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Design and Analysis of LED-Based Artificial Plant-Growing Fixture for Vertical Indoor Farming Systems

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Abstract: The ability to perform photosynthesis with artificial lighting has eliminated the dependence on the sun in the agricultural industry. With the elimination of dependence on the sun, indoor plant production has been enabled by using artificial lighting in facilities such as vertical farming facilities. As a result of making soilless agriculture possible in vertical farming facilities, more organic and healthier plant production can be achieved as the plant is free from diseases and pests and therefore there is no need for pesticides. At the same time, thanks to the facilities to be established in city centers, the access process and cost of the plants grown will be reduced. In this study, the light needed for the growth of plants in the indoor vertical soilless agriculture facility was artificially designed using LED chips. In the luminaire(fixture) design, the wavelength and level of light can be adjusted according to the needs of plant growth periods. Comparative analyzes were made of the LED-based internal vertical luminaire design results carried out within the scope of the study and equivalent products used for the same purpose.

Keywords: Vertical farming, Plant-growing fixture, Indoor growth, LED-based fixture, Horticulture.

Introduction

The 21st century is an era where agricultural production methods change rapidly. As negative returns of the rapidly growing population, the decrease in the amount of land suitable for agriculture, the uncertainty and anomalies brought by climate changes as a result of global warming, the rapid depletion of natural resources as a result of the increase in production and consumption due to the increase in the world population, pose difficulties in food security and sustainability. The vertical farming industry is an innovative approach that can provide solutions to global problems such as food shortage by providing solutions to these challenges. This technology, which brings traditional horizontal agricultural fields to a vertical perspective, is a technology that has the potential to reshape the future of agriculture. (Bourget, 2008)

Effective use of technology is the key to the development of modern agriculture. One of the areas where technology is used most effectively in the agricultural sector is artificial lighting applications. By affecting the photosynthesis processes of plants through artificial lighting applications, more efficient products can be produced and time can be used more efficiently. In this way, the efficiency of operations in food production facilities is increased. With the more effective use of lighting technologies in modern agriculture, sustainable and efficient agricultural practices can be developed. (Shareef & Hannan, 2011)

Nowadays, control can be achieved over the growth rate of the plant and the efficiency obtained from the plant by using LED lighting systems, one of the modern lighting technologies. This control is achieved by using targeted light spectrums in LED lights. In agricultural applications, LEDs are used in indoor agricultural facilities and vertical farming facilities to play the role of sun and enable the plant to develop by providing the light it needs for photosynthesis. The color of the light emitted by LEDs varies depending on the type of semiconductor material used. The wavelengths of light emitted by LEDs vary from 250 nm (Ultraviolet) to 1000 nm (Infrared). LEDs are generally not dangerous, but care should be taken when using them in the ultraviolet range because these wavelengths can be dangerous to the eyes and skin when sufficient power is provided. General standards for LEDs are a supply voltage of 3V, a current of 350 mA and a power consumption of 3W. (Birkby, 2016)

In agricultural applications, LEDs are used in indoor agricultural facilities and vertical farming facilities to play the role of sun and enable the plant to develop by providing the light it needs for photosynthesis. In this study, a fixture containing LED light sources was designed to be used as an artificial light source in a vertical farming facility. The designed luminaire(fixture) provides the light needed by the plants with an adjustable brightness level in the spectrum range of 400 nm-850 nm.

A Strategic Approach: Urban Soilless Agroecosystems

The concept of indoor soilless vertical farming is touted as a solution to the food crisis that is predicted to arise with the increasing population, especially in large metropolises. In this context, it can be thought that it should be addressed as a strategic issue. Vertical farming systems should be evaluated for the following five basic points;

- space saving,
- saving water,
- season independent production and optimum climate control,
- disease and pest control,
- high production capacity

Establishing vertical farming facilities in city centers allows the products obtained to be delivered to consumers in a short time. This not only significantly shortens the time spent during logistics activities, but also ensures that the shelf life of the plants is long, and also provides energy and cost savings by reducing transportation activities with trucks, ships and planes in the logistics process. In addition, vertical farming facilities located in city centers provide employment for people living in the city center. (Rouphael et al., 2016)

Vertical farming facilities provide significant water savings compared to traditional agriculture. The main reason for this is that vertical farming systems have the ability to use and reuse water more efficiently. The use of water in vertical farming facilities is provided by hydroponic, aeroponic and aquaponic systems. Hydroponic and aeroponic systems enable the cyclical use of water. If we give an example of water saving in vertical farming facilities; While 400 liters of water are consumed to grow 1 kilogram of tomatoes in traditional agricultural methods, 70 liters of water are consumed in hydroponic systems and 20 liters in aeroponic systems. (Zhang et al., 2021)

Since vertical farming facilities are designed to be as isolated as possible from external influences, the plants grown are not affected by climate changes. Production can continue without interruption by providing optimum climatic conditions for the plant grown within the facility. Additionally, production efficiency can be maximized by applying the desired amount of light for the desired period of time, regardless of the day and night cycle. (Perdahcı et al., 2018).

Diseases and harmful organisms are inevitable in traditional open field agriculture. Vertical farming, on the other hand, takes place in a closed and controlled environment. This prevents diseases and harmful organisms from entering the agricultural field. Therefore, the risk of spreading harmful organisms and diseases in vertical farming facilities is much lower than in open field farming. Additionally, these closed systems also allow plants to be more resistant to diseases.

Due to the nature of vertical farming, the air circulation between plants has a positive effect on the development of the plant. This makes it harder for disease to spread between plants and improves the overall health of the plants. This air circulation between plants also contributes to faster plant growth and higher productivity. (Taiz et al., 2015)

In vertical farming, unlike traditional farming, the production per square meter is much higher as a result of placing and growing a series of plants on top of each other. Producing with vertical farming in the same area is much more efficient than producing with traditional agriculture. In addition, the fact that vertical farming facilities are closed and controlled areas makes it possible to optimize the growth conditions of plants. Providing light to the plant in the desired amount and for the desired duration, unlike sunlight, reduces the growing time of the plant. Thus, thanks to the space advantage and time advantage in vertical farming, the production capacity is much higher than in traditional agriculture. (Caglayan & Ertekin, 2018)

Plant-Growing LED Fixture Design

Within the scope of the study, the LED-based vertical farming luminaire was designed, the PID control card was designed to keep the operating temperature of the LED diodes under control, and the DALI master communication card was designed to control the luminaires within the facility.

Design Criteria and Materials

While designing the PCB, LEDs that can achieve intermediate wavelengths were selected. Placements were made on the luminaire where these selected LEDs could work with the best efficiency. While this settlement was being carried out, studies were carried out on online horticulture calculation tools. The output of the study is given in Figure 1.

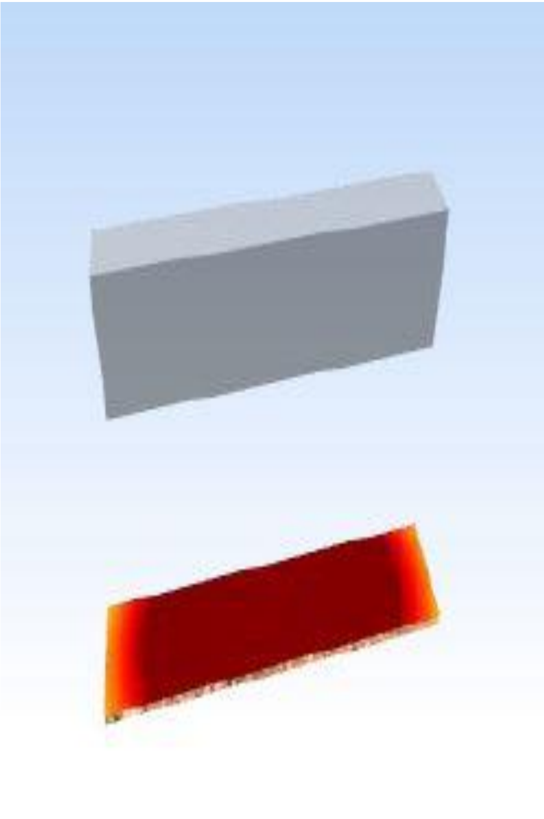

Figure 1. Horticulture calculation program image

A DALI luminaire driver suitable for separate luminaire power was used for each LED color on the PCB. Optical improvements have been made to the design and finish of the luminaire casing. Information about the LEDs used is given in Table 1.

Table 1. Features of the LEDs used

Variables	Wavelength (nm)	Forward Voltage(VF)	Forward Current(IF)	Color
LH351H Blue (Samsung)	450nm	2.86V	1000mA	Deep Blue
LH351H Red (Samsung)	730nm	1.9V	1000mA	Hyper Red
LH351 2W (Samsung)	660nm	2.07V	1000mA	Deep Red
LH351D (Samsung)	-	3.2V	3000mA	White

PID Control Card Design

A digital PID fan control circuit has been designed to keep the operating temperature of the LED luminaire at an ideal level and to ensure stabilization. PID control method is an automatic control system based on proportional, derivative and integral principles. By trying to keep the temperature value read from the NTC on the armature PCB at a constant value, when the PCB temperature rises, it increases the speed of our fans and contributes to cooling. When the temperature drops, the fan keeps the fan in balance by reducing the speed.

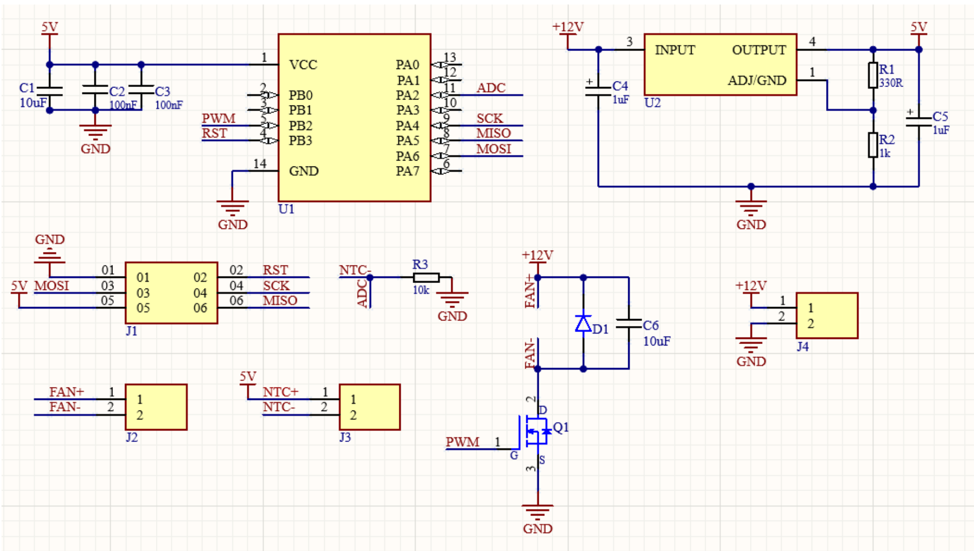

Figure 2. PCB schematic image

PCB schematic connections are given in Figure 2. The control card software is optimized to keep the temperature at a constant 40°.

DALI Master Communication Card Design

Within the scope of the project, DALI LED drivers were used to control the fixtures. DALI is a digital protocol that provides two-way data transmission for lighting systems. This protocol allows each LED driver to be controlled individually by giving an address, and 64 LED drivers can be connected to this system. Figure 3. shows the DALI Master PCB schematic connection.

In order to use this protocol, an intermediate converter circuit was designed and a communication protocol was written. According to the written software, the address and DIM value of each fixture is entered and controlled. Tested on 4 LED drivers. According to the results obtained, revision processes on the software continue.

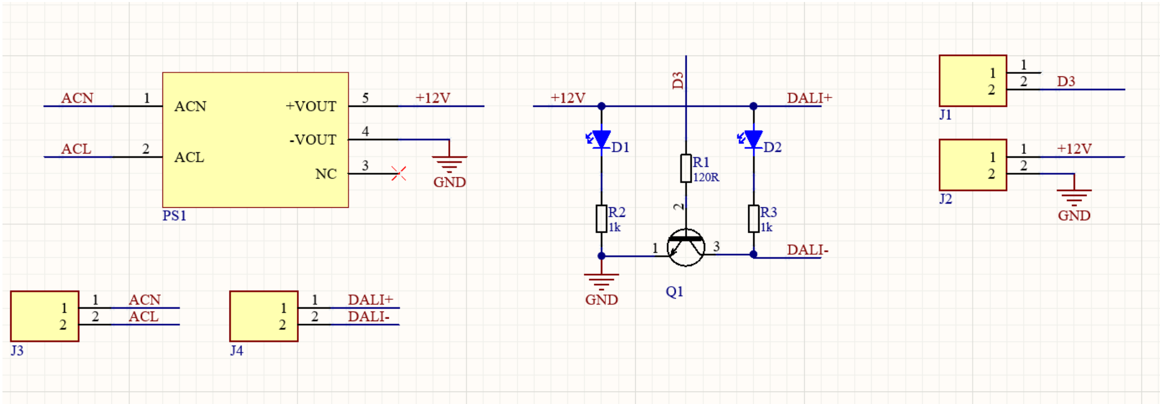

Figure 3. DALI master PCB schematic image

PCB Design

Separate PCB designs were made for the two different LED brands supplied. The number and sequence of LEDs to be used on a PCB were determined by performing various tests and applications. According to these studies, 20 of each LED were designed. These designed PCBs were typed and checked. The PCB design image is given in Figure 4.

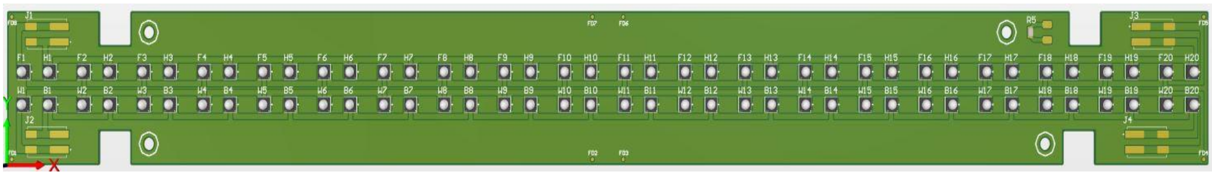

Figure 4. PCB image

Fixture External Body Design

The body design was made in accordance with the designed PCB. With the aim of passively distributing the heat of the designed body, prototype production was carried out on an aluminum block with dimensions of 40.6 mm x 406 mm on the cooling block. Figure 5. shows the luminaire body design components for which prototype production was carried out.

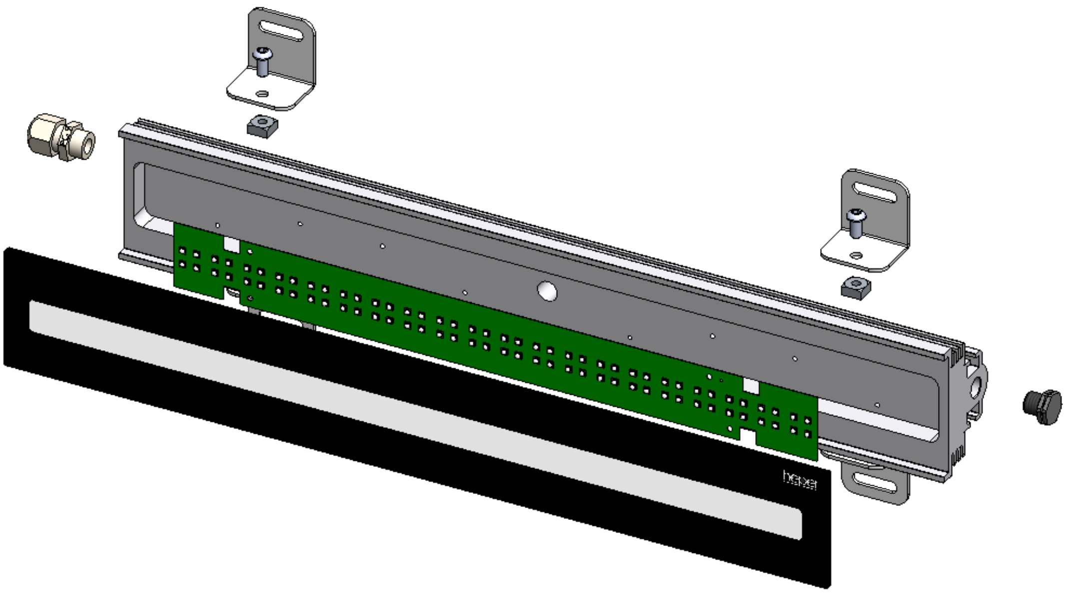

Figure 5. Luminaire body design components

The designed luminaire components were brought together and the product was brought to the prototype production point. The final version of the luminaire body design is seen in Figure 6. Thermal calculations were carried out to ensure that the designed luminaire could remain at optimum operating temperature. In this context, firstly the thermal resistance was calculated.

Figure 6. Luminaire body design image

When a voltage is applied to LED, current passes over semiconductor material and heat is created on LED under effect of this current. General formula of thermal resistance that will occur as a result of current passing is shown in Eq (1).

$$R_{a-b} = \frac{T_a - T_b}{P_{th}} \quad (1)$$

Thermal surface calculation formulas are calculated with the help of Equation 2-5 when heat sink channels are designed horizontally on ground:

$$P_d = P_{th} * (Verim) \quad (2)$$

$$T_{sp} = T_j - (R_{j-sp} * P_d) \quad (3)$$

$$T_{hs} = T_{sp} - (R_{sp-hs} * P_d) \quad (4)$$

$$R_{hs-a} = \frac{T_{hs} - T_a}{P_{th}} \quad (5)$$

P_d is amount of heat that must be cooled as a result of power consumed by LED. If an insulating material is used between LED and heat sink, value of R_{sp-hs} should be chosen between $0{,}2$ and $0{,}5$.

According to result obtained from eq. 5, required surface area for horizontal heat sink channels is calculated based on graphic in Figure 7. If heat sink channels are designed vertical to ground, horizontal surface wideness is calculated as follows (Sy):

$$S_y = \sqrt{P_d * 10} \quad (6)$$

In order to calculate required heat sink area per total watt of luminaire, surface areas calculated for both horizontal and vertical design must be collected. Material used as heat sink was chosen as aluminum because it is cheap and easy to process (Yuksel & Kıyak, 2020). Figure 7 is heat sink area-thermal conduction graph of aluminum (Antrak, 2023).

Solder point temperature (T_{sp}) value was taken as 76,82 °C, heat sink temperature (T_{hs}) 63,71°C, and ambient temperature (T_a) value as 26,27 °C in calculations conventional method calculations. Thickness value (R_{sp-hs}) between solder point and the heat sink was taken $0{,}2$ and the results were obtained. Resistance value of luminaire obtained as a result of resistance calculation by conventional method is 2,523 °C/W.

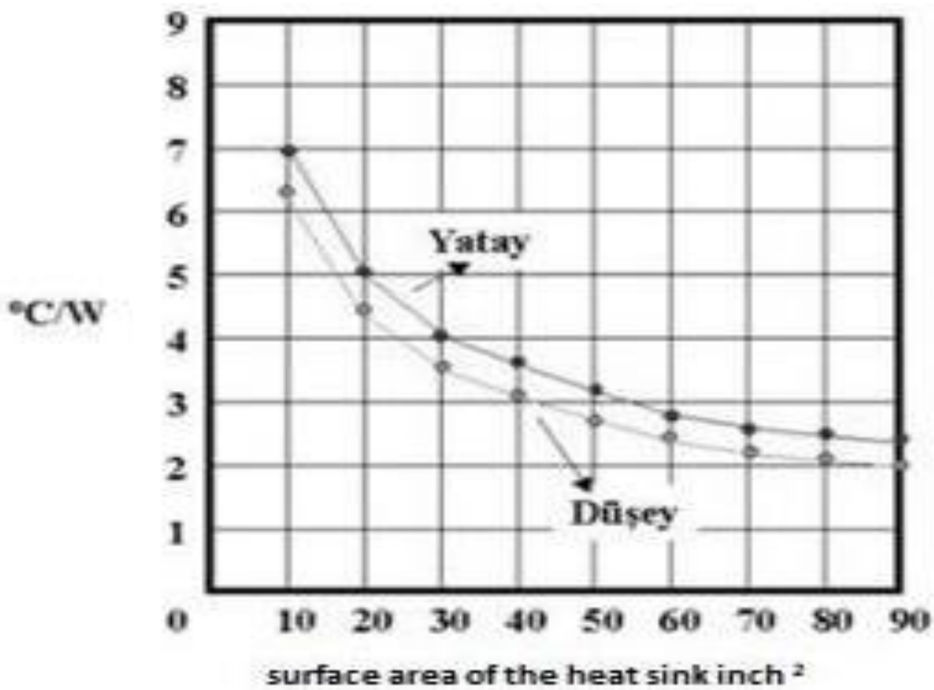

Figure 7. Heat sink area- thermal conduction

Design and Analysis Results

Testing and analysis of the body and PCB studies were carried out in a simulation environment and laboratory environment. Accordingly, analysis images of the designed armature are available below. The luminaire brightness analysis graph is seen in Figure 8.

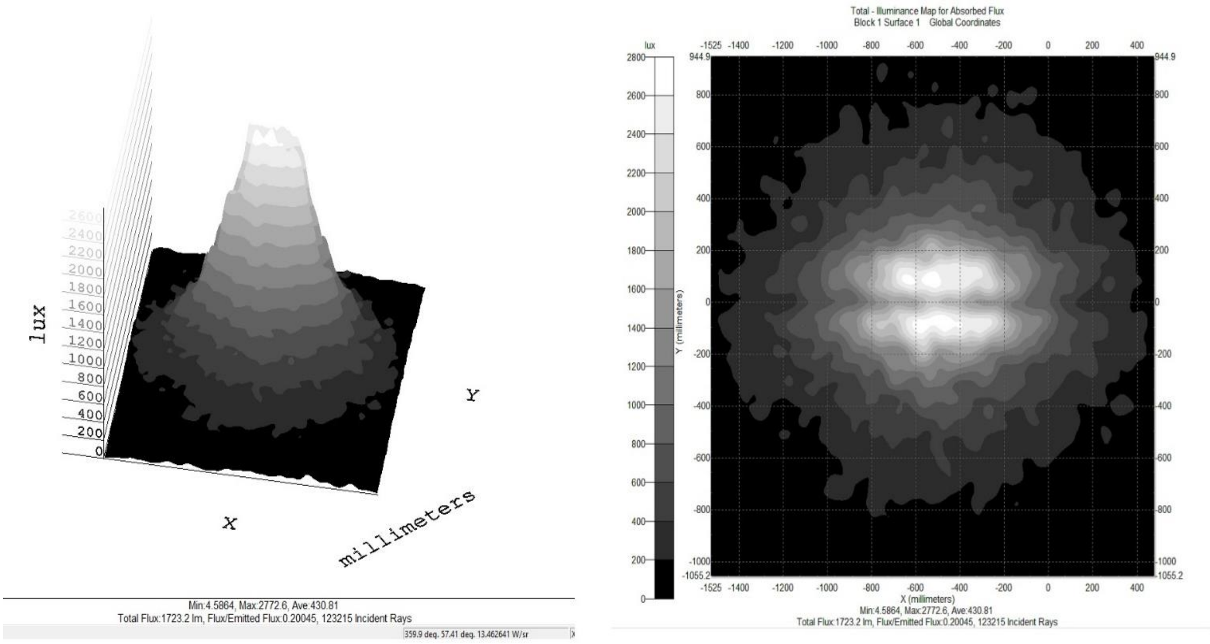

Figure 8. Luminaire(fixture) brightness analysis graph

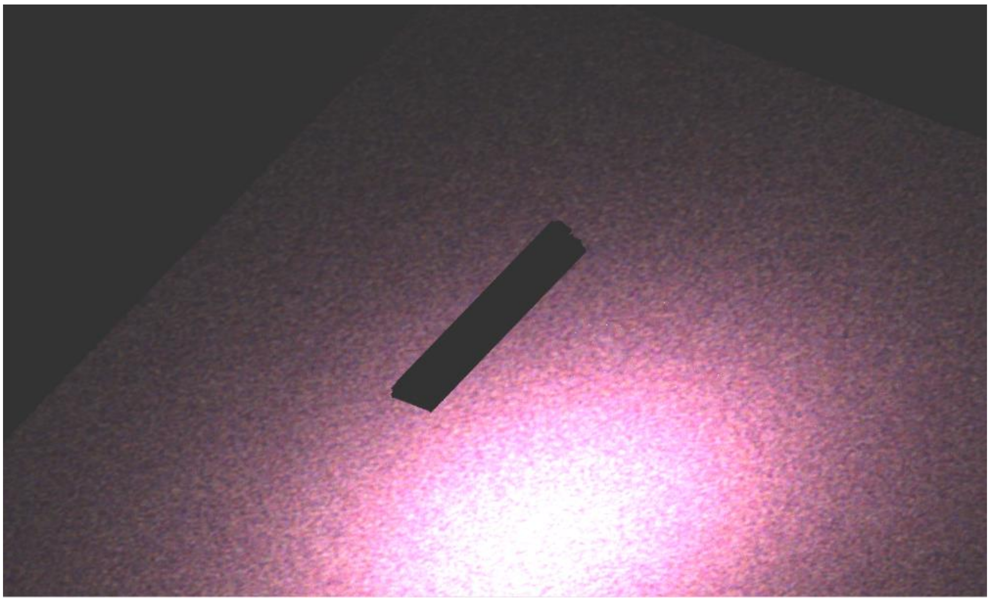

Figure 9. Real time rendered image of luminaire

The real-time rendered image of the designed luminaire is shown in Figure 9. The polar candela chart of the designed luminaire is shown in Figure 10.

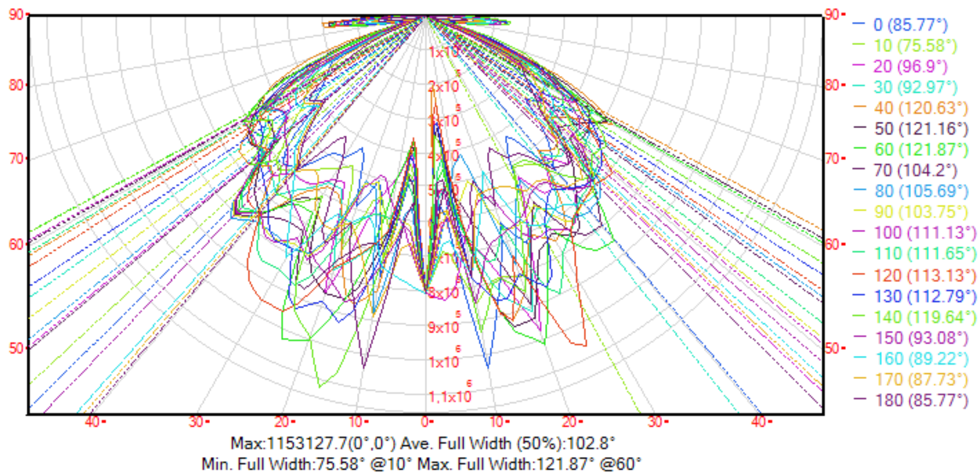

Figure 10. Polar candela chart.

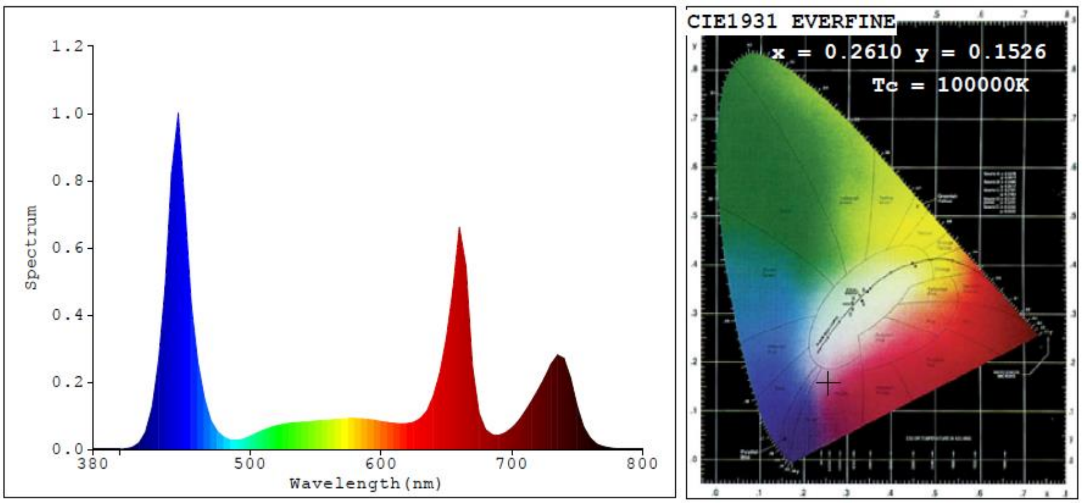

Figure 11. Spectrum analysis graph.

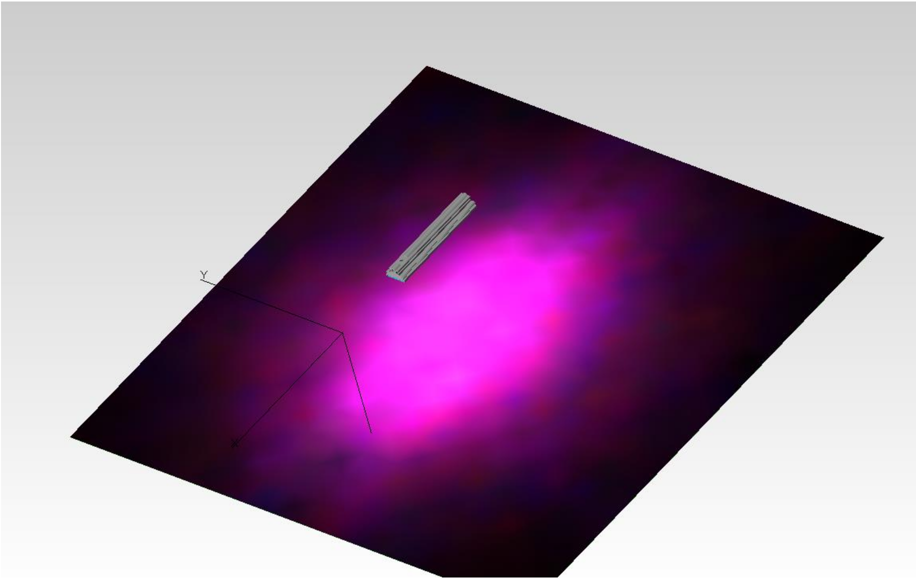

Figure 12. Simulation image.

Conclusion

The luminaire designed according to the data obtained as a result of the studies can provide illumination at the desired intermediate wavelengths. With the LED selection and driving technique, it can output any wavelength between 450nm and 780nm. A body design has been made that has passed thermal tests. Figure 11 shows the spectrum analysis obtained when all LEDs on the fixture are controlled with 350mA, and Figure 12 shows the analysis visual of this control data in the simulation environment.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements or Notes

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