with a fraction of the energy. The integration of solar PV panels ensures that the greenhouse operates with near-zero grid dependence. Despite its strengths, the system's thermal performance can be improved. On exceptionally hot days, internal temperatures exceed 40 °C, which poses potential stress on biota. Recommended enhancements include upgrading cooling measures through evaporative systems, improved shading, or increased ventilation. Automating pH correction via the solenoid valve would also reduce manual intervention and maintain chemical stability. Accurate logging of daily feed intake would refine feed efficiency calculations and help optimize feeding protocols. Additionally, fine-tuning stocking densities and feed distribution would address observed growth variability among fish. In conclusion, this project validates the concept that an IoT-enabled, solar-powered urban aquaponics greenhouse can sustain high growth rates and excellent resource efficiency while consuming minimal energy.

Acknowledgement

This research was funded by a grant from Ministry of Higher Education of Malaysia (FRGS Grant R.J130000.7824.4X172).

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