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Development of a Microcontroller-Based Dynamic Lighting System with Automated Dimming and Color Adjustment

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***Abstract*—Office buildings in dense urban areas often experience limited natural daylight penetration, while conventional artificial lighting systems typically operate at constant intensity and color. This study proposes a microcontroller-based dynamic lighting control system that adjusts light intensity and color to improve energy efficiency during working hours. The system incorporates dynamic dimming and color modulation, with light intensity monitored and visualized through a web-based interface. Laboratory-scale experiments were conducted to evaluate electrical energy consumption under different lighting control scenarios. The results show that, under the evaluated operating conditions, dynamic dimming achieves energy savings of approximately 15%, while dynamic color modulation provides comparable reductions of about 14–15%. The combined application of dynamic dimming and color control, implemented with a reference dimming level of 50% lamp intensity, yields the highest energy-saving performance, with reductions of up to approximately 29%.**

***Index Terms*—Dynamics Lighting, Light Intensity Level, Programmable Dimmer, Power Consumption.**

I. INTRODUCTION

In general, most office buildings designed in dense urban areas tend to have minimal sunlight, so they require artificial lighting with a fixed illuminance level, and the lighting color remains constant throughout the day. However, based on studies, it is known that sunlight can have a strong effect on the response of the human body; therefore, sunlight, which is most of the time exposed from the window, becomes a key cue of the human biological clock, where the body will naturally feel fresh in the morning and feel tired in the afternoon [1-3].

The color of the light emitted by the sun constantly changes throughout the day. There are dynamics of variations or shifts ranging from blue, white, yellow, orange, and even red light. White light at noon can trigger increased human productivity. This is because the signals sent by the eyes to the brain can trigger the release of the hormone serotonin, a natural antidepressant in the body that can increase alertness, productivity, and concentration in workers. In the evening, the orange hue of the setting sun may stimulate the secretion of the hormone melatonin within the body [4].

An effective approach to recalibrating the biological clock of workers involves the implementation of an adaptive lighting system. This system should be meticulously designed to align with the natural cycles of the human body, taking into account the position, duration, and color of sunlight at various times throughout the day. By mimicking the natural light and dark cycles of the sun, such a system can enhance occupant performance, fostering focus, creativity, and productivity during working hours. Furthermore, appropriate light signals can significantly improve sleep quality and mitigate fatigue, thereby enhancing future productivity [5]. Research conducted by various scholars has indicated that exposure to elevated light levels on the cornea during daylight hours can facilitate a better alignment of circadian rhythms with daily activities [6-7]. Additionally, dynamic lighting systems have shown promise in altering the resting patterns of elderly individuals in nursing homes [8], while variations in light color temperature have been found to influence alertness among office workers [9].

The Indonesian National Standard (SNI) stipulates that the minimum illumination level in workrooms should be 350 lux. This standard has also been adopted in several studies related to the assessment for the initial preparation of building certification and retrofitting practices in Indonesia [10-11].

The environment examined in this study remains static, as it relies solely on artificial lighting. This paper aims to assess the implications of this setup for the development of an adaptive lighting system, which allows adjustments in both color and light intensity. This technological approach seeks to optimize the synergy between artificial lighting and natural sunlight.

Furthermore, this study compares the instantaneous power demand of conventional static lighting systems and adaptive lighting schemes implemented at a prototyping scale under controlled operating conditions.

Commercially available lighting solutions in the local context typically support manual color and brightness adjustment via remote control or preset scenes, but lack adaptive control based on time-of-day scheduling or real-time environmental sensing. The proposed system implements an adaptive lighting strategy in which both brightness and color are automatically adjusted using temporal conditions and sensor inputs. Accordingly, this study focuses on demonstrating the feasibility of adaptive dynamic lighting at a prototyping scale rather than conducting direct performance comparisons with commercial products.

II. Dynamic Lighting & Dimming Systems

A. Dynamic Lighting

Dynamic lighting refers to a lighting system designed to align with the natural cycles of day and night, thereby responding to the physiological needs of individuals. Such systems have been shown to enhance physical well-being and promote alertness and rejuvenation, effects that are closely associated with the regulation of the human circadian rhythm. The operation of dynamic lighting involves the automatic adjustment of both light color temperature and intensity according to the time of day. Proper implementation of dynamic lighting has been reported to support improved visual comfort and can positively influence workplace interaction, including teamwork, communication, and overall employee cohesion [12-13].

B. Diming Systems

In this study, lamp brightness is regulated by a microcontroller using pulse width modulation (PWM). The resulting light intensity is governed by the duty cycle (D), which is proportional to the assigned brightness level relative to its maximum value, as expressed in Equation (1):

$$D \propto \frac{B}{B_{\max}} \quad (1)$$

where B represents the brightness level and B_{max} denotes the maximum brightness value supported by the system. Accordingly, a higher duty cycle corresponds to increased illumination, while a lower duty cycle produces reduced light output. For instance, operating the lamp at 25% of its maximum brightness implies that the illumination output is reduced by 75% relative to full intensity. Conventional dimming mechanisms often rely on manual adjustment, which limits their adaptability to changing environmental conditions.

III. Design Methods & Experiment

A. System Architecture and Design

The software utilized in this phase is the Arduino platform, which interfaces with the NodeMCU ESP8266 microcontroller. The NodeMCU ESP8266 is widely adopted in digital sensing, monitoring, and data acquisition systems. A visual representation of the system workflow is illustrated in Figure 1.

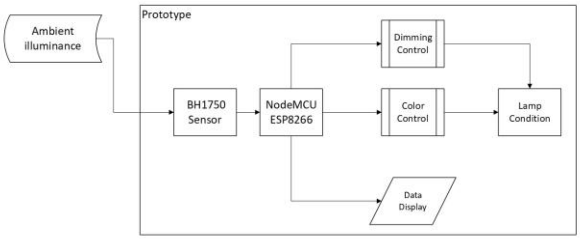


Fig. 1. Block Diagram of Dynamic Lighting System Design

Ambient illuminance was detected using a BH1750 ambient light sensor installed at desk height within the workspace. The sensor detects combined light contributions from both artificial lighting and incoming natural daylight. Prior to system operation, the sensor output was adjusted using reference readings obtained from a lux meter (GM1030) to ensure reasonable consistency of detected illuminance levels. The microcontroller processes the incoming data to adjust the lighting output parameters, including lamp dimming level and color. In addition, the processed data are transmitted to a web-based interface, enabling real-time monitoring of light intensity by users.

For the dimming operation of the dynamic lighting system, six discrete operating conditions are defined, namely lights off and illumination levels of 10%, 25%, 50%, 75%, and 100%. These conditions are illustrated in Figure 2.

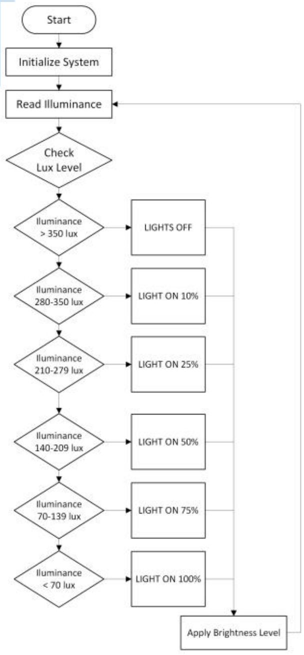


Fig. 2. Light Dimming Schematic Flowchart

Unlike the dimming function, the color adjustment mechanism operates based on the time of day according to the following conditions:

- During periods after sunrise and before sunset, the lighting system emits a warm white color with an orange hue.
- At midday, the illumination shifts to bright white, resembling direct sunlight.
- A transitional color is applied prior to the change from warm white to bright white and vice versa.

This transitional phase lasts for one hour to allow occupants to adapt gradually to the change in light color, as illustrated in Figure 3.

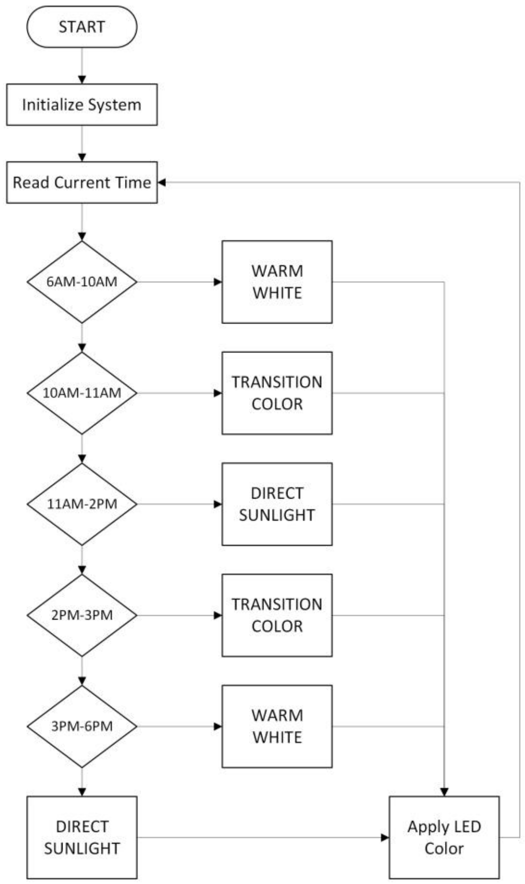


Fig. 3. Light Coloring Schematic Flowchart

The system employs an RGB LED strip actuator, where the emitted color is generated through controlled modulation of the red (R), green (G), and blue (B) channels. The resulting output color is produced as a weighted combination of the individual R, G, and B intensities, enabling precise chromatic reproduction in accordance with the desired lighting profile.

The coloring mechanism is implemented using a time-based discrete control strategy. Instead of continuous color weighting, predefined RGB color profiles are assigned according to specific time intervals throughout the day. Each color profile represents a specific lighting condition, including warm white, transitional lighting, and bright white, selected to emulate natural daylight variations.

The output color of the lighting system can be expressed as a piecewise function of time:

$$C_{output}(t) = C_k, \quad \text{for } t \in T_k \qquad (2)$$

where $C_k = (R_k, G_k, B_k)$ represents a predefined RGB color profile and T_k denotes the corresponding time interval. The index k identifies the active lighting condition, including warm white, transitional, bright white, or nighttime lighting.

During periods following sunrise and preceding sunset, warm white profiles are selected. Around midday, bright white profiles are applied to resemble direct sunlight. Transitional profiles are introduced before and after the midday period to allow gradual visual adaptation. During nighttime hours, a predefined profile is applied to maintain adequate illumination.

This discrete, time-based approach enables adaptive color behavior while avoiding continuous RGB weighting or interpolation. As a result, the coloring mechanism remains computationally efficient and suitable for prototyping-scale implementation.

An overview of the system design developed in this project is presented in Figure 4.

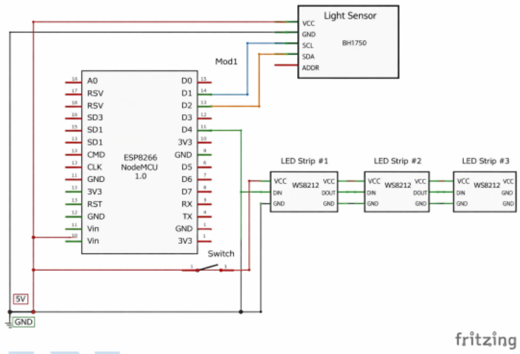


Fig. 4. Schematic Diagram of System Design

In this study, the maximum and minimum illuminance of the LED strips were not measured as isolated source characteristics. Instead, the evaluation focused on the total ambient illuminance detected at the sensor location, which represents the combined effect of the LED lighting system and environmental lighting conditions within the workspace.

B. Field Measurement Setup

The experimental setup was conducted in a selected indoor workspace representing a typical workroom environment. The workspace belongs to an institutional quality assurance department consisting of six employees, all of whom participated as respondents in a preliminary occupant survey.

To investigate differences in system performance, the workspace was subjected to controlled alterations in lighting conditions, including variations in lamp brightness and color, in accordance with the prescribed methodology.

Prior to prototype testing, a field measurement phase was conducted within the study area to collect baseline data on existing lighting conditions. During this phase, a lux meter (GM1030) was used to quantify ambient illuminance levels within the environment. This assessment aimed to determine whether the prevailing illumination complied with established lighting standards. The lux meter operates by detecting incident light through its sensor and displaying the corresponding illuminance values, which increase as the sensor is positioned closer to or directly aligned with the light source.

The collected measurement data were subsequently processed using analysis software to generate visual representations of illuminance distribution and color characteristics across the workspace. Measurements were conducted under multiple scenarios, including conditions with artificial lighting enabled and those influenced by the presence of natural daylight.

The experimental evaluation was conducted over standard working hours during one workweek. This duration was intentionally selected to reflect the operational scope of an initial prototyping phase. The primary objective of the study was to assess the functional performance, responsiveness, and feasibility of the proposed adaptive lighting system under typical daily usage conditions rather than to evaluate long-term physiological effects or seasonal variations.

As a result, aspects such as sustained user alertness improvement, long-term system stability, seasonal daylight variability, and sensor drift over extended periods were not within the scope of the present study. These factors are identified as important directions for future work, which will involve extended deployment periods and longitudinal evaluation under varying environmental conditions.

In addition to field measurements, an initial occupant survey was conducted to obtain a comprehensive understanding of lighting usage patterns and occupant conditions within the workspace. The survey was structured into several targeted question groups, as illustrated in Figure 5.

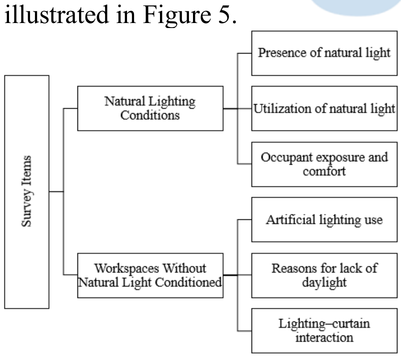


Fig. 5. Survey Instrument Structure

The preliminary occupant survey involved six employees working in the selected workspace. The respondents represented full-time staff members who regularly occupied the room during standard working hours, ensuring consistent exposure to the existing lighting conditions. The demographic composition included adult office workers with routine visual task demands, which is considered representative of typical workroom occupants.

The sample size was determined by the total number of occupants assigned to the workspace. Given that the primary objective of this study focuses on the technical performance evaluation of a prototyping-scale adaptive lighting system rather than statistical generalization of human factors, the number of respondents was deemed sufficient to capture initial occupant perceptions and usage patterns relevant to the lighting environment.

IV. Results

A. *Preliminary survey of occupants*

The survey results presented in Figure 6 indicate that the room receives natural daylight. However, the daylight distribution is non-uniform across the workspace. Several work areas experience limited or no direct daylight exposure due to their greater distance from the windows and the presence of partially closed curtains, which restrict sunlight penetration into these zones.

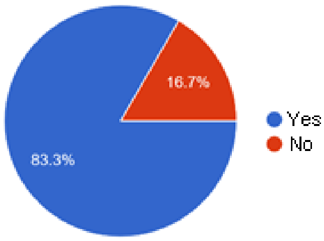


Fig. 6. Workplace Conditions Survey Results

All respondents (100%) reported using window curtains to regulate the amount of incoming natural light. Nevertheless, Figure 7 shows that not all occupants actively utilize available daylight by switching off the room's artificial lighting during working hours.

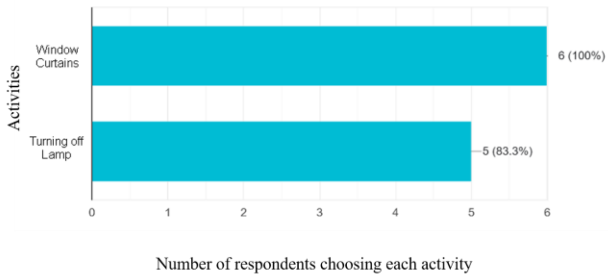


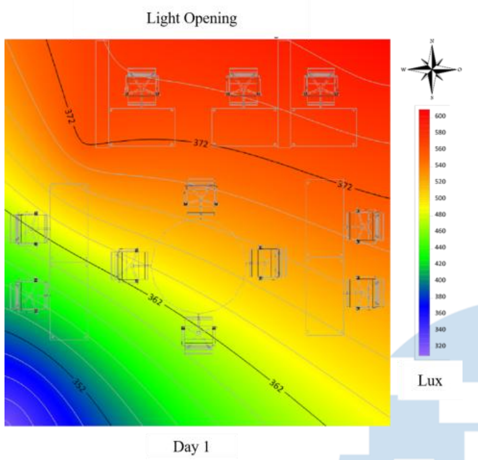
Fig. 7. How respondens to utilize natural light in a room

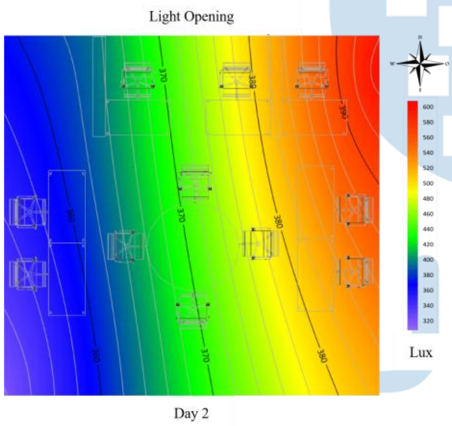
Regarding occupancy duration, 67% of respondents reported spending approximately 8 hours per day in the workspace. When asked about drowsiness during working hours, 100% of respondents indicated experiencing drowsiness "sometimes."

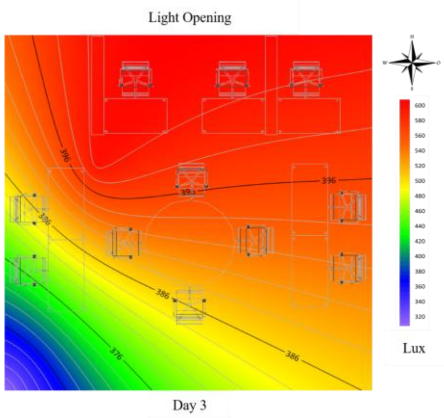
The reported time window for drowsiness occurrence ranged from 10:00 a.m. to 3:00 p.m. This temporal distribution corresponds to a commonly observed reduction in alertness during the early afternoon period, particularly between 2:00 p.m. and 3:00 p.m., which is widely reported in studies on circadian-related variations in human alertness.

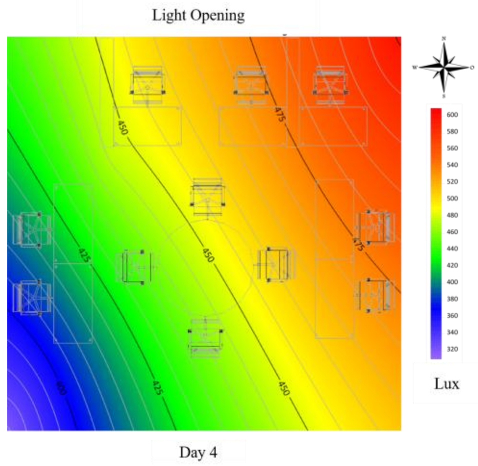
B. Field Measurement Results

An analysis of illumination levels in the object room was conducted during weekdays within standard working hours (08:00–17:00), considering varying weather conditions.









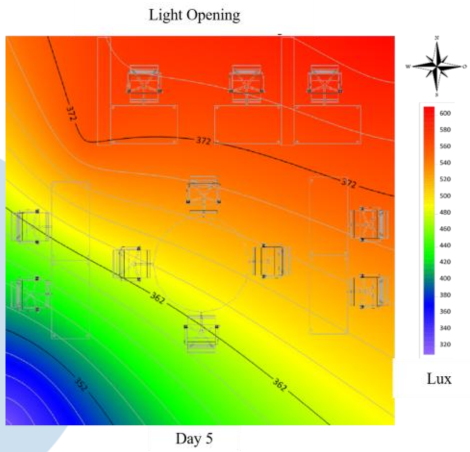


Fig. 8. Contour Map of Light Distribution Over 5 Working Days

Measurement data collected during the period of 11:00–13:00, which was used as the reference interval for minimum illumination levels, yielded illumination values ranging from 351 to 646.33 lux.

As illustrated in Figure 9, measurement points 1, 2, and 3, located adjacent to the window openings, recorded the highest average illumination levels (499.6–646.33 lux). Measurement points 4, 5, and 6, positioned in the central area of the room, exhibited moderate average illumination levels ranging from 439.33 to 540.2 lux. In contrast, measurement points 7, 8, and 9, located in the rear area near the door and furthest from the windows, consistently showed the lowest illumination levels, with average values between 351 and 403.13 lux.

Despite this spatial variation, all measured illumination levels satisfy the minimum lighting requirement of 350 lux specified in the Indonesian National Standard SNI 6197:2020 for Energy Conservation in Lighting Systems.

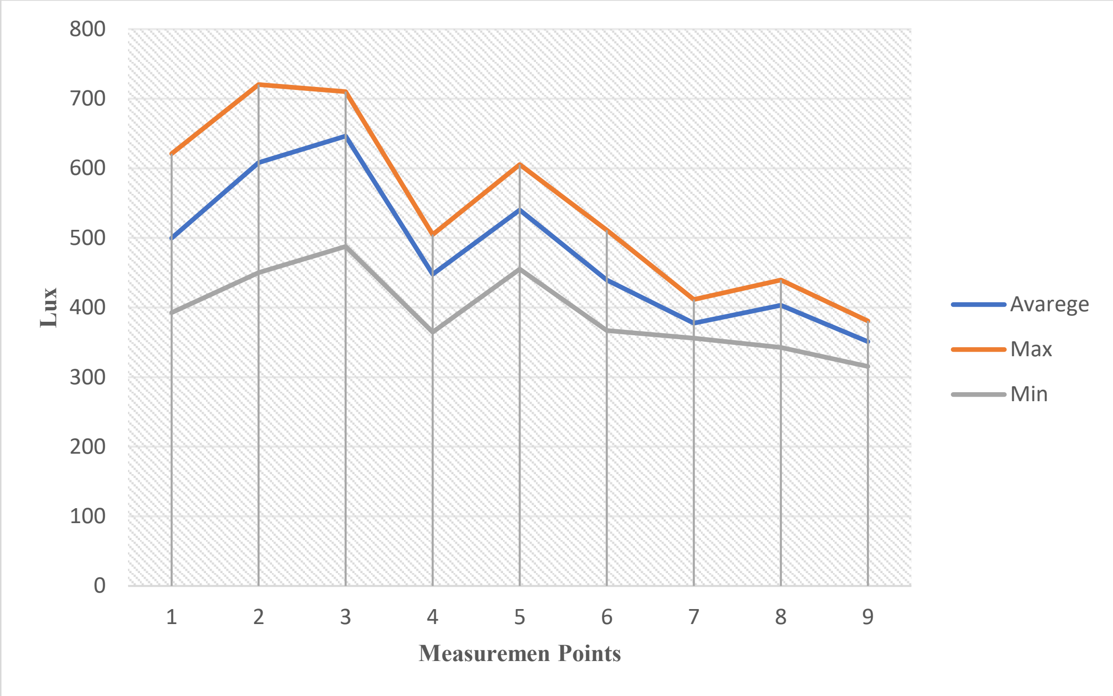


Fig. 9. Measured illumination levels at nine measurement points in the object room.

C. Electrical Energy Consumption Experiment

This subsection presents a comparative experimental evaluation of the electrical energy consumption of the lighting system during standard working hours, from 08:00 to 17:00. The instantaneous electrical power (W) was measured using a power meter, and the total electrical energy consumption (Wh) was calculated by integrating the measured power over the operating period. The experiment aims to quantify potential energy savings achieved through the implementation of dynamic lighting control strategies, including dynamic dimming, dynamic color adjustment, and their combined operation.

Four energy-saving scenarios were defined for comparison:

- The first scenario compares a static lighting condition, in which the lamp operates at a constant output, with a dynamic dimming condition, where the lamp output is adjusted based on predefined control parameters.
- The second scenario compares static lighting with a dynamic color condition, in which the lamp color temperature is varied without dimming.
- The third scenario evaluates static lighting against a system that simultaneously applies dynamic dimming and dynamic color control.
- The fourth scenario compares dynamic color operation with the combined dynamic dimming and color control configuration.

For the dynamic dimming scenario, the lamp output was controlled to 50% of its maximum intensity, which was used as the reference dimming level for calculating the corresponding electrical energy consumption.

TABLE I. THE 1ST SCENARIO EXPERIMENT: STATIC LIGHTING VS. DYNAMIC DIMMING

Percentage of Lights on	*Lamp Color*	*Time Range*	*Electric Energy Consumption (Wh)*
100%	Direct Sunlight	08-05 PM	60
Total			60
50%	Direct Sunlight	08-05 PM	51
Total			51
Energy Saving			9
			15%

Table I presents the electrical energy consumption of the lighting system under static and dynamic dimming conditions using the Direct Sunlight color setting throughout the working hours (08:00–17:00). Under the static lighting condition (100% intensity), the total electrical energy consumption was measured at 60 Wh. When dynamic dimming was applied, with the lamp operating at 50% intensity, the total electrical energy consumption decreased to 51 Wh.

This reduction corresponds to an absolute energy saving of 9 Wh, equivalent to a relative reduction of 15% compared to the static lighting condition. These results indicate that implementing dynamic dimming alone, without altering the lighting color, can yield a measurable reduction in electrical energy consumption during working hours. The observed savings demonstrate the effectiveness of intensity-based control in reducing lighting energy demand while maintaining a consistent lighting color.

TABLE II. THE 2ND SCENARIO EXPERIMENT: STATIC DIRECT SUNLIGHT VS. DYNAMIC COLOR OPERATION

Percentage of Lights on	***Lamp Color***	***Time Range***	***Electric Energy Consumption (Wh)***
100%	Direct Sunlight	08-05 PM	60
Total			60
100%	Warm White	08-10 AM & 03-05 PM	22,4
	Transition	10-11 AM & 02-03 PM	10,8
	Direct Sunlight	11 AM – 02 PM	18
Total			51,2
Light Power Saving			8,8
			14,7%

Table II compares the electrical energy consumption of the lighting system under two static operating conditions during standard working hours (08:00–17:00). In the first condition, the lamp operates at 100% intensity with a constant Direct Sunlight color throughout the working period, resulting in a total electrical energy consumption of 60 Wh.

In the second condition, the lamp also operates at 100% intensity, but with a dynamic color schedule comprising Warm White, Transition, and Direct Sunlight applied over predefined time intervals. Under this dynamic color-only configuration, the total electrical energy consumption is reduced to 51.2 Wh.

The comparison indicates an absolute energy reduction of 8.8 Wh, corresponding to a relative energy saving of approximately 14.7% compared to the static Direct Sunlight condition. This reduction demonstrates that dynamic color modulation, even without the application of dimming control, can contribute to lower electrical energy consumption. The results suggest that variations in lamp color temperature influence power draw and, consequently, total energy use during working hours.

TABLE III. THE 3RD SCENARIO EXPERIMENT: STATIC LIGHTING VS. COMBINED DYNAMIC DIMMING AND COLOR CONTROL

Percentage of Lights on	***Lamp Color***	***Time Range***	***Electric Energy Consumption (Wh)***
100%	Direct Sunlight	08-05 PM	60
Total			60
50%	Warm White	08-10 AM & 03-05 PM	18
	Transition	10-11 AM & 02-03 PM	9,6
	Direct Sunlight	11 AM – 02 PM	15,1
Total			42,7
Light Power Saving			17,3
			28,83%

Table III presents a comparison of electrical energy consumption between a static lighting condition and a combined dynamic dimming and color control strategy during standard working hours (08:00–17:00). Under the static condition, the lamp operates at 100% intensity with a constant Direct Sunlight color throughout the working period, resulting in a total electrical energy consumption of 60 Wh.

In contrast, under the combined dynamic dimming and color control condition, the lamp operates at 50% intensity, with scheduled color variations (Warm White, Transition, and Direct Sunlight) applied across predefined time intervals. Under this configuration, the total electrical energy consumption is reduced to 42.7 Wh.

This represents an absolute energy saving of 17.3 Wh, corresponding to a relative reduction of approximately 28.83% compared to the static Direct Sunlight condition. The results demonstrate that the combined application of intensity-based dimming and dynamic color control yields a substantial reduction in electrical energy consumption.

TABLE IV. THE 4RD SCENARIO EXPERIMENT: DYNAMIC COLOR VS. COMBINED DYNAMIC DIMMING AND COLOR CONTROL

Percentage of Lights on	***Lamp Color***	***Time Range***	***Electric Energy Consumption (Wh)***
100%	Warm White	08-10 AM & 03-05 PM	22,4

Percentage of Lights on	*Lamp Color*	*Time Range*	*Electric Energy Consumption (Wh)*
	Transition	10-11 AM & 02-03 PM	10,8
	Direct Sunlight	11 AM – 02 PM	18
Total			51,2
50%	Warm White	08-10 AM & 03-05 PM	18
	Transition	10-11 AM & 02-03 PM	9,6
	Direct Sunlight	11 AM – 02 PM	15,1
Total			42,7
Light Power Saving			8,5
			16,6%

Table IV summarizes the electrical energy consumption of the lighting system under dynamic color operation and combined dynamic dimming and color control during standard working hours (08:00–17:00). Under the dynamic color condition with full lamp intensity (100%), the total electrical energy consumption was recorded at 51.2 Wh. This value represents the accumulated energy consumption across different color settings, namely Warm White, Transition, and Direct Sunlight, applied over their respective time intervals.

When combined dynamic dimming and color control was implemented, with the lamp operating at 50% intensity, the total electrical energy consumption decreased to 42.7 Wh. This corresponds to an absolute energy reduction of 8.5 Wh, equivalent to a relative energy saving of approximately 17% compared to the dynamic color-only condition.

These results indicate that while dynamic color adjustment contributes to visual and circadian lighting objectives, the addition of intensity-based dimming provides a further reduction in electrical energy consumption. The findings suggest that combining dimming control with color modulation is more effective in reducing overall lighting energy use than applying dynamic color control alone.

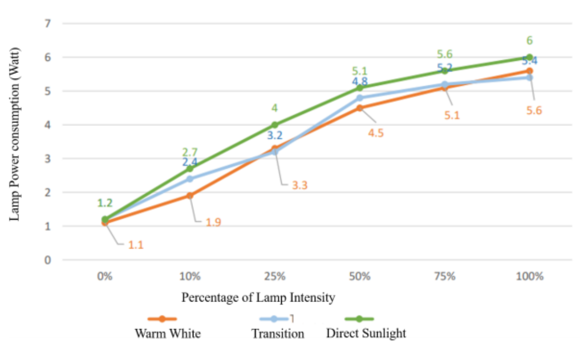


Fig. 10. Lamp Power Consumption Based on Color and Dimming Levels

Figure 10 illustrates the relationship between lamp power consumption and the percentage of lamp intensity for three color settings, namely Warm White, Transition, and Direct Sunlight. The results show that electrical power consumption increases monotonically with increasing lamp intensity for all color modes, indicating a consistent and predictable power–intensity relationship.

At low intensity levels (0–25%), the differences in power consumption among the three color settings are relatively small. At 0% intensity, the measured power ranges from approximately 1.1 W to 1.2 W, suggesting the presence of baseline power consumption associated with the control circuitry. As the intensity increases to 10% and 25%, the Direct Sunlight mode exhibits slightly higher power consumption (2.7 W and 4.0 W, respectively) compared to Transition and Warm White modes.

At medium to high intensity levels (50–100%), the divergence in power consumption among color settings becomes more pronounced. At 50% intensity, the measured power reaches 4.5 W for Warm White, 4.8 W for Transition, and 5.1 W for Direct Sunlight. This trend continues at 75% and 100% intensity, where Direct Sunlight consistently records the highest power consumption, reaching approximately 6.0 W at full intensity, while Warm White exhibits the lowest power consumption at approximately 5.6 W.

V. Conclusion

Survey results show that all respondents in the objected room occupants report experiencing drowsiness between 10:00 and 15:00. This condition is influenced by continuous static artificial lighting and variations in natural daylight, which together contribute to reduced alertness during these hours. Surveys indicated that 100% of occupants occasionally experienced drowsiness between 10 AM–3 PM due to static artificial lighting and dynamic sunlight.

Field observations revealed uneven natural light distribution in the room, despite meeting the recommended illuminance level (351–646.33 lux). Issues included five non-functional lamps and curtains obstructing natural light.

Dynamic dimming alone achieves energy savings of approximately 15%, while dynamic color modulation provides comparable reductions of about 14–15%. The combined application of dynamic dimming and color control yields the highest energy-saving performance, with reductions of up to approximately 29%. These findings indicate that integrating intensity-based dimming with color modulation is more effective than applying either strategy individually for reducing lighting energy consumption during working hours.

Although this work focuses on the development and energy performance evaluation of a dynamic lighting control system, a detailed assessment of the controller's performance characteristics, such as response time, stability, and tracking accuracy, has not yet been conducted. Future work will include a comprehensive evaluation of the control algorithm under varying lighting and occupancy conditions, as well as comparisons with alternative control strategies to further assess system robustness and performance.

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