# Circadian Lighting System (e-Yantra)


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**Abstract**

*Circadian lighting seeks to replicate the natural variations in sunlight to align with human biological rhythms. The sun's position, intensity, and color temperature change throughout the day, influenced by factors such as geographic location, time of year, and atmospheric conditions. Accurately emulating these variations requires a methodical approach to gather and analyze data on sunlight's characteristics. This report outlines the methods employed to achieve an efficient and cost-effective implementation of circadian lighting with a high degree of accuracy. It details the processes for simulating sunlight patterns in an artificial lighting system capable of dynamically adjusting its intensity and color spectrum. Here is a Google NotebookLM generated audio podcast that takes into account our code and entire procedure to make reading this article easier: [1]*



***Keywords*** *— color temperature, short-wavelength ratio*


## I. Introduction

The circadian rhythm, a natural biological process that regulates the sleep-wake cycle and other physiological functions, is closely synchronized with the daily light-dark cycle. However, modern lifestyles, which confine individuals to indoor environments for up to 90% of their time, have disrupted this alignment. Traditional indoor lighting systems often fail to replicate the dynamic spectral and intensity changes of natural sunlight, leading to potential adverse effects on health, mood, and productivity.

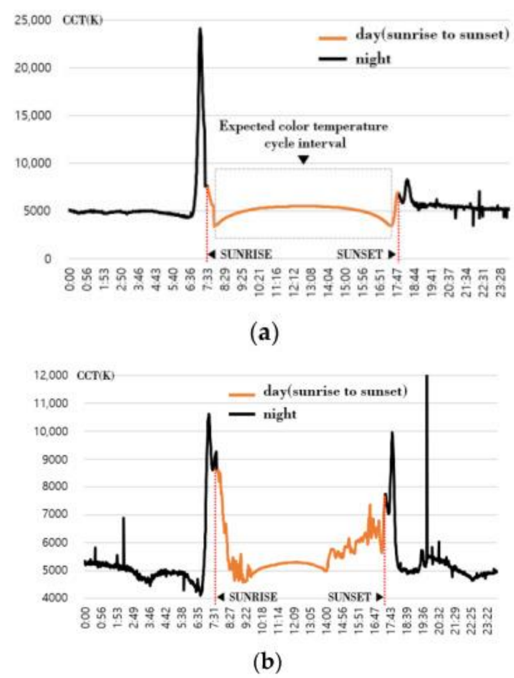
This project explores a novel approach to circadian lighting, focusing on recreating natural sunlight patterns in indoor spaces through a simplified and cost-effective methodology. Unlike current systems that rely on advanced sensors or complex machine learning algorithms, our solution employs a graphical approximation to model and simulate daily light temperature variations. This approach balances biological accuracy with practical considerations, ensuring energy efficiency and reduced system complexity.

The proposed system aims to provide an accessible and effective means of fostering healthier indoor environments by promoting alignment with the human circadian rhythm. This report outlines the conceptual framework, design methodology, and performance evaluation of the system, highlighting its potential to transform indoor lighting standards while addressing the growing need for biologically-appropriate illumination.

## II. Related Work

### A. Data Collection for Circadian Lighting

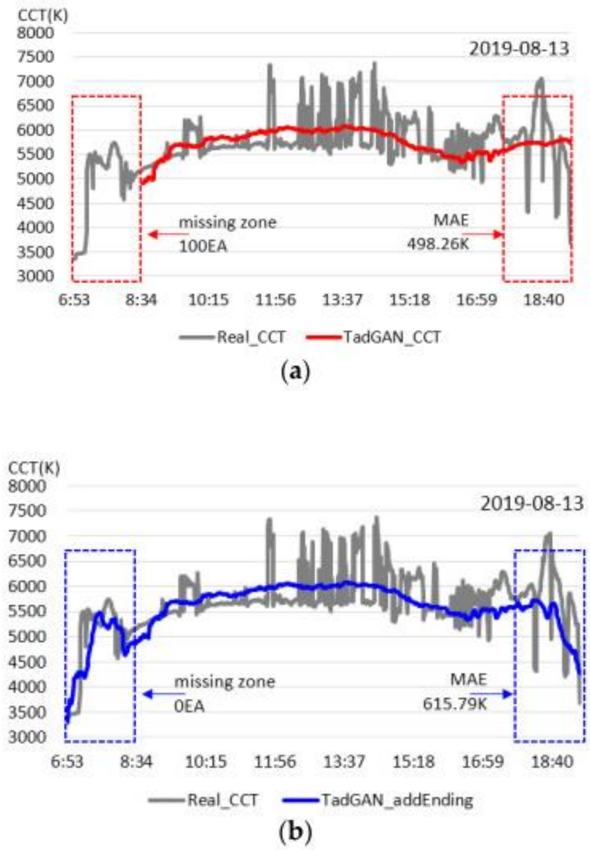
The implementation of circadian lighting systems hinges on accurately replicating natural sunlight, which requires precise data on solar intensity and color temperature. Traditional data collection involves high-cost equipment like spectroradiometers (e.g., CAS 140CT-152) and solar trackers, as seen in studies conducted at Kongju National University[3]. These setups provide detailed measurements, including correlated color temperature (CCT), intensity, and spectral distribution, over extended periods and under varied seasonal conditions.




*Source:* Kongju National University[3]

### *B. Machine Learning-Based Approaches*

Machine learning offers an alternative to resource-heavy data collection. Regression models like TadGAN[3] can analyze historical sunlight data to predict intensity and spectral variations, effectively addressing circadian lighting requirements. Although this reduces reliance on continuous real-world measurements, it necessitates extensive training datasets and computational resources, making it a complex solution for cost-sensitive implementations




Source: [Kongju National University[3]]

### *C. Advancements in Short-Wavelength Ratio-Based Methods*

Recent advancements have introduced a method of calculating color temperature based on the short-wavelength ratio (SWR) of natural light, which can be derived using RGB sensors. This approach emphasizes the spectral characteristics critical for circadian rhythm support. Experiments have shown that this method provides comparable results to high-end spectroradiometers, with an average error rate below 1% for CCT and approximately 5% for SWR measurements.

### *D. RGB Sensors for CCT Estimation*

To mitigate the complexity and cost of traditional methods, RGB sensors have emerged as a promising alternative. Studies have demonstrated that RGB sensors, paired with algorithms, can approximate CCT values with high accuracy. For instance, an RGB sensor-based method achieved an error rate of less than 1% compared to spectroradiometers. This approach[6] relies on transforming RGB outputs into CCT using mathematical models or chromaticity calculations, offering a cost-effective and simpler solution.

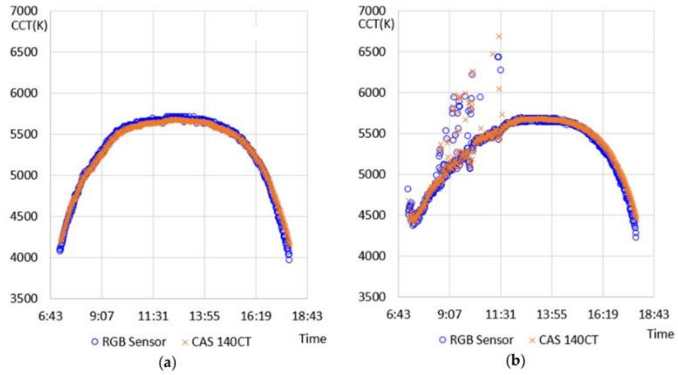



**Figure 5.** Comparison of measurement and calculation results for color temperatures. (**a**) Clear day (5 April 2020); (**b**) Cloudy day (4 April 2020).

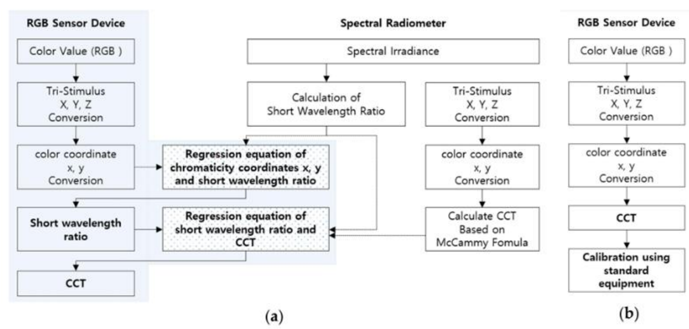
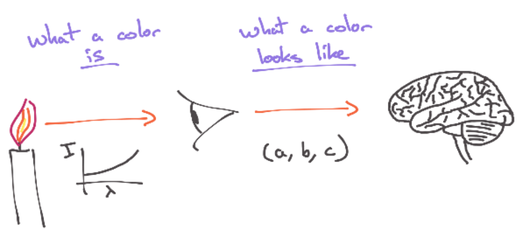



**Figure 4.** Color temperature calculation process: proposed method and existing method. (**a**) Proposed method; (**b**) Existing method.

Source: [RGB To CCT, Kongju National University[6]]

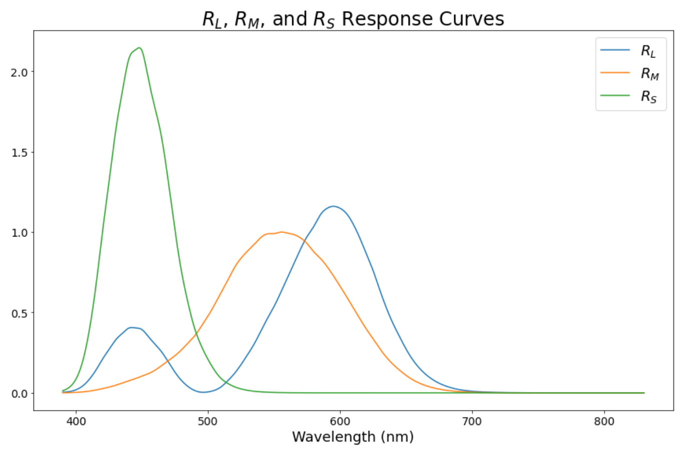
The integration of SWR calculations further enhances the biological relevance of lighting systems by accurately simulating spectral characteristics of natural light and this works because, the perception of light by the human visual system is inherently limited by the physiology of our cone cells. While light enters the eye as an infinite-dimensional spectrum, it is compressed into just three signals by the cone cells' long (L), medium (M), and short (S) wavelength receptors.




*The human eyes respond to three quantities as we have three cones, (L for Long, M for Medium and S for short)* [(source[5])]

### *E. Comparative Insights*

While spectroradiometer-based approaches deliver the highest accuracy and comprehensive data, their cost and operational complexity make them less viable for general use. Machine learning reduces dependence on physical instruments but introduces computational overhead. RGB sensor-based methods balance accuracy, affordability, and simplicity, making them particularly suitable for practical circadian lighting systems.




*The technical name for these curves are the "10-deg XYZ CMFs transformed from the CIE (2006) 2-deg LMS cone fundamentals". If you're interested in more detail, you can find the origin of the curves themselves here[7], and some more details about the derivation of them at this wikipedia page[4]. (According to this source[5])*

This insight emphasizes the strength of RGB sensor-based systems in approximating color temperatures effectively. By leveraging mathematical models and precise spectral data, such systems can deliver high levels of perceptual accuracy despite the inherent limitations of the human visual system. This approach further demonstrates the balance of affordability, simplicity, and capability inherent in RGB-based solutions, particularly when enhanced with computational techniques to simulate the spectral qualities of natural light.

## III. Methodology

Our methodology leverages the insights from previous work and proposes a scalable approach to circadian lighting based on the observed patterns in color temperature variations. Through approximation, we discovered that the variation in color temperature over time follows certain well-defined curves, which can be modeled effectively using mathematical functions. Our approach builds upon experimental data cited in earlier research, particularly from the RGB-based approach[6] and machine learning models developed by the same university. By analyzing these data points, we identified recurring patterns in circadian lighting that guided our selection of appropriate mathematical models.

The process of shifting the circadian lighting graphs to align with the user's local sunrise and sunset times is central to personalizing the lighting experience based on environmental cues. This adjustment ensures that the lighting transitions naturally follow the day-night cycle of the user's location, promoting a seamless circadian rhythm synchronization. The shifting of graphs involves using location-based data obtained through APIs such as geolocation services, which provide the user's latitude and longitude. These coordinates are then passed to sunset-sunrise APIs, which calculate the exact times for dawn, sunrise, sunset, and dusk at the specified location.

The circadian lighting graph, whether represented as Gaussian, sinusoidal, or parabolic, is initially created for a standard day with sunrise at 6:00 AM and sunset at 6:00 PM. However, real-world sunrise and sunset times vary significantly depending on geographical location, season, and time of year. To adapt the graph to local conditions, the center of the curve is shifted so that the brightest part of the day aligns with the actual midday point, while the start and end of the curve are adjusted to coincide with the local sunrise and sunset.

Several factors influence how the graph is shifted:

1. *Latitude and Longitude*: Locations closer to the equator have relatively stable sunrise and sunset times throughout the year, while higher latitudes experience significant seasonal variations.
2. *Seasonal Variations*: During summer months, the days are longer, requiring an extension of the graph's daylight period. Conversely, shorter days in winter necessitate a compression of this period.
3. *Time Zone and Daylight Saving Adjustments*: Time zone differences and daylight saving transitions can affect the alignment of the curve with local time.

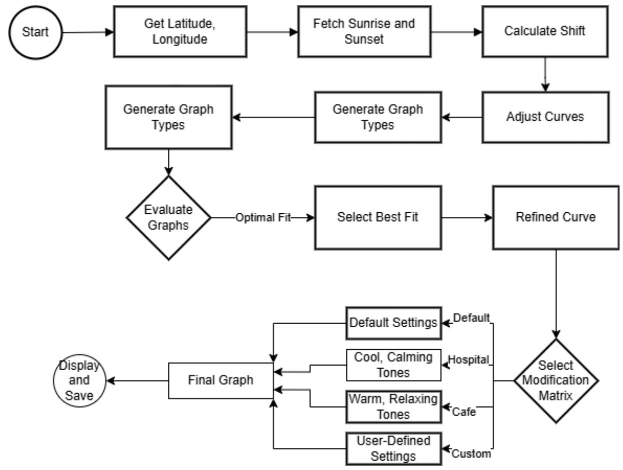
The adjustment process involves calculating the temporal offsets from the default sunrise and sunset times to the actual times provided by the APIs. These offsets are applied to the lighting graph functions by modifying parameters such as the mean ($\mu$) in the Gaussian function or the phase shift in the sinusoidal function. This ensures that the graph dynamically shifts to match the local environmental conditions.

By aligning the lighting graphs with real-time sunrise and sunset, the system emulates natural light transitions more effectively, contributing to the user's well-being and promoting better sleep-wake cycles. The graph-shifting process also accommodates flexibility, allowing modifications based on user preferences or external factors like indoor settings (e.g., hospitals or cafes), where artificial lighting might need to override natural patterns.

### *A. Conversion Workflow and Mathematical Underpinnings:*

The color temperature conversion involves three broad steps:

1. ***Getting the Color Temperature Graph using the following workflow***:




***Gaussian Function (Curve Fitting for CCT Curve)***

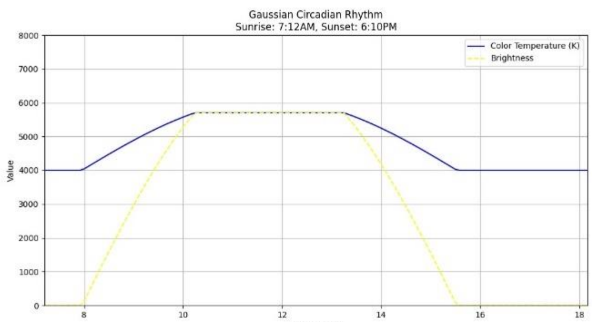
The Gaussian function is used to fit the reference data of color temperature to time:

$$g(t) = A \cdot \exp\left(-\frac{(t-\mu)^2}{2\sigma^2}\right)$$

Where:

- A is the amplitude,
- μ is the mean (center),
- σ is the standard deviation,
- t is the time.

This function models the natural variation of color temperature over time.

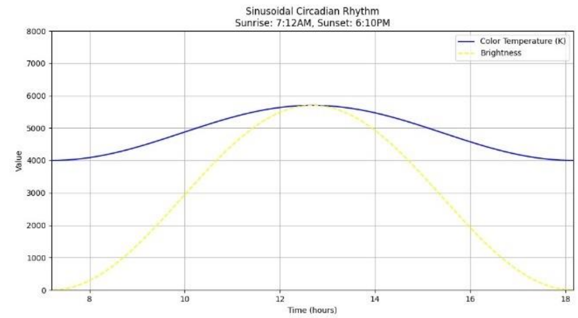



***Sinusoidal Function (Alternative for CCT Curve)***

To generate a sinusoidal representation of the color temperature curve:

$$f(t) = 2700 + 3800 \cdot \frac{1 + \cos\left(\frac{\pi(t - \text{midday}) \cdot \text{scale\_factor}}{6}\right)}{2}$$

- Midday and scale factors normalize the time around a 12-hour period.,
- The output is scaled between 2700 K (minimum) and 6500 K (maximum)



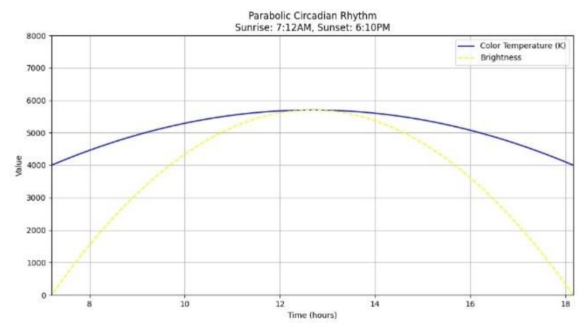

***Parabolic Function (Alternative for CCT Curve)***

To generate a parabolic representation of the color temperature curve:

$$f(t) = \text{MAX\_COLOR\_TEMP} + a \cdot (t - \text{midday})^2$$

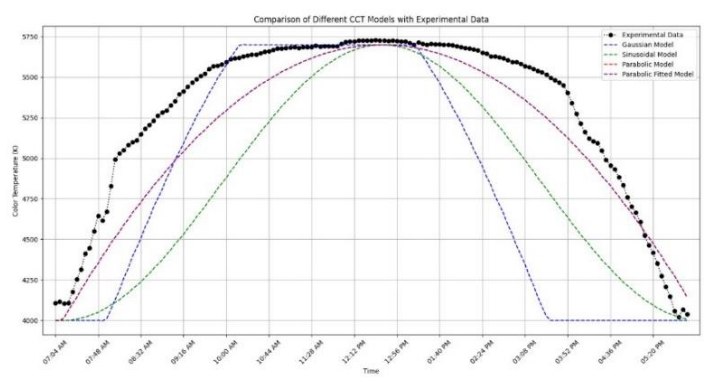
Where:

- $a = -\frac{\text{AMPLITUDE}}{\left(\frac{\text{daylight\_duration}}{2}\right)^2}$,
- $a$: Coefficient ensuring the curve peaks at the maximum color temperature.
- Midday and daylight duration define the parabola's symmetry.

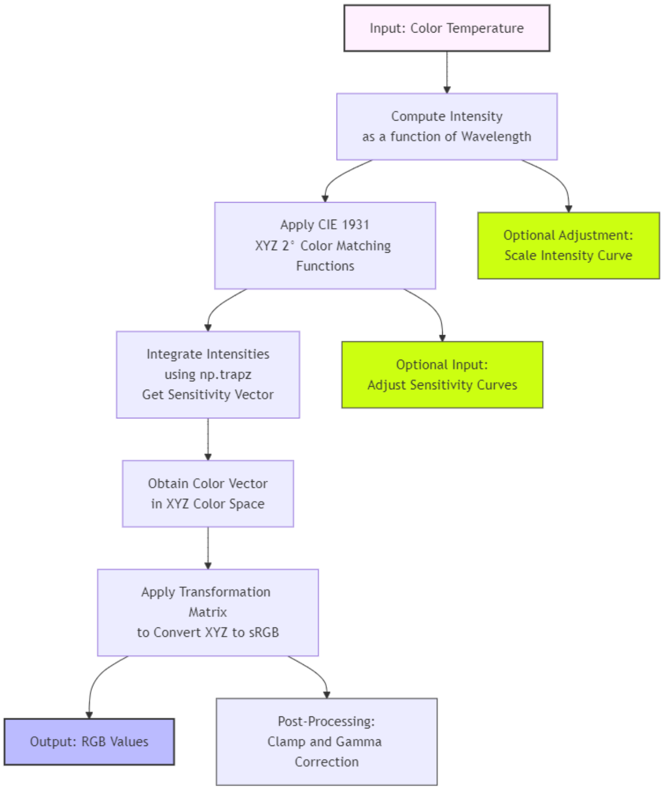



This function models the natural variation of color temperature over time.

Using experimental data extracted from the tables of these papers[6], we have put together these graphs to approximate the best curve for CCT (Correlated Color Temperature)



2. ***Color Temperature to CIE XYZ*:**
   The desired color temperature, measured in Kelvin, is translated into its corresponding coordinates in the CIE XYZ color space. This involves the Planck's law formula, which describes how objects emit light based on their temperature. The system uses numerical integration via the NumPy library to efficiently perform this conversion.




***Planck's Law (Spectral Radiance for CCT)***

The spectral radiance of a black body at temperature T (Kelvin) is given by Planck's law:

$$B(\lambda, T) = \frac{1}{\lambda^5} \cdot \frac{1}{\exp\left(\frac{hc}{\lambda kT}\right) - 1}$$

Where:
- $h = 6.626 \times 10^{-34}$: Planck's constant.
- $c = 2.998 \times 10^{8}$: Speed of light.
- $k = 1.381 \times 10^{-23}$: Boltzmann constant
- T: Correlated color temperature (in Kelvin)

To derive the desired quantities in the XYZ color space, we utilize the X, Y, and Z receptor functions, which represent the response of the X, Y, and Z components to specific wavelengths. These receptor functions are analogous to how the cone cells in the human eye respond to different wavelengths of light, mimicking the physiological perception of color. However, because directly measuring this biological response is challenging, we employ an equivalent computational approach using the standardized data provided in the CIE Dataset[8] for the XYZ color space. This dataset serves as an empirically derived model, enabling precise and consistent transformations between spectral data and the XYZ tristimulus values.

***CCT to XYZ Conversion***

To convert spectral radiance to the CIE 1931 XYZ color space:

$$X = \int_{\lambda} B(\lambda, T) \cdot \bar{x}(\lambda)\, d\lambda$$
$$Y = \int_{\lambda} B(\lambda, T) \cdot \bar{y}(\lambda)\, d\lambda$$
$$Z = \int_{\lambda} B(\lambda, T) \cdot \bar{z}(\lambda)\, d\lambda$$

Where:
- $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$:CIE color matching functions.
- B (λ, T): Spectral radiance from Planck's law.

The XYZ values are normalized to ensure consistent scaling.

The integral expressions for X, Y, and Z represent the response of each color component to a small wavelength interval dλ. This term quantifies how much each receptor (X, Y, or Z) responds to a specific segment of the wavelength spectrum. To obtain the total response across the entire visible spectrum of light as perceived by the human eye, we integrate this term over the visible wavelength range. This integration provides the X, Y, and Z values as functions of color temperature (CCT), thus enabling the transformation of color temperature to the corresponding XYZ color space. This process allows for the accurate representation of the spectral power distribution of light sources in terms of the XYZ color space, which is essential for various color science applications.
Then, we proceed to step 3, which is converting the XYZ to the RGB Color space for each color temperature.

3. ***CIE XYZ to sRGB*:**
   These XYZ coordinates are then converted into the sRGB color space, the standard for digital displays and LEDs. This ensures the colors are displayed correctly by the system. The sources explain that clipping can occur when converting from XYZ to sRGB. This happens when the calculated RGB values fall outside the displayable range, leading to inaccurate color reproduction. To mitigate this, the system implements a normalization step to ensure RGB values remain within the valid range.

***XYZ to RGB Conversion***

Using a transformation matrix for sRGB color space we get:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 3.2406 & -1.5372 & -0.4986 \\ -0.9689 & 1.8758 & 0.0415 \\ 0.0557 & -0.2040 & 1.0570 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

- Where X, Y, and Z are the tristimulus values from the XYZ color space, and RGB are the resulting red, green, and blue components in the RGB color space.
- More algorithms or transformation matrices to other color spaces can also be found in websites like these - RGB/XYZ Matrices[11]

The matrix coefficients are derived from the standard RGB color matching functions and are used to map the linear XYZ values to the corresponding RGB values. The first row corresponds to the red channel, the second row to the green channel, and the third row to the blue channel. Each channel's RGB component is a weighted sum of the XYZ values, and the matrix coefficients ensure that the resulting RGB values are within the displayable color range.

This linear transformation assumes the use of a specific RGB color model, typically sRGB, and is effective for standard color displays. Post-processing steps, such as gamma correction, are typically applied to the resulting RGB values to adjust them for display devices.

#### 4. *Customization Options*

Additional matrices adjust the RGB values by matrix multiplication for specific environments using a tuneable warmness factor $\ni$.

Hospital lighting typically emphasizes green tones, promoting calmness and focus, essential for both patients and medical staff. The cooler lighting helps reduce fatigue and supports alertness. In office environments, the lighting matrix prioritizes blue tones to enhance focus and productivity, improving cognitive performance while maintaining an energizing atmosphere. For cafes, the lighting is warmer, with a focus on red and yellow hues to create a relaxing, inviting ambiance, encouraging comfort and social interaction. Each environment tailors its lighting spectrum to suit the desired emotional and functional response.

***Warmness Factor :***

$$\begin{bmatrix} 1 + 0.3 \ni & 0 & 0 \\ 0 & 1 + 0.3 \ni & 0 \\ 0 & 0 & 1 + 0.3 \ni \end{bmatrix}$$

***Green Factor***

$$\begin{bmatrix} 0.7 & 0 & 0 \\ 0 & 1.4 & 0 \\ 0 & 0 & 0.7 \end{bmatrix}$$

***Blue Factor***

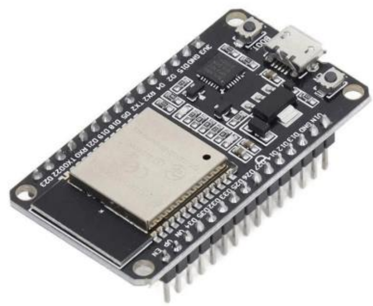
$$\begin{bmatrix} 0.8 & 0 & 0 \\ 0 & 1.0 & 0 \\ 0 & 0 & 1.4 \end{bmatrix}$$

***Red Factor***

$$\begin{bmatrix} 1.3 & 0 & 0 \\ 0 & 1.1 & 0 \\ 0 & 0 & 0.7 \end{bmatrix}$$

## IV. HARDWARE/UI IMPLEMENTATION

### A. *Components Used*



*ESP-32*

*NeoPixel Ring 12 RGB LED*

ESP32 plays a crucial role as a microcontroller that interfaces with Wi-Fi, controls NeoPixels, and serves a web interface for remote control. Here's an overview of how the ESP32 functions:

**Wi-Fi Connectivity**: The ESP32 connects to a Wi-Fi network using the provided SSID and password. In the *setup()* function, *WiFi.begin(ssid, password)* initiates the connection. The ESP32 continues to attempt connection until it successfully connects, indicated by *WiFi.status()*. Once connected, the ESP32 is ready to interact with the network.

**Web Server**: The ESP32 hosts a simple web server using the *WebServer* class. The server listens for HTTP requests on port 80 and responds accordingly. Specifically, it handles a POST request at the */set_color* route, where it expects parameters for Red (R), Green (G), Blue (B) values, and brightness. These parameters are used to set the color and brightness of the NeoPixel strip.

**NeoPixel Control**: The NeoPixel strip, connected to the ESP32, is controlled through the Adafruit_NeoPixel library. The function *setNeoPixelColor()* takes RGB values and a brightness factor to calculate the appropriate color, which is applied to all pixels in the strip using *pixels.setPixelColor()* and *pixels.show()*.

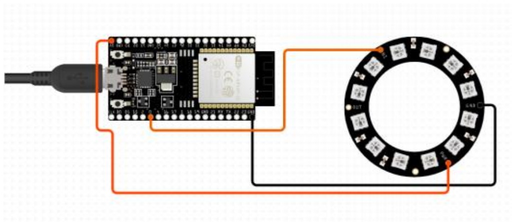
**HTTP Request Handling**: When a POST request is made to the */set_color* route, the server checks for the presence of valid RGB and brightness parameters. If the parameters are valid, the *setNeoPixelColor()* function is invoked to update the NeoPixel strip. The server then sends a success message or an error response depending on the request validity.

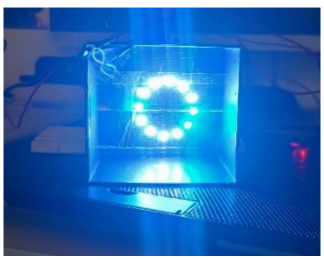
**Loop Function**: In the *loop()* function, *server.handleClient()*

ensures that the ESP32 is constantly listening for incoming requests. Each time a client sends a request, it is processed in real-time.

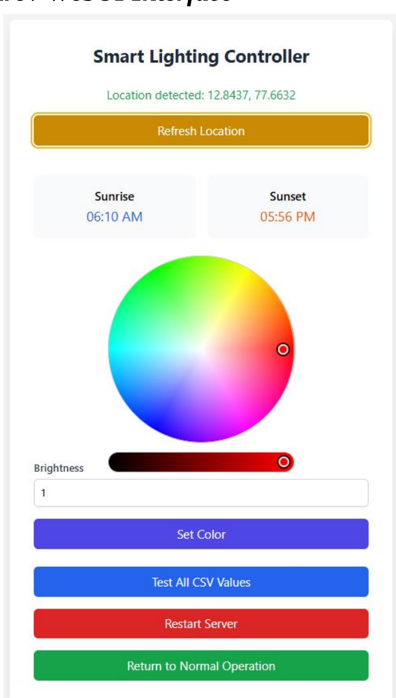
### *B. Wiring*

Here's a simple diagram of all the connections needed. (only three are needed, and a power source to the ESP32)
Note: the NeoPixel LEDs are best powered with atleast a 5V powers source. This setup can be powered with a power bank or a separate power supply module as well.





### *C. Software / WebUI Interface*




The Flask web interface in this project enables users to control the lighting system through several features, primarily focusing on circadian rhythm simulation and manual RGB adjustments. The manual RGB control allows users to set specific color values for the lighting, providing flexibility to tailor the lighting to personal preferences. Additionally, the circadian rhythm simulation adjusts the lighting automatically based on the time of day, following natural daylight patterns with cooler tones during the day and warmer tones in the evening. The interface provides the option to return to automatic mode after manual adjustments, ensuring the lighting system reverts to the circadian rhythm simulation when no further input is detected. Furthermore, the system incorporates a location-based feature that uses the user's geographic information to adjust the lighting according to local sunrise and sunset times. This feature enhances the simulation of natural daylight by ensuring that the lighting patterns are geographically appropriate, optimizing the user's experience based on their time zone and local environment.

Below figures show some of the different lighting conditions during different times of the day.

Sunrise Between Sunrise/Noon Noon

Visit the GitHub Repo[15] for more information.

## V. BENEFITS AND IMPROVEMENTS FROM CIRCADIAN LIGHTING

Disrupting the Circadian Rhythm can prove to be detrimental to not only mental but physical health as well [12].

In hospitals, proper circadian lighting can help reduce patient confusion, anxiety, and depression by promoting natural sleep-wake cycles. This is particularly crucial for elderly patients, who may suffer from circadian rhythm sleep disorders, and psychiatric patients, where circadian misalignment is linked to exacerbated mood disorders such as seasonal affective disorder or bipolar disorder. In psychiatric settings, using light therapy aligned with natural circadian rhythms can also improve therapeutic outcomes by stabilizing mood and enhancing sleep quality. Although specific numeric improvements in symptoms vary across studies, evidence suggests significant improvements in sleep quality and mood stabilization with the use of circadian-aligned lighting. For example, light therapy has been found to improve daytime alertness, sleep quality, and activity levels in patients, especially those with dementia and Alzheimer's disease ([13],[17]). In hospitals, patients have reported better sleep quality and fewer mood disturbances when exposed to lighting that mimics natural light cycles ([13]

The health consequences of circadian disruption are vast, ranging from increased fatigue and lack of focus to cardiovascular diseases and certain cancers. One of the most common effects of disrupted circadian rhythms is altered sleep. Artificial light exposure, especially at night, impairs the ability to fall asleep and shortens sleep duration ([14]). Disrupted circadian rhythms can affect cognition and mood and may lead to increased anxiety and depression. Depression, characterized by mood changes and diminished pleasure, is often accompanied by sleep disruptions ([2]), implicating circadian disruption as a key feature of depression and other mood disorders ([9]). Typically, individuals performing shift work will adjust to their nontraditional schedules and their rhythms will shift to match the time that they are awake ([16]). However, anywhere from 10% to 30% of individuals performing shift work are never able to adapt and instead develop shift work disorder, characterized by extreme sleepiness during work hours and insomnia during rest hours ([10]). Interestingly, individuals who have performed shift work for many years may lose tolerance (as shown by increased digestive issues, fatigue, and impaired sleep) ([16]).

## VI. CONCLUSION

In conclusion, the disruption of the circadian rhythm poses significant risks to both mental and physical health. The evidence is clear that misalignment of natural sleep-wake cycles can lead to a range of adverse outcomes, from impaired cognition and mood disorders to severe physical health issues such as cardiovascular diseases and cancer. In healthcare settings, particularly for vulnerable populations such as the elderly and psychiatric patients, circadian-aligned lighting and light therapy offer a promising solution to mitigate these effects. By supporting natural sleep patterns and stabilizing mood, these interventions can significantly improve the quality of life and therapeutic outcomes for patients. However, as studies show, the challenge of adapting to disrupted rhythms, especially in shift workers, remains a complex issue. Ongoing research and the implementation of circadian-based solutions will be crucial in addressing the widespread impact of circadian rhythm disruption on public health. Our project aims to solve this issue by providing efficient, scalable and affordable Circadian Lighting solutions.

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