

DESIGN OF AUTOMATIC ARTIFICIAL LIGHT CONDITIONING CONTROL SYSTEM FOR INDOOR AQUAPONICS USING MULTI-POINT SENSOR TECHNIQUE

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Abstract

Food security at the global, national, and household levels has become a shared focus of the global community, as outlined in one of the key points of the 2030 Agenda for Sustainable Development (SDGs), specifically Goal 2: “Zero Hunger.” The urban environment, characterized by limited direct access to food sources, renders urban populations vulnerable to hunger due to the unavailability of food resources, which can result from various disruptions in the supply chain, such as natural disasters, food shortages, supply chain interruptions, and a lack of self-reliance in food production (food resilience). One critical factor contributing to the lack of food resilience in urban settings is the absence of agricultural land as a food source. The use of aquaponics as a food security solution in urban areas has long been recognized as a proactive measure. However, the efficiency of food production from conventional aquaponics systems remains suboptimal. This study proposes a concept and preliminary testing of an innovation to engineer environmental conditions, specifically the lighting parameters, within aquaponics systems by incorporating and applying automation technology. This approach aims to enhance agricultural productivity in aquaponics systems while prioritizing energy efficiency. The application of a multi-point sensing technique using eight LDR sensors positioned at various test points within the aquaponics system has been demonstrated to improve energy efficiency. This is achieved by implementing a selective algorithm to determine the optimal times for activating grow lights.

Keywords: Automation technology, Food security, Lighting efficiency, Multi-Point sensing, Urban aquaponics.

INTRODUCTION

Food security, as one of the critical aspects of sustainable development, serves as a primary focus in the advancement of efficient and environmentally friendly modern agricultural systems. Food security refers to a condition where all individuals have reliable access to sufficient, safe, and nutritious food to meet their dietary needs for an active and healthy life (Drebot *et al.*, 2024). Food availability, as a component of food security, pertains to the presence of food within a specific area or region, determined by food production, stock levels, and net trade, ensuring efficient availability and productivity within the supply chain (Hendriks & Babu, 2024; Kumar *et al.*, 2024). Stable food availability is essential to support economic growth and improve the quality of life, thus necessitating innovations in agricultural technology alongside policies that promote sustainable practices.

One of the key agendas in the 2030 Sustainable Development Goals (SDGs) is the eradication of hunger, ensuring that available food is sufficient, of high quality, and accessible to everyone without exception, to achieve equitable global food security for all communities (Hyink *et al.*, 2024). However, the realization of food security faces several challenges that hinder its attainment, such as climate change, food price fluctuations, and political instability, which can affect the distribution and accessibility of resources (Hyink *et al.*, 2024; Agboklou *et al.*, 2024). These uncertainties demand

collaboration among governments, the private sector, and society to develop innovative solutions capable of effectively addressing these challenges.

Organic farming, grounded in the principles of agroecology, offers a sustainable alternative to conventional agriculture. This approach supports food security, economic sustainability for smallholder farmers, and biodiversity, all of which align with the goals of SDG 2 (Batra *et al.*, 2024). Sustainable Smart Agriculture also plays a critical role in achieving Zero Hunger. This initiative incorporates the integration of technologies such as the Internet of Things, automation, artificial intelligence, and precision agriculture to enhance resource management and also to minimize environmental impact (Mishra & Mishra, 2024).

Urban communities are particularly vulnerable to food security instability due to their reliance on food supplies from external regions, primarily rural areas dominated by agricultural and plantation activities (Macalou *et al.*, 2023). Additionally, environmental instabilities such as floods, extreme droughts, earthquakes, and even conflicts can significantly impact food security in urban areas (Haider *et al.*, 2023). Consequently, the development of innovative urban agriculture can play a pivotal role in enhancing food accessibility and sustainability amidst these challenges.

Urban agriculture and community resilience strategies, such as household or small community gardens, can reduce food insecurity by providing fresh food and supplemental income while improving environmental quality and community empowerment (Awason, 2021; Salleh *et al.*, 2020). Aquaponics systems, which combine fish farming and plant cultivation in a symbiotic ecosystem, offer an efficient solution for urban areas. This system reduces water consumption by recirculating water, making it more resource-efficient than traditional farming (Garnida, 2023; Mukherjee & Nath, 2024).

The cultivation of plants within an aquaponics system is highly dependent on the light intensity provided. For leafy green vegetables, high light intensity typically enhances photosynthesis, leading to greater biomass accumulation and higher yields (Matuszak-Slamani & Ulan, 2023). Furthermore, optimal light intensity significantly influences nutrient uptake and metabolite synthesis (Bueno & Vendrame, 2024), while also inducing stress responses in plants that result in increased antioxidant enzyme activity (Hashemifar *et al.*, 2024).

While increased light intensity generally promotes plant growth and photosynthesis, it can also trigger stress responses that impact plant health and quality. The optimal light intensity varies among plant species and even among different cultivars of the same species, necessitating tailored light management strategies to maximize growth and quality. Understanding these dynamics is crucial for optimizing plant production in both natural and controlled environments.

This study proposes a novel concept in light management systems for plants in aquaponics, particularly for indoor aquaponics systems with limited access to natural sunlight, necessitating artificial lighting. An effective light management system can enhance photosynthetic efficiency and support plant growth by providing an appropriate light spectrum while optimizing its duration and intensity. The concept of multi-point sensors is employed to monitor the light intensity levels received by plants, enabling real-time adjustments to lighting conditions. This approach is expected to achieve optimal growth and higher yields in aquaponics systems while simultaneously reducing energy waste and operational costs.

LITERATURE REVIEW

Engineered lighting conditions in indoor aquaponic environments involve selecting appropriate lighting technologies and integrating smart systems to optimize plant growth and energy efficiency. The choice of lighting significantly impacts plant development, energy consumption, and economic sustainability. Various studies have explored different lighting technologies and their effects on plant growth in aquaponic systems, offering valuable insights into best practices for engineered lighting conditions.

LED-based lighting technology is the most efficient option for aquaponic systems, offering superior plant growth performance and energy efficiency compared to other lighting technologies (Oliver *et al.*, 2017). Additionally, low-cost LED options have been shown to sustain adequate plant growth while reducing production costs, making them economically viable for aquaponic producers (Lohman *et al.*, 2024).

Scheduling artificial lighting in aquaponic systems plays a crucial role in enhancing energy efficiency and promoting plant growth. By optimizing photoperiod, light intensity, and spectrum, aquaponic systems can significantly reduce energy consumption while maximizing plant productivity. This approach not only addresses the economic and environmental sustainability of aquaponics but also aligns with global sustainability goals.

Implementing an intermittent lighting schedule aligned with periods of lower energy costs can reduce operational expenses and improve energy efficiency. This strategy enables vertical farms to function as flexible energy consumers, adjusting energy usage based on the availability of renewable energy sources (Robbiani & Törn, 2024). Adjusting the photoperiod can significantly impact plant growth and yield. For instance, a 16-hour photoperiod under artificial red and blue light has been shown to enhance biomass accumulation and metabolite concentration in *Stevia rebaudiana*, resulting in higher productivity compared to natural daylight conditions (Rengasamy *et al.*, 2022).

While optimizing lighting schedules can lead to significant improvements in energy efficiency and plant growth, it is essential to consider potential challenges and limitations. For instance, continuous lighting may cause stress or damage to plants if the photoperiod exceeds the species-specific tolerance threshold (Lanoue *et al.*, 2022).

Light intensity measurement using Light Dependent Resistors (LDR) in a multi-point monitoring model can significantly enhance artificial light regulation by providing precise and distributed data on light intensity within a specific area. This approach enables more accurate lighting system control, optimizing energy usage and improving lighting quality. Integrating LDR sensors into lighting control systems creates a more efficient and responsive lighting environment, particularly in settings where light distribution and intensity are critical.

LDRs can be arranged in a matrix to measure light intensity at multiple points within a room, providing a comprehensive map of light distribution. This method surpasses traditional single-point luxmeter measurements, which may overlook variations in light intensity across different areas of the room (Sowa, 2018), the use of a photoresistor matrix reduces measurement errors associated with manual luxmeter readings, resulting in more reliable data for controlling lighting systems (Sowa, 2018).

LDR-based systems can dynamically adjust artificial lighting in response to changes in natural light, ensuring consistent illumination levels. This is achieved by integrating LDR data into a control system that modulates light intensity based on real-time measurements. By precisely controlling the activation and intensity of artificial lights, this system can reduce energy consumption. For instance,

it ensures that artificial lighting is used only when necessary, complementing natural light to maintain the desired lighting levels (Pacheco-Macas *et al.*, 2023).

In certain cases, the use of a multi-point LDR-based light intensity measurement model can also be applied in renewable agricultural cultivation, such as in the automation of activating water pump motors used for irrigation in hydroponic systems. By utilizing multiple LDRs placed at various points, this approach can maximize the accuracy of sunlight intensity readings (Hidayat, 2023).

RESEARCH METHOD

The research conducted in this study employs a design and preliminary simulation approach focused on the utilization of multiple Light Dependent Resistors (LDR) to measure light intensity in an aquaponic environment. The measurement results are used to determine the activation of grow lights as artificial light sources substituting sunlight for plant growth processes. This study employs six LDR sensors and two grow lights, where the ambient light intensity data (expressed in voltage values) obtained from the LDR sensors are processed by an Arduino Mega2560, which serves as the control device. Data from the six LDR sensors are utilized to make decisions regarding the activation of the two grow lights. The system block diagram, illustrating the input devices, control processes, and output mechanisms, is presented in Figure 1.

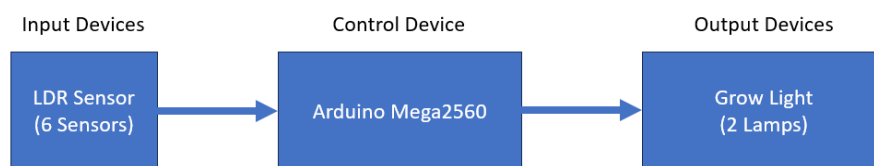


Figure 1. System block diagram: Input – Process – Output Devices

The six LDR sensors used are divided into two clusters, with each cluster consisting of three LDR sensors. Each cluster will control the activation of one grow light. The first light is positioned on the left side of the aquaponic system, while the second light is positioned on the right side. The illustration of the sensor and light placement can be seen in Figure 2.

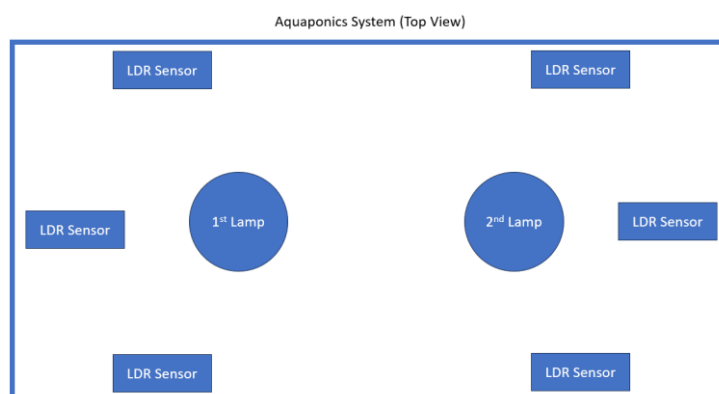


Figure 2. Illustration of sensor and lamp placement

The data from the six LDR sensors is collected sequentially by the control device and then compared and processed according to the predefined control rules. The relationship between the six LDR sensors and the two grow lights used is presented in Table 1.

Table 1. Relationship between LDR sensors and grow lights

LDR Sensor Conditions	Lamp 1 Condition	Lamp 2 Condition
No sensors detect light above the expected threshold	Turned On	Turned On
All sensors detect light above the expected threshold	Turned Off	Turned Off
Only one sensor in the left cluster detects light	Turned On	Not Affected
Only one sensor in the right cluster detects light	Not Affected	Turned On
Only two sensors in the left cluster detects light	Turned Off	Not Affected
Only two sensors in the right cluster detects light	Not Affected	Turned On

The Arduino Mega2560 device used in this study has the ability to read voltage data in the range of 0 to 5 Volt DC, which is scaled to a value range of 0 to 1023. Based on this range, light detection is considered when the voltage reading exceeds a value of 650, or when the LDR sensor voltage exceeds 3.2 Volt DC. The value of 650 was obtained from light intensity measurements taken at 7 AM and 5 PM, when the plants undergo minimum photosynthetic activity.

In each cluster, the data from the three LDR sensors used will be examined and then compared with each other to test the scenario provided against the actual conditions. The results of this analysis will control the activation of the lights in each cluster. Specifically, for full activation control (turning both lights on or off), the sensor data will no longer be compared at the cluster level, but at the full level. Data from all six sensors will be checked to determine whether all of them detect light or if none of them detect light.

This lighting conditioning is necessary because the system developed in this study is specifically intended for indoor use, where sunlight is not always available. Therefore, automation in artificial lighting is required to support efficiency and ensure that plant growth remains in optimal conditions.

RESULTS AND DISCUSSION

The tests conducted in this study are divided into three tests: (1) testing the system performance on the left cluster, (2) testing the system performance on the right cluster, and (3) testing the system performance as a whole. In addition, an energy savings analysis is also performed between the operation of plant growth lights in the conventional system (where the lights are left on continuously during the general photosynthetic period) and the system proposed in this study.

Table 2. Left cluster measurement data

Time	Value of LDR 1	Value of LDR 2	Value of LDR 3	Light Condition
7 AM	433	467	420	On
8 AM	481	495	488	On
9 AM	574	673	591	On
10 AM	642	685	637	On
11 AM	723	776	704	Off
12 AM	873	881	892	Off
1 PM	927	912	944	Off
2 PM	812	793	805	Off
3 PM	688	603	672	Off
4 PM	624	622	618	On
5 PM	322	275	341	On

In the left and right cluster system tests, the intensity readings from the three sensors in each cluster were measured every hour from 7 AM to 5 PM, and the automatic activation of the lamps was

observed to see whether the system successfully controlled the activation of the lamps in each cluster.

Table 2 displays the light intensity measurement data from the LDR sensors in the left cluster and the corresponding lamp conditions during these measurements. It can be seen that from 7 AM to 10 AM, the lamps were on because the light intensity values detected by the three sensors did not meet the criteria to turn off the lamps. From 11 AM to 3 PM, the lamps were off because the light intensity values detected by the three sensors met the criteria to turn off the lamps. Then, from 4 PM to 5 PM, the lamps were on again because the light intensity values detected by the three sensors met the criteria to turn the lamps on.

Table 3. Right cluster measurement data

Time	Value of LDR 1	Value of LDR 2	Value of LDR 3	Light Condition
7 AM	421	443	456	On
8 AM	499	491	422	On
9 AM	689	544	682	Off
10 AM	711	692	700	Off
11 AM	728	744	738	Off
12 AM	899	902	917	Off
1 PM	1002	1016	1020	Off
2 PM	954	728	805	Off
3 PM	678	598	663	Off
4 PM	601	612	590	On
5 PM	305	339	372	On

Table 3 shows the light intensity measurement data from the LDR sensors in the right cluster and the corresponding lamp conditions during these measurements. It can be seen that from 7 AM to 8 AM, the lamps were on because the light intensity values detected by the three sensors did not meet the criteria to turn off the lamps. From 9 AM to 3 PM, the lamps were off because the light intensity values detected by the three sensors met the criteria to turn off the lamps. Then, from 4 PM to 5 PM, the lamps were on again because the light intensity values detected by the three sensors met the criteria to turn the lamps on.

In the full system testing, it can be observed that from 11 AM to 2 PM, all the LDR sensors detected light intensity values above the threshold, causing both lamps to turn off. From 9 AM to 10 AM, only the left lamp was on, as the LDR sensors used in the left cluster did not all detect light intensity above the threshold during that time. This proves that under certain conditions, not all lamps need to be turned on. The activation of the lamps can be controlled according to the light intensity present around each lamp.

In the energy efficiency analysis, it is known that for the conventional system, both lights are kept on continuously from 7 AM to 5 PM, totaling 10 hours. The lights used in this study are plant growth lights, each consuming 50 watts of power. Therefore, the total energy used per day for the conventional system can be calculated as follows:

$$\text{Total Power} = 50 \text{ Watt} \times 2 \text{ lamps} \times 10 \text{ hours} = 1000 \text{ Wh} \cong 1 \text{ kWh}$$

Meanwhile, in the system proposed in this study, the effective time during which both lamps are on is approximately 5 hours, using half of the total electricity consumption required by the conventional system (0.5 kWh).

CONCLUSION

The utilization of a multi-point light intensity measurement method employing LDR sensors within aquaponic systems for controlling artificial lighting activation has proven effective in improving energy efficiency for plant growth lamps while maintaining the effectiveness of plant growth within the aquaponic setup. Six LDR sensors, evenly distributed across the aquaponics frame, independently or collectively measure ambient light intensity in the system environment. The collected data is processed using a selection algorithm to determine whether artificial plant growth lamps need to be activated. Energy efficiency is achieved by avoiding continuous activation of the lamps during the plant photosynthesis period, only activating them when the ambient light intensity falls below the permissible threshold.

For further development, incorporating IoT and Data Acquisition systems is recommended to enable remote monitoring and control. Additionally, implementing robust control methods, such as fuzzy control, would further enhance decision-making accuracy, thereby optimizing system performance.

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