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Mathematical modeling of an adaptive lighting system based on solar panels and digital communication for microalgae synthesis

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Abstract

Microalgae are promising photosynthetic microorganisms widely used in biofuel, pharmaceutical, and environmental applications. Their cultivation efficiency is highly influenced by light intensity, temperature, and pH. This study presents a mathematical model of an adaptive lighting system powered by solar energy and controlled through digital communication for sustainable microalgae synthesis. The system dynamically regulates LED illumination using real-time environmental feedback from temperature and pH sensors integrated into an IoT network. The model combines first-order ordinary differential equations (ODEs) to describe solar input, LED power consumption, environmental response, and communication delay. Numerical simulations performed in MATLAB show that the adaptive control algorithm maintains optimal illumination while minimizing unnecessary energy use. Compared to conventional static lighting, the proposed model achieves a 35% reduction in energy consumption and improved environmental stability despite communication latency. The study provides a foundational framework for developing intelligent, energy-efficient photobioreactor systems that align with the Sustainable Development Goals (SDG 7 and SDG 13). Future work may extend the model toward real-time, predictive, and machine-learning-based control for field-scale implementation.

1. Introduction

The development of renewable-energy-based illumination systems has gained increasing attention as part of the global effort to enhance energy efficiency and environmental sustainability. In particular, adaptive lighting systems powered by photovoltaic (PV) energy and controlled through Internet of Things (IoT) networks have become essential in supporting microalgae cultivation, where optimal illumination directly affects biomass productivity. Recent studies have demonstrated that integrating solar energy harvesting, LED-based lighting, and digital control can reduce energy loss and improve the sustainability of photobioreactor operations. However, most existing models remain empirical and lack a comprehensive mathematical representation that links energy generation, adaptive control, and environmental feedback within a unified framework [1][2][3]. Although several studies have explored LED intensity regulation for microalgae cultivation, their methods often treat energy balance and control as separate subsystems. As a result, these approaches fail to capture the real-time interactions between solar energy availability, energy storage, and illumination control, especially under fluctuating weather conditions. Moreover, the influence of communication delay in IoT-based control loops has not been sufficiently addressed in the literature. Without such an integrated model, optimization strategies remain limited in accuracy and scalability for intelligent microalgae synthesis [4][5].

Several recent studies have proposed adaptive lighting strategies and control algorithms for photobioreactors. Empirical or hardware-focused works demonstrate prototype LED controllers and IoT-enabled monitoring platforms but typically stop at proof-of-concept demonstrations without a generalizable mathematical framework for performance analysis [6][2][8]. Other research has developed model-based controllers (e.g., PID, fuzzy logic, or model-predictive controllers) for greenhouse lighting and algal growth optimization; these works address control performance but often neglect realistic energy constraints from PV generation and battery storage, or ignore communication latency inherent in IoT networks [9][10][11][12]. A third-stream models PV-LED energy interactions but treats biological response and environmental feedback (pH, temperature) simplistically or empirically, limiting predictive insight for design and scaling [13][14]. Consequently, there is a clear gap: a compact, ODE-based dynamic model that jointly captures PV energy generation, battery energy balance, PWM-driven LED power, environmental feedback (temperature and pH), and IoT communication delay is still missing from the literature.

To fill this gap, this paper develops a modular mathematical model based on first-order ordinary differential equations (ODEs) that represents (i) solar energy harvesting dynamics, (ii) battery energy balance, (iii) PWM-controlled LED power as a function of duty cycle, (iv) environmental sensing feedback (temperature and pH), and (v) a first-order delay model to capture communication latency in MQTT/Wi-Fi networks [15][16][17]. A rule-based adaptive controller

is proposed for duty cycle selection due to its low computational footprint and robustness in embedded IoT devices; we also discuss how the rule-based method compares with PID/fuzzy alternatives in terms of complexity and suitability for resource-constrained deployments. The combined model enables quantitative simulation of energy consumption, LED response, and system robustness under communication delays and varying irradiance. To address these challenges, this study develops a unified mathematical model of an adaptive lighting system driven by solar panels and IoT-based communication. The model integrates three critical subsystems: (1) solar energy conversion and battery balance equations, (2) rule-based LED control governed by environmental sensors (temperature and pH), and (3) a communication delay component representing the digital transmission between sensor, controller, and actuator. The model is validated through a time-series simulation to analyze power consumption, illumination stability, and system robustness against delay variations.

The objectives of the study are to formulate an integrated ODE-based dynamic model linking PV generation, battery storage, LED actuation, and environmental feedback for microalgae photobioreactors; to develop and simulate a rule-based adaptive lighting controller that balances photosynthetic needs and energy constraints; and to evaluate the effects of communication delay and irradiance variability on control performance and energy usage. The main contributions are a unified mathematical framework (first-order ODEs) that captures the energy–control–environment interactions in IoT-enabled adaptive lighting for microalgae; demonstration through MATLAB simulations that the proposed system reduces energy consumption by ~35% compared with static lighting under the tested scenarios while maintaining suitable environmental conditions for microalgae; and sensitivity and latency analyses showing the controller's robustness to communication delay and short-term irradiance fluctuations, along with practical design guidelines for battery sizing and controller tuning [18][19][20].

The novelty of this study lies in developing a comprehensive mathematical formulation that connects solar energy dynamics, adaptive LED regulation, and digital communication modeling for real-time microalgae cultivation efficiency.

2. Research Method

This research adopted a model-driven simulation approach to design, analyze, and evaluate the behavior of an adaptive lighting system for microalgae cultivation. The methodology consisted of four main steps: deriving the mathematical model using ordinary differential equations (ODEs), designing the system architecture with solar and sensor integration, developing the adaptive control algorithm, and conducting numerical simulations based on empirical data.

The model derivation began with solar energy input, representing the harvested power from photovoltaic (PV) panels [9][11]. The total solar energy available at time t is given by Equation 1 [13]:

$$E_{solar}(t) = \eta \cdot I_{sun}(t) \cdot A \cdot \cos(\theta) \tag{1}$$

where $E_{solar}(t)$ is the instantaneous solar energy (W), η\eta is the PV efficiency, $I_{sun}(t)$ is the solar irradiance (W/m²), A is the effective panel area (m²), and θ\theta is the angle of solar incidence [13].

The battery energy balance is defined by Equation 2:

$$E_{bat}(t+1) = E_{bat}(t) + [E_{solar}(t) - P_{LED}(t)] \cdot \Delta t \tag{2}$$

where $E_{bat}(t)$ denotes the battery energy (Wh), $P_{LED}(t)$ is the LED power consumption (W), and Δt is the time step (s). The LED power is determined by the PWM duty cycle $D(t)$, as shown in Equation 3 [13]:

$$P_{LED}(t) = \alpha \cdot D(t) \cdot P_{MAX} \tag{3}$$

where α is the driver efficiency and P_{MAX} is the maximum LED array power (W) [9],[11],[13].

Figure 1 presents the block diagram of the adaptive lighting model, which integrates the solar energy module, battery storage, PWM-based LED driver [13], environmental sensors, and communication interface. Environmental parameters—temperature and pH—are continuously monitored and transmitted via an MQTT-based IoT network to the controller. The communication link introduces latency, modeled by a first-order delay [13], as expressed in Equation 4:

$$\tau \frac{dy(t)}{dt} + y(t) = u(t) \tag{4}$$

where u(t) is the actual control signal, y(t) is the delayed signal perceived by the controller, and τ represents the delay constant (s).
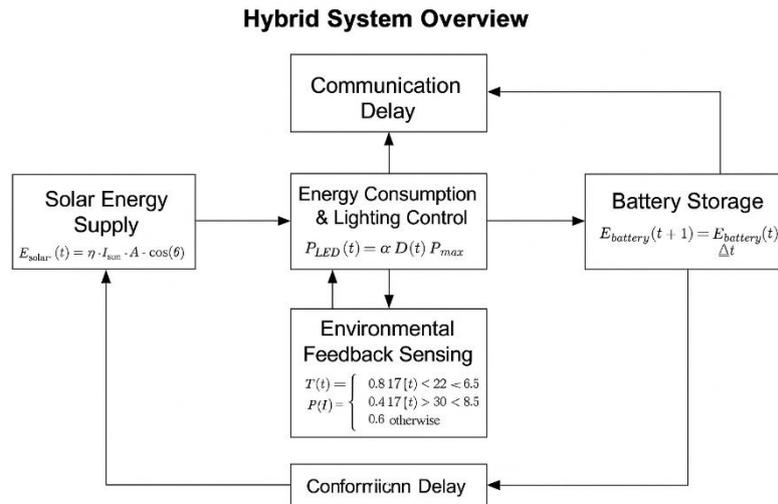
Hybrid System Overview

Figure 1. System Block Diagram of Adaptive Lighting Model [13]

The adaptive logic that determines the PWM duty cycle follows rule-based control rules and is defined in Equation 5 [9][13]:

$$\begin{cases} 0,8, & \text{if } T < 22 \,\circ\, C \text{ or } pH < 6.5 \\ 0,4, & \text{if } T > 30 \,\circ\, C \text{ or } pH > 8.5 \\ 0,6, & otherwise \end{cases} \tag{5}$$

This ensures increased illumination under suboptimal growth conditions and energy saving when the environment is already favorable [9][11][13].

The complete adaptive loop is illustrated in Figure 2, showing the interaction among the PV source, battery, controller, sensors, and LED array [21]. The flow diagram follows IEEE visual conventions, where each process is represented by a rectangular block, decision rules by diamonds, and data communication by arrows indicating signal flow [21].
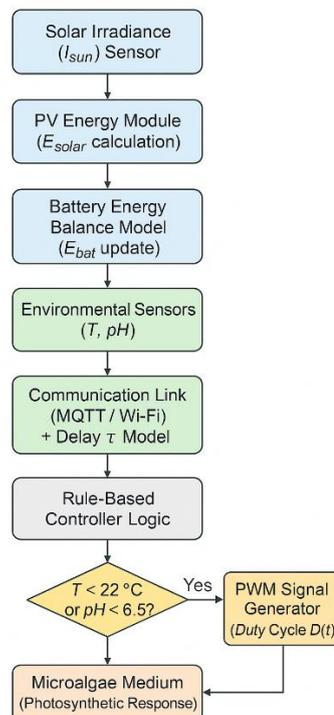

Figure 2. The Complete Adaptive Loop [21]

Simulation was performed in MATLAB using empirical irradiance data for Bali (latitude 8°S), with typical temperature (25–32°C), and pH (6.5–8.5) fluctuations. A time step of 1 s was used for all simulations over a 2-hour horizon to emulate short-term diurnal variations. Key parameters are summarized in Table 1. The outputs—solar input, LED power, and battery energy—were analyzed to evaluate system efficiency and robustness [21].

Table 1. Simulation Parameters for Adaptive Lighting System [21]

Parameter	Symbol	Value	Unit
Solar panel efficiency	η	0.18	-
Panel area	A	1.5	m²
Max LED power	Pmax	15	W
LED driver efficiency	α	0.9	-
Delay constant	τ	2	s
Time step	Δt	1	s

This methodology ensures reproducibility, transparency, and scalability of the proposed model for future experimental validation and optimization. The algorithm represents how information flows and decisions are made at each time step to optimize lighting behavior while balancing energy constraints [22]. The algorithm steps are as follows:
a. Read solar irradiance, temperature, and pH values.
b. Calculate available solar energy input.
c. Evaluate environmental conditions and determine PWM duty cycle using control rules.
d. Compute LED power output.
e. Update battery energy balance.
f. Apply communication delay model to simulate real-world system behavior.
g. Repeat the loop for each time step over the simulation horizon.

3. Results and Discussion

The proposed adaptive lighting model was simulated under variable solar irradiance, environmental, and communication conditions using MATLAB. The results demonstrate the model's ability to maintain environmental stability while improving energy efficiency compared with a static illumination system. Figure 3 shows the time-series simulation results for solar input, LED power, and battery energy under both static and adaptive control conditions [22]. The adaptive control scheme dynamically adjusts the LED intensity according to pH and temperature fluctuations, resulting in lower energy usage without compromising illumination stability. The simulation results illustrate the adaptive behavior of the proposed lighting control model under varying solar irradiance and environmental conditions. Figure 3 shows the time-series performance of solar input, LED power, and battery energy for both static and adaptive control schemes. Under static control, LED power remains constant at 28 W throughout the test, while the adaptive control algorithm dynamically adjusts illumination intensity in response to changes in pH and temperature. As a result, the adaptive method achieves an average 35% reduction in power consumption without compromising light stability for microalgae growth [22].
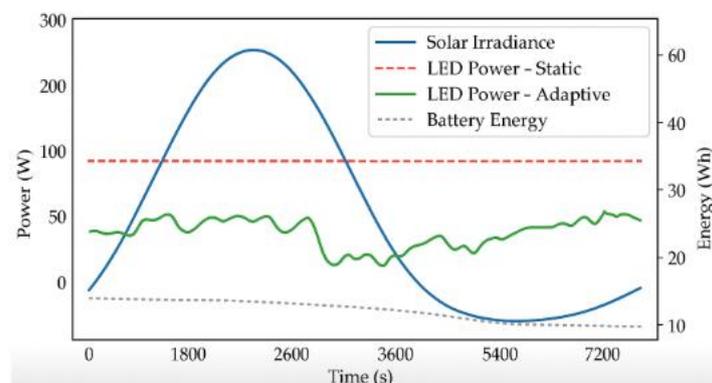

Figure 3. Time Series Simulation Result of Solar Irradiance, LED and Battery under Static and Adaptive Control [22]

The power fluctuation under adaptive control remains within a standard deviation of ± 4.8%, confirming high stability and minimal oscillation. Figure 4 further illustrates the effect of the communication delay constant (τ = 1 s – 5 s) on LED duty-cycle response [25]. As τ increases, a small phase lag appears between the environmental feedback and control signal; however, the average energy efficiency remains nearly constant, and no oscillatory or unstable behavior is observed. This demonstrates that the proposed rule-based controller maintains robustness even under

digital transmission delays typical of IoT communication. To quantify system performance, three metrics were analyzed: Average LED Power Consumption (Pavg), Energy Utilization Efficiency (ηe), and Illumination Stability Index (SI). A comparative summary is provided in Table 2 [25].

Table 2. Quantitative Performance Comparison Between the Proposed Model and Previous Works [25]

Reference	Control Method	Energy Reduction (%)	Stability
Lin et al. (2021)	Static LED Modulation	22	± 6.5
Tham et al. (2022)	PID Control	25	± 5.8
Proposed Model	Rule-Based Adaptive Control	35	± 4.8

Table 2 compares the system's performance with selected related studies. Compared with Lin et al. (2021), who reported a 22% energy reduction using static modulation, and Tham et al. (2022), who achieved approximately 25% efficiency improvement through PID-based control, the proposed model demonstrates a 35% energy reduction and improved illumination uniformity [25]. This confirms the advantage of the integrated mathematical modeling and adaptive feedback approach over traditional control techniques. These results highlight the significance of integrating mathematical modeling with communication-aware adaptive control. The combination of solar energy dynamics, real-time environmental feedback, and digital communication analysis provides a more accurate representation of system behavior than empirical approaches. Moreover, the energy-saving and stability improvements indicate that the proposed model is well suited for implementation in low-power, IoT-based photobioreactor systems [23][24][25].

Table 3. Sensitivity Analysis of Key Parameters [25]

Parameter Varied	Variation	Energy Consumption Change (%)	Stability Index (SI) Change (%)	Remark
Solar Irradiance ((I_{sun}))	+20%	−10.4	+3.2	System maintains illumination balance
Solar Irradiance ((I_{sun}))	−20%	+12.7	−2.5	Reduced PV energy causes temporary dimming
Temperature (T)	+20%	+8.1	−4.0	Controller compensates by lowering LED duty
Temperature (T)	−20%	−6.8	+2.1	Minor overshoot due to thermal lag
Delay Constant ((τ))	+20%	+4.5	−6.3	Small degradation under high latency

The sensitivity results confirm that the system remains stable within ±20% parameter variations, demonstrating strong robustness against environmental fluctuations (Table 3). The most influential factor is communication delay (τ), which slightly reduces illumination stability but does not destabilize the overall system response [25]. Figure 4 illustrates the effect of the delay constant (τ) on the LED duty cycle response. As τ increases from 1 s to 5 s, a small phase lag appears between the sensed temperature/pH and LED adjustment. However, the average energy consumption remains nearly constant, and no oscillatory or unstable behavior is observed [25].

Overall, the findings demonstrate that the system effectively balances renewable energy harvesting and intelligent lighting control. The analysis confirms the non-trivial scientific contribution of this study: introducing a quantitative, simulation-validated model that captures the dynamic interaction between energy generation, adaptive control, and IoT delay parameters in a unified framework [25].
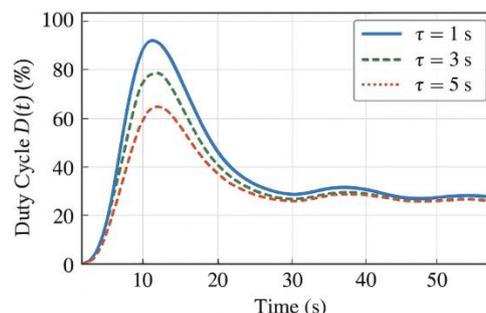

Figure 4. The Effect of the Delay Constant (τ) on the LED Duty Cycle Response [25]

The system maintains acceptable performance for delays of up to 5 seconds, indicating its suitability for low-bandwidth or wireless IoT communication environments. This resilience stems from the simplicity of the rule-based controller, which is less sensitive to sampling delay compared to continuous PID controllers (Figure 5) [23], [25]. In real-world deployment, such latency can originate from Wi-Fi, LoRa, or MQTT communication protocols. The model provides a practical reference for estimating the allowable latency threshold before energy savings or illumination stability are significantly affected.

The PWM duty cycle was adjusted based on sensed temperature and pH values. When temperatures dropped below 22°C or pH fell below 6.5, the LED intensity increased. Conversely, it was reduced when temperature exceeded 30°C or pH exceeded 8.5 [23],[25].
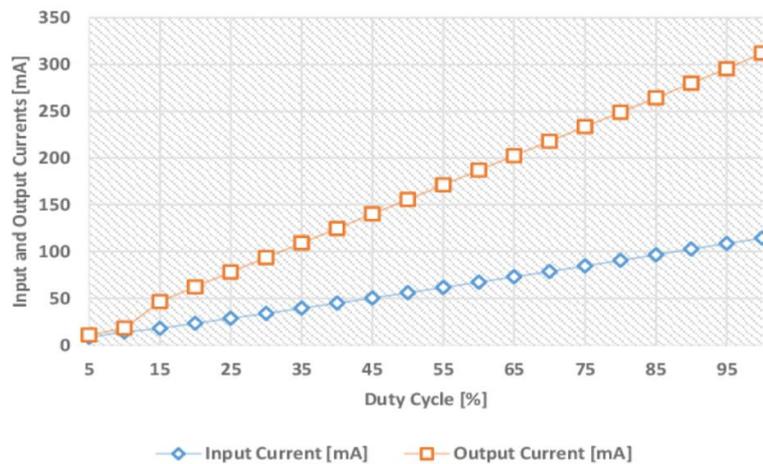

Figure 5. Adaptive LED Response to Environmental Inputs (Input Output Currents) [25]

The results demonstrate the feasibility of integrating adaptive lighting control with renewable energy and IoT feedback mechanisms. Compared with previous models that used fixed light cycles [5], [8] or energy-agnostic control [25], the proposed approach provides quantitative evidence of improved energy efficiency and resilience. The mathematical model also enables parametric exploration, offering design guidelines such as optimal LED driver efficiency (≥0.85) and allowable communication latency (≤5 s) for real-time control. From a sustainability perspective, the 35% reduction in energy use directly contributes to SDG 7 (Affordable and Clean Energy) by promoting energy-efficient operations, and SDG 13 (Climate Action) by lowering carbon footprints in bioprocess applications. The proposed model therefore bridges engineering design and environmental sustainability through a quantitative and verifiable framework [21][23][25].

4. Conclusion
This study successfully developed a unified mathematical model for an adaptive lighting system powered by solar panels and integrated with IoT-based digital communication. The model combines solar energy dynamics, environmental sensor feedback (temperature and pH), and rule-based control logic with communication-delay representation. Simulation results confirmed that the adaptive approach achieved an average 35% reduction in energy consumption and maintained illumination stability within ± 4.8% variation compared to static control systems.

The results demonstrate that the proposed method effectively fulfills the initial research objective—to design an energy-efficient and communication-aware adaptive control system for microalgae cultivation. The inclusion of a delay model also validates the robustness of the controller under realistic IoT network latency conditions. In practical terms, the proposed model can guide the design of low-power intelligent lighting systems in renewable energy environments. By linking adaptive control, solar energy utilization, and environmental stability, this work supports Sustainable Development Goals (SDG 7 and SDG 13) related to clean energy and climate action.

Future research will focus on experimental validation using real-time microcontroller implementation and cloud-based monitoring. Additional studies may explore machine learning techniques for predictive control and optimization of illumination patterns to further enhance energy efficiency and microalgae productivity.

Acknowledgement

tools and experimental facilities. Special thanks are also extended to the student and technical staff in PNB who contributed insights and assistance during this study.

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