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LED Research System On Light Spectra For Indoor Growing

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Abstract

The development of an LED system for indoor agriculture research on the effects of light spectrum and plant growth. The system is designed to wirelessly mix four different light spectra, allowing for highly customizable and precise control of lighting conditions for plant growth. The project involves programming an ESP32 microcontroller for controlling four individual LED drivers and setting up a wireless access point with web interface for real-time monitoring and control of the LED system. The system also consists of more features such as day/night cycles, temperature, and humidity sensing. The photon output per light spectrum is calculated and displayed on the web interface for more insight on the light spectrum emitted by the system. The project is motivated by the increasing global demand for sustainable food production in urban environments, with indoor agriculture as a promising solution to overcome challenges such as limited land availability and climate change impacts. The system can contribute to the knowledge and technologies needed for sustainable indoor agriculture, bringing food production closer to the population.

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1 Introduction

The focus of the project will be the research, development and testing of an innovative LED research system for indoor agriculture. This system will have the capability of wirelessly mixing four different light spectra through a web interface. The aim is to create a highly customizable and precise system than can perform research on the effect of different electromagnetic wavelengths or light spectra on plants in indoor environments.

The project will involve programming an ESP32 for controlling four individual LED-drivers. A wireless access point will be set up with a web interface. Relevant information about the LED-system will be displayed, creating a good platform for doing research with real-time capability. Besides mixing the light spectra, day/night cycles can be programmed from the interface as well.

The research is of importance due to the increase of global demand for sustainable food production in urban environments. With the world population projected to reach 9.7 billion by 2050, traditional agriculture methods face challenges such as limited land availability, water scarcity and climate change impacts. Indoor agriculture with the development of LED lighting, has been a promising solution to overcome these challenges by providing a controlled environment for growing.

To frame the research, the terminology used in LED lighting and indoor farming such as DLI (Daily Light Integral) and PPFD (Photosynthetic Photon Flux), will be explained. The technical aspects of programming the ESP32 microcontroller and designing the LED-PCB will be elaborated on.

The objective of this research is to physically test the designed LED lighting system and grow a plant while collecting and displaying relevant information on the web-interface. To create a flexible and intriguing research tool that can further investigate the effects of different light spectra on plant growth.

2 Material and methods

2.1 Hardware

The Hardware of the project consists of the main PCB with ESP32 and power electronics, LED-drivers with current controlled PWM dimmable capabilities, SMD-LEDs in four different light spectra and an LED-PCB for mounting the LEDs.

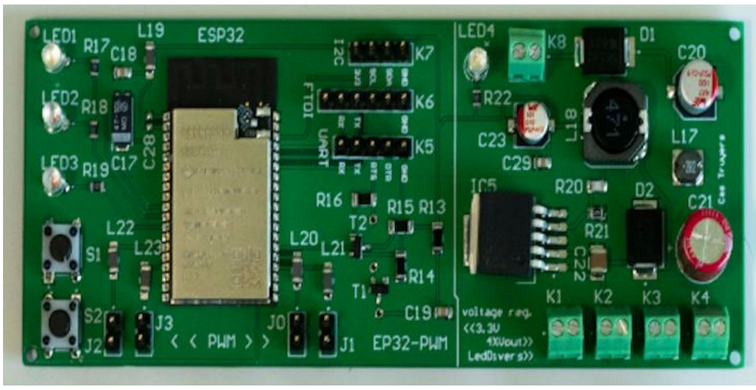
The schematics of the main PCB and LED-drivers are based on the Elektor September–October 2019 magazine. [1] In a previous project these PCB were designed, and the components soldered. The next sections on these PCBs will further explain their functionality.

2.1.1 Main PCB

The main PCB as seen in Picture 1 consists of a lot of common components such as resistors, capacitors, inductors, and semiconductors. There are two interesting modules on this PCB, the LM2576HVS and the ESP32-WROVER-B

The LM2576HVS is a step-down converter that converts an input between 4V and 60V to an adjustable constant voltage between 1.23V and 57V. This is determined by its arrangement of passive components. On this PCB, the passive components are arranged to get a constant voltage of 3.3V for the ESP32.

ESP32-WROVER-B is a powerful, generic Wi-Fi-BT-BLE MCU module that targets a wide variety of applications. [2] In this design, the ESP32-WROVER-B generates four PWM signals, 1 for each LED driver. The module is programmed to set up a Wi-Fi Access Point (AP) and be controlled through a web interface.

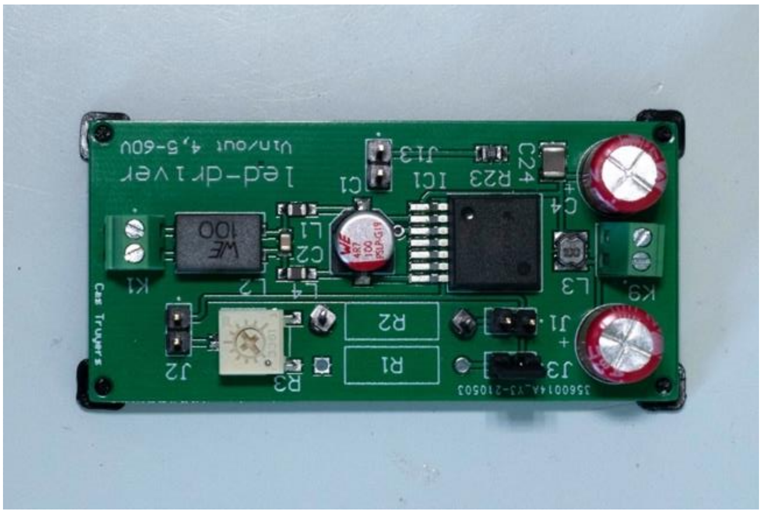


Picture 1: Main PCB

2.1.2 LED-Drivers

The LED-Driver also has a lot of passive components, used for smoothening out the output and reducing the pollution back to the grid. The main driver is the MagI³C-LDHM module. [3] This is an LED driver module that provides an adjustable constant current. The current is determined by connecting a certain resistance value to one of its pins.

It needs a minimum of 4.5V and tolerates a maximum of 60V as input and output, which determines how many LEDs can be placed per LED-driver. With a forward voltage of 3V per LED, 20 LEDs can be placed per driver, using a voltage of 60V. This module can provide up to 450mA of current. With this module, LEDs can be dimmed with the use of PWM signals connected to one of its pins. This will dim the LEDS using PWM with constant current. The LED driver can be seen in Picture 2.



Picture 2: LED driver

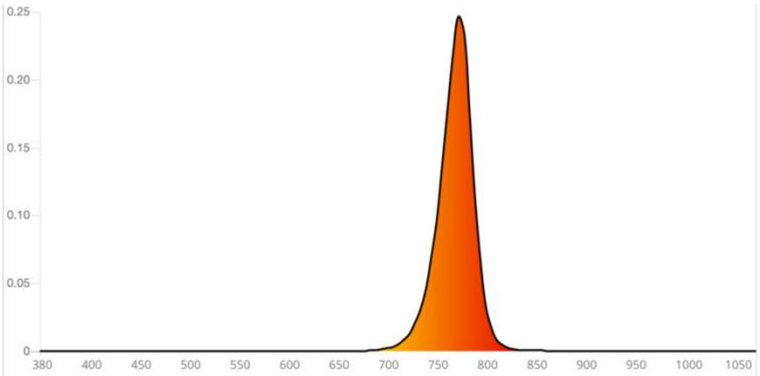
2.1.3 SMD-LEDs

A specific led must be chosen for a particular application, the focus of this project is on vertical farming. After researching multiple LEDs, The LUXEON SunPlus 2835 LEDs are the most suitable for vertical farming because they produce little heat. [4] Therefore, they can be placed closer to the plant and thus save space, which is critical in vertical farming.

Other LEDs such as the SunPlus 35 from LUXEON emit more photons per Watt but are meant to be placed in greenhouses at a long distance from the plant because of the high heat production. Therefore, these kinds of LEDs are not suitable for our application.

2.1.3.1 Far Red

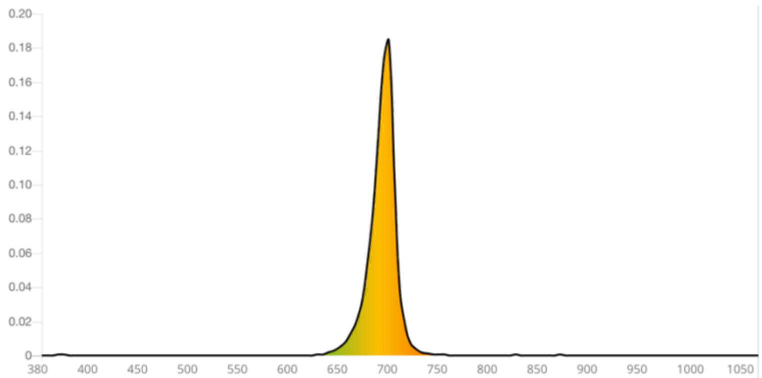
The SunPlus 2835 Far-Red LEDs have a wavelength of 720-740nm as seen in Graph 1. When far-red is exposed to plants, it can trigger a specific physiological response, with the main one being promoting leaf expansion. This spectrum is very efficient for increasing yield on leafy plants such as lettuce.



Graph 1: Far Red wavelength (x axis in nanometer) vs Spectral Distribution (y axis)

2.1.3.2 Deep Red

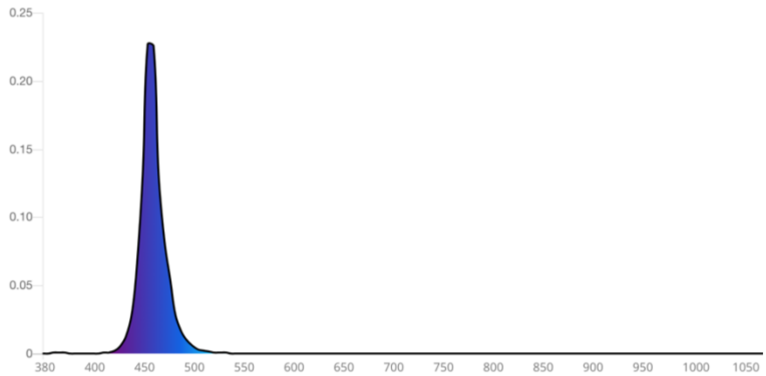
The SunPlus 2835 Deep-Red LEDs have a wavelength of 650-670nm as seen in Graph 2. It is an important part of the photosynthetic spectrum and has significant effects on plant growth and development. It is considered the most efficient light spectrum for photosynthesis.



Graph 2: Deep Red wavelength (x axis in nanometer) vs Spectral Distribution (y axis)

2.1.3.3 Royal Blue

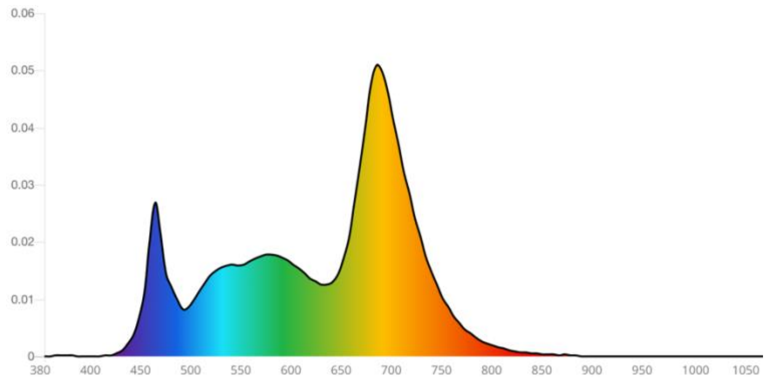
The SunPlus 2835 Royal-Blue LEDs have a wavelength of 440-455nm as seen in Graph 3. This is also an important part of the photosynthetic spectrum and has a significant effect on plant growth. It specifically promotes the vegetative stage in plant growth.



Graph 3: Royal Blue wavelength (x axis in nanometer) vs Spectral Distribution (y axis)

2.1.3.4 Horticulture White

The SunPlus 2835 Horticulture White LEDs emit a broad-spectrum that includes blue, green, and red as seen in Graph 4. This LED makes for a balanced light optimized for plant growth. It also helps for physical inspection of the plants. A plant can grow from the spectrum emitted by this LED. But to get more control and efficiency, specific light spectrum LEDs as discussed above are also used.



Graph 4: Horticulture White wavelength (x axis in nanometer) vs Spectral Distribution (y axis)

2.1.4 LED-PCB

For making the LED-PCB, the ProtoMat S62 milling machine is used. The machine used was in the laboratory of Lapland AMK.

2.2 Software

2.2.1 Programming

The ESP32 will be programmed using the following techniques.

2.2.1.1 Language

The ESP32 will be programmed in object-oriented C/C++. Other popular and supported languages for the ESP32 is micropython, but because the project can get very specific, micropython can be a limiting factor because of the lack in customizability.

2.2.1.2 Framework

The ESP-IDF (Espressif IoT development Framework) is chosen for programming the ESP32 due to its advantages over the Arduino framework. The ESP-IDF aligns with good programming practices and offers advanced features such as lower-level access to hardware peripherals, efficient memory management and support for multithreading.

The ESP-IDF SDK (software development kit) is a comprehensive set of software tools and utilities that are used for developing and debugging the ESP32 applications. It includes components such as the ESP32 boot loader, FreeRTOS for task management and various system libraries for memory management, networking and more.

The ESP-IDF framework comes with comprehensive documentation that includes API references, programming guides, tutorials, and examples, which provide detailed information on how to use the ESP-IDF libraries, SDK, and tools for developing applications.

2.2.1.3 Toolchain

The ESP-IDF toolchain, which includes a set of compilers, linkers and other tools that are used for compiling and building ESP32 applications. It supports both windows and Unix-like operating systems.

2.2.1.4 IDE

Visual studio code is used as an IDE, together with the ESP-IDF extension it provides a streamlined way to build and flash firmware directly from VSCode. Additionally, it provides Intellisense and code completion that offers context-aware suggestions for ESP-IDF libraries. Using VSCode with the ESP-IDF extension greatly accelerates the coding and reduces the number of errors.

2.2.2 KiCad

The ease-of-use nature of KiCad makes it the preferred choice for creating simple PCB design such as the LED-PCB. Compared to more advanced software such as Altium Designer, KiCad is an open-source and free software.

2.2.3 LumiLeds horticulture calculator

The horticulture calculator by LumiLeds is an online tool to help you design your LED system. [5] The calculator calculates the photon output per light spectrum with a specific setup of different LEDs and power. This is a good tool to get an understanding on how many LEDs you need for creating an LED-PCB that is sufficient for growing and doing research.

3 Results

3.1 Embedded Programming

A link to the GitHub repository consisting of the codebase for this project is attached in the Attachments under section 7.1 GitHub Repository.

3.1.1 Object Oriented LED-Driver's control

The ESP32 controls the output of 4 LED-Drivers by sending a PWM signal to one of its pins. A PWM signal can be created by the hardware timers of the ESP32 by configuring the PWM modules. Because four different LED-Drivers must be controlled independently from each other, a LED-Driver Class is created. This class consists of methods to initialize and control the PWM. This abstraction gives a lot more oversight in the coding.

3.1.2 Wi-Fi

The ESP32 operates as an Access Point (AP), creating its own wireless network. This AP enables users to interact with the LED system through a web interface when connected to its IP address.

Furthermore, the ESP32 also connects to an existing wireless network, enabling internet access. This is necessary for synchronizing the time using NTP.

When the ESP32 is powered on, both the AP and internet station connection are active all the time.

3.1.3 webserver

For delivering the web interface to the user, a webserver is set up on the ESP32. When a client connects to the ESP32's IP address, the webserver sends the required HTML/CSS/JS files.

3.1.4 WebSocket communication

The ESP32 implements a WebSocket connection to facilitate efficient and real-time bidirectional communication between the webserver and MCU. By utilizing the WebSocket protocol instead of the traditional HTTP request, the system has reduced latency and establishes a persistent connection. This results in more system responsiveness and efficiency. The process consists of performing a handshake and enabling event-driven communication keeping the connection alive.

Each time a new client connects to the system, the latest data is automatically transmitted and updated on the web interface. Whenever another client changes something on the web interface, the change is immediately transmitted to all clients to keep every interface up to date.

3.1.5 Network Time Protocol

By utilizing the Network Time Protocol (NTP), the system ensures that the internal Real-Time Clock (RTC) maintains accurate time information, which is essential for automating the on/off schedule of the LED drivers. When the ESP32 establishes a station connection to a wireless network and gains internet access, it connects to an NTP server and synchronizes the time.

3.1.6 Real-time clock

The ESP32 consists of an internal real-time clock or RTC, which is a dedicated hardware clock for keeping track of the time. Synchronized with the NTP protocol, the RTC provides an accurate reference for comparing the user defined on/off time of the drivers. This provides automated control over day/night cycles.

3.1.7 Non-volatile storage

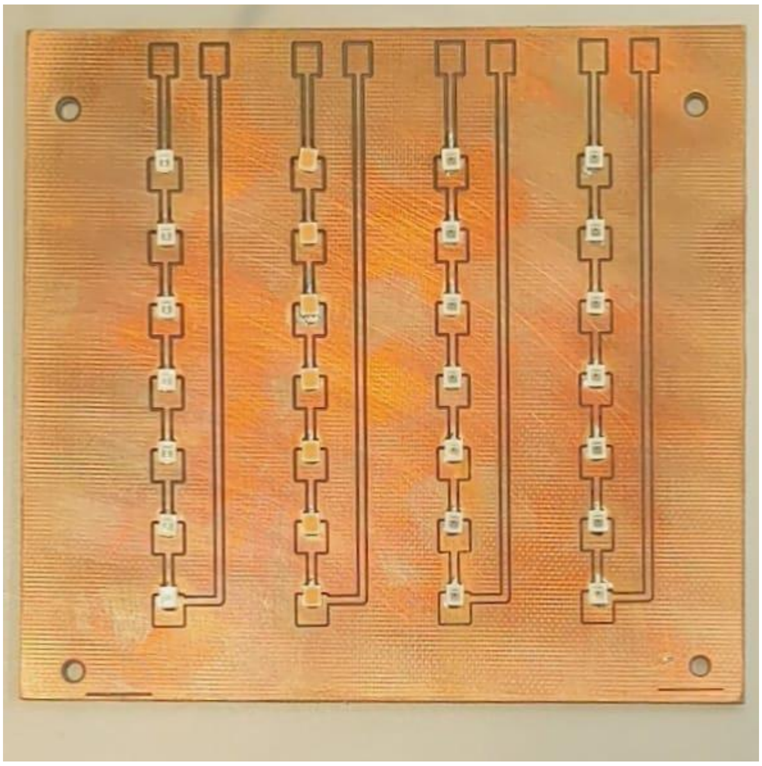
For preserving important data, such as duty cycle values for the LED drivers and user-defined on/off times, the non-volatile memory (NVS) is used. By utilizing the NVS, the system can retrieve the information again even after reboots or power losses. During system initialization, the ESP32 reads the stored data from the NVS and updates the system accordingly.

3.2 Web Interface

The web interface allows for controlling the duty cycle of the LED drivers, but also displaying important information about the system such as temperature and humidity. The on-time and off-time can be specified to automate the day and night cycles of the plant. The total PPF output and PPF output per light spectra is estimated using the user input of the slider and the characteristic of the LEDs used. This gives precise insight in the light spectrum emitted.

3.3 LED-PCB

The SMD-LEDs are soldered on a PCB board as seen in Picture 4. They are soldered in a grid pattern with 4 rows for each light spectrum and 7 of each in the columns. Luxeon provides a paper with information about footprint design for the luxeon SunPlus 2835 series [5]. The anode of the LEDs dissipates the most heat, so they recommend a copper area extending at least 3 mm from its footprint at the anode. Because there is a lot of space on the PCB, the tracks can be made wide and help with thermal cooling.



Picture 3: LED-PCB

3.3.1 Light spectrum research

When designing a LED-system for research on light spectrum influences on plant growth, it is crucial to have a solid understanding of the effects of different light spectra on plant physiology. This knowledge serves as the foundation for designing the LED-PCB. Additionally, considerations need to be made regarding the photon output of the LED-PCB to ensure it is sufficient for doing research solely on each light spectrum. The grow area and illumination need to match, and the distance must be considered.

Some important terminology for doing research in light spectrums influence on plant growth are PAR, PPFD, McCree curve and DLI, the meaning of them is explained in the following points.

3.3.1.1 PAR

Photosynthetically Active Radiation or PAR refers to the range of wavelengths of light that plants use for photosynthesis. PAR includes wavelengths of light in the range of 400 to 700 nanometers. Which corresponds to the visible light spectrum. Later research exposes that wavelength outside of PAR range, such as UV-B (280-315nm) and Far Red (700-800nm), are also important in plant physiology.

3.3.1.2 PPFD

Photosynthetic Photon Flux Density or PPFD is a measure of the intensity of light that is in the PAR region. It is expressed in the units of micromoles of photons per square meter per second. It represents the number of photons within the PAR range that are received by a surface in a given time. It differs from PPF since PPF does not account for the density or area of the received photons. PPF is the total photon output emitted by a light source that is in the PAR range. Monitoring the PPF and PPFD values can help ensure that plants receive the proper amount of light for photosynthesis.

3.3.1.3 McCree Curve

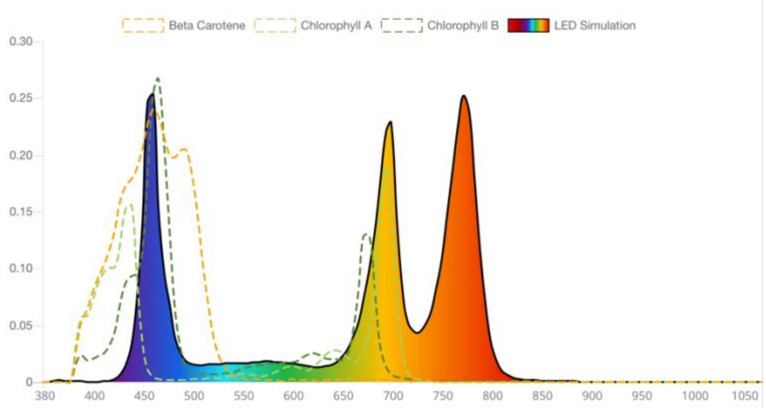
The McCree curve is a graphical representation that shows the efficiency of photosynthesis at different wavelengths within the PAR range. It illustrates that plants have varying degrees of photosynthetic efficiency at different wavelengths, with peaks of high efficiency at certain points, such as around 450nm (blue) and 660nm (red), while other wavelengths are less effective for photosynthesis.

3.3.1.4 DLI

Daily Light Integral or DLI is a measure used in horticulture to quantify the total amount of PAR received by plants over a 24-hour period. It is expressed in the units of moles of photons per square meter per day. DLI is an important parameter as it helps to optimize light exposure for different plant species and growth stages.

3.3.2 LED-PCB Light Spectrum

When the 4 light spectra from the LEDs, as discussed in materials and methods, are combined they result into this total light spectrum. On Graph 5, you can see the wavelength on the x axis, and its spectral distribution on the y axis.



Graph 5: Total Light Spectrum wavelength (x axis in nanometer) vs Spectral Distribution (y axis)

Graph 5 also includes chlorophyll A, chlorophyll B and Beta Carotene. These are important plant pigments that respond to specific light spectrums, the graph illustrates how strong they respond to specific wavelengths. By plotting the reactance of these pigments to the wavelengths, along with the total light spectra, a good light distribution can be determined. The following points explain the importance of each pigment.

3.3.2.1 Chlorophyll A

This is the primary pigment involved in photosynthesis. It absorbs light most efficiently in the red and blue regions of the light spectrum. Plants can benefit from targeted red and blue light to maximize chlorophyll an absorption and promote photosynthesis.

3.3.2.2 Chlorophyll B

This pigment acts as an accessory pigment that works in conjunction with chlorophyll a, it absorbs light primarily in the blue and red-orange regions of the light spectrum. chlorophyll b helps broaden the range of wavelengths that plants can utilize for photosynthesis.

3.3.2.3 Beta Carotene

While not directly involved in photosynthesis, beta carotene is an important accessory pigment called a carotenoid. It absorbs light in the blue and green regions of the light spectrum, complementing the absorption spectra of chlorophyll A and B. Beta carotene also serves as a protective agent against damage from high light levels. Maintaining a good balance of blue and green can support the presence and function of beta carotene.

3.3.3 Calculations for the LED-PCB

This subject will consist of the calculations used for determining the design of the LED-PCB. It also gives insight in the performance of the LED-PCB. Table 1 shows the specifications for the four different LEDs.

Name	Wavelength (nm)	Voltage (V)	Current (A)	PPF/W (µmol/j)	Watt(max)	PPF
Far-Red	720-740	2.2V	300mA	2.32	0.66	1.53
Deep Red	650-670	2.2V	250mA	2.32	0.55	1.27
Royal Blue	440-455	3.0V	240mA	2.06	0.72	1.48
White	Full Spectrum	2.9V	480mA	2.28	1.30	2.96

Table 1: LEDs specifications

The consideration of voltage for each chain of LEDs holds significance. Considering practicality and cost-effectiveness, a 24V power supply is used. This enables the connection of 8 LEDs in series for the LED with the highest voltage drop, namely royal blue. To account for any voltage losses, 7 LEDs are connected in series for each of the different LEDs. This arrangement results in a total of 28 LEDs.

The total photosynthetic photon flux (PPF) required for a given photosynthetic photon flux density (PPFD) and coverage area is a calculated using the formula PPF = PPFD * A. For Lettuce, a recommended PPFD is 300 µmol/m2/s, while for cherry tomatoes, it is 600 µmol/m^2/s. The LED-PCB will be designed for reaching the light level needed for growing cherry tomatoes.

Aiming for a higher maximum light intensity and lowering the current for plants that require less light is advisable for keeping flexibility. Considering a growing area of 0.2m by 0.2m, equivalent to 0.04m^2, the total PPF needed to achieve a PPFD of 600 µmol/m^2/s can be calculated used the previous mentioned formula. The calculation results in a value of 24 µmol/s.

Utilizing the Horticulture calculator provided by Luxeon, the specifications of the 4 different LEDs, with 7 LEDs in each chain, are inputted. Subsequently, the total PPF and PPF per wavelength are calculated. This result can be seen in Table 2.

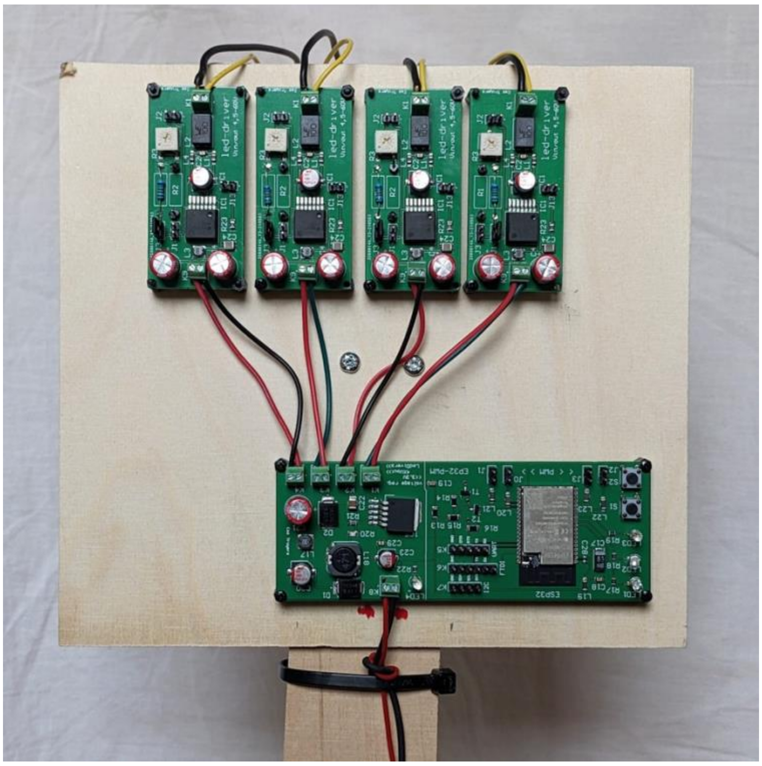
PPF in PAR (400nm - 700nm) [micromol/s]	37.08
PPF/W_electric (400nm - 700nm) [micromol/J]	1.42
Total (380nm - 850nm) [micromol/s]	48.40
WPE [%]	37.8
Total Electrical Power [W]	26.12
UV (350nm - 400nm) [micromol/s]	0.06
Blue (400nm - 500nm) [micromol/s]	12.64
Green (500nm - 600nm) [micromol/s]	5.36
Red (600nm - 700nm) [micromol/s]	19.09
FarRed (700nm - 800nm) [micromol/s]	11.20
Blue% of PPF	34.08
Green% of PPF	14.45
Red% of PPF	51.47
FarRed% of PPF	30.19
Red+FarRed% of PPF	81.66
Red/Blue Ratio	1.51
(Red+FarRed)/Blue Ratio	2.40

Table 2: Horticulture calculator result

The overall PPF amounts for 37 µmol/s, significantly surpassing the previously calculated value of 24 µmol/s. However, as this result is obtained with all the LEDs operating at maximum current, it is not conducive for research purposes. Upon examining the individual PPF outputs, the values for red, blue, and far-red spectrums, are 19, 12 and 11 µmol/s respectively. These values are in close enough proximity to the desired PPF of 24 µmol/s, thereby proving sufficient for conducting research and implementing certain spectra at lower currents.

3.4 System platform structure

To use the system, a wooden structure is built, the PCBs are attached to the structure with standoffs. Holes for routing cables are in place. Picture 5 presents the electronics, the PCB with the ESP32 and power management, and the four LED drivers. Picture 6 presents the LED PCB attached to the top of the system. A plant can be placed under this construction to start growing. Picture 7 shows the use of the system, growing a spinach plant in its early stages inside a closet for isolating it from external light.



Picture 4: Mounted Electronics

Picture 5: Mounted LED-PCB

Picture 6: System/Construction in use

4 Discussion

4.1 Significance of research

The significance of this project lies in its contribution to addressing the increasing global demand for sustainable food production. With the projected world population reaching 9.7 billion by 2050, traditional agriculture methods face numerous challenges, including limited land availability, water scarcity and the impacts of climate change. Indoor agriculture supported by LED light systems is a promising solution to these challenges. By developing an innovative LED system research tool with the capability of mixing different light spectra, this study enhances the customization and precision of indoor agriculture systems. The research not only advance our understanding of the effects of light spectra on plant growth but also contribute to the development of research tools. ultimately, this project supports the contribution to the global efforts for more resilient and resource conscious future.

4.2 Interpretation of findings

To facilitate effective communication with the microcontroller for managing the LED-drivers, a web interface proves to be a good option due to the high customizability using JavaScript, HTML and CSS.

A WebSocket connection can give real-time low-overhead communication between the web interface and the microcontroller, which makes updating all the connected clients efficiently and in real-time possible. Having this sense of real-time adjustment between the driver and multiple clients gives a feeling of reliability.

By implementing Non-Volatile Storage (NVS) it ensures that configurations are preserved even during power cycles. This means that whenever the system loses power, it will start up with the same intensity values for the drivers, day and night cycle times, and other configurations made by the user. This increases user experiences dramatically.

4.3 difficulties

4.3.1 ESP32 defect

The internal ESP32 on the PCB can no longer be programmed through the UART interface. Presumably, one of the pins have been shorted making it unusable. The internal ESP32 has been replaced with an external one. This external ESP32 runs all the software to control the system. For the first 2 months of the project, the internal ESP32 was programmable. The external ESP32 is a good solution but creates extra wiring and redundancy. Presumably this problem can be solved by soldering a new ESP32 to the PCB. But the specific ESP32 WROVER-B used on the PCB was not on offer online or in the lab.

4.4 Limitations and future directions

4.4.1 ESP32 GPIO availability

The PCB Made in a previous stage did not provide any GPIO for external connections to the ESP32. This limits the options for simple hardware expansion. It does provide an I2C interface to communicate with other devices. This allows sensors with I2C interfaces to be used for hardware expansion. The absence of GPIO is not a drawback but can add complexity. Since I2C is a good standard to use for expansion, it is only an ease-of-use limitation and not necessary to add in the future.

4.4.2 Wire management

With each driver and ESP32 having its own PCB, a lot of external wiring is needed to connect everything together. This resulted in increased work to cut and install cables to the correct length. In the future this can be simplified by developing a PCB where the drivers, esp32 and power management are on a single PCB.

4.4.3 UV-light

The LED light PCB contains four different spectrums, the typical red and blue spectrum, full spectrum white and far red. This is because in the Elektor magazine, on which the project is based, it is set up this way. However, when I did my own research, I saw that UV spectrums also affect plant growth, a spectrum that is still being researched a lot. In the future, this UV spectrum can be included in the PCB.

4.4.4 Environmental control

Currently, the only environmental factors that can be adjusted is the light spectrum. Since heat, humidity and other environmental factors also affect plant growth, it is useful to not only sense them, but also control them. In the future, the system can be expanded to include control of heat elements, humidifiers and more.

4.4.5 PPF sensor

The total and individual photosynthetic photon flux or PPF per light spectrum is calculated and displayed on the user interface. This gives the user an indication of how much of each spectrum is emitted by the LEDs. In the current version this is calculated using a formula and parameters derived from the datasheet of each LED. Since this is just a calculation with ideal values, it is not accurate. To measure this more dynamically and accurate in the future, a PPF sensor can be used. A calibration can be performed where the intensity of each light spectrum is varied, and a function can be created based on the PPF measured by the sensor. Due to the high price of a PPF sensor, this has not been implemented in the current system.

4.4.6 Camera

To make the research system more remote, a camera module can be included to provide an image about the growth of the plant on the web interface. This will allow the user to remotely monitor plant growth without disturbing the growing environment for visual inspections.

4.4.7 Image processing and Artificial Intelligence

When a camera is connected to the system, image processing can be used to extract parameters of growth such as leaf size and plant width. The parameters of the growing environment, light spectrum, temperature and more can thus be linked to the growth results. On this data, an AI model can be trained to predict the appropriate light spectrum for a desired outcome.

5 Conclusion

A system is created where users can mix different light spectra by adjusting their intensity. This can be done through the web interface that sends real-time information to and from the microcontroller. Multiple users can collaborate on this system without synchronization problems because each client gets updated when changes are made to the configuration. In addition to adjusting the light intensity of a light spectrum, users can set day and night cycles to automatically dim the LEDs on specific times. This is accomplished by obtaining the time utilizing NTP over an internet connection.

Different light spectra LEDs are soldered together on a single PCB specifically designed for optimized photon output and efficiency. This PCB along with the other hardware is mounted accordingly on a custom-made mount, ready for plant growth and research.

The software is written in C/C++ using object-oriented practices under an ESP-IDF framework. This results in uncluttered and extensible code base. And because of the I2C interface on the ESP32, the system is ready to be further expanded with sensors and or actuators.

6 Reference list

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7 Attachment

7.1 GitHub Repository

Attached is a GitHub repository named "LED_RESEARCH_SYSTEM" under the account CasTruyers. It contains the codebase and weekly reports for this project. The project is open source.

Link: https://github.com/CasTruyers/LED_Research_System