

## EVALUATION OF THE DISTRIBUTION AND INTENSITY OF PHOTOSYNTHETICALLY ACTIVE RADIATION (PAR) EMITTED BY A MOBILE ROBOTIC PLATFORM TO IMPROVE PLANT GROWTH CONDITIONS

Athanasios MAKRIS, Ioannis GRAVALOS, Isaak KAVASIDIS, Zisis TSIROPOULOS

*University of Thessaly, Department of Agrotechnology, Gaiopolis, 41500, Larisa*

### **Abstract**

*This work focuses on the evaluation of a photosynthetically active radiation (PAR) emission system integrated into a mobile robotic platform, aiming to extend the photoperiod of long-day plants by irradiating them during nighttime or on overcast days. The mobile robotic platform is height-adjustable, while the PAR system is power-adjustable. Measurements were conducted over a 1.35 m<sup>2</sup> area, divided into 15 equal sections (30×30 cm each). In each section, PAR values were recorded for different operating power scenarios of the lighting system (36÷299 W) and for different height levels from the measurement surface. The results are displayed in the form of 3D plots, presenting the PAR distribution and the zones of high/low radiation intensity. The proposed system dynamically regulates the intensity of PAR radiation, providing light with photo regulatory characteristics that enhance the photosynthetic activity of plants.*

**Key words:** *plants; photoperiod; photosynthetically active radiation; robotics.*

### **INTRODUCTION**

One of the most important factors affecting the photosynthetic capacity of plants is Photosynthetically Active Radiation (PAR), defined as the spectrum of electromagnetic radiation between 400 and 700 nm, which is responsible for activating the photosynthetic mechanisms of plants (Ouzounis *et al.*, 2015). In modern controlled-environment cultivation systems, particularly in greenhouses or indoor farming setups, the use of artificial light sources has become essential for maintaining stable and extended photoperiods (Adams & Langton, 2005; Kozai *et al.*, 2016; Lozano-Castellanos *et al.*, 2025), in order to maintain optimal photosynthetic activity throughout the entire growth cycle. Light-Emitting Diode (LED) technology has emerged as the most efficient solution, offering high energy efficiency, extended lifespan, and the ability to spectrally tailor light to meet the specific needs of plants (Zou *et al.*, 2025).

Photoperiod - defined as the duration of light exposure within a 24-hour cycle - plays a pivotal role in regulating key developmental stages of plants, including flowering, leaf area expansion, and overall yield performance (Adams & Langton, 2005). Long-day plants, as opposed to short-day or day-neutral species, require extended periods of light to initiate their reproductive phase. In open-field cultivation systems, the total amount of incident solar radiation may be insufficient to meet the plants' light requirements during the growing season. Therefore, supplemental artificial lighting is often necessary, either to extend the photoperiod or to compensate for reduced irradiance on overcast days (Kuniga, 2020). However, the effectiveness of an artificial lighting system is not solely dependent on the intensity of emitted radiation. The uniform spatial distribution of PAR across the plant canopy is of critical importance, as it prevents the occurrence of photoinhibition and shading effects while minimizing energy losses. Non-uniform light distribution adversely affects plant growth and can ultimately lead to significant reductions in productivity (Wenxiong & Chengwei, 2019). At present, various artificial lighting systems are available that regulate PAR intensity (assimilation lighting), although most are not designed to actively control the photoperiod (Kozai *et al.*, 2016; Serrano-Bueno *et al.*, 2017). Nonetheless, studies evaluating the effectiveness of such systems in terms of PAR uniformity and required intensity under varying environmental and operational conditions remain scarce.

This study focuses on the evaluation of an artificial lighting system integrated into a mobile robotic platform, capable of dynamically adjusting both its vertical height and the operating power of the lighting unit. Moreover, the study contributes to a better understanding of how such a mobile lighting

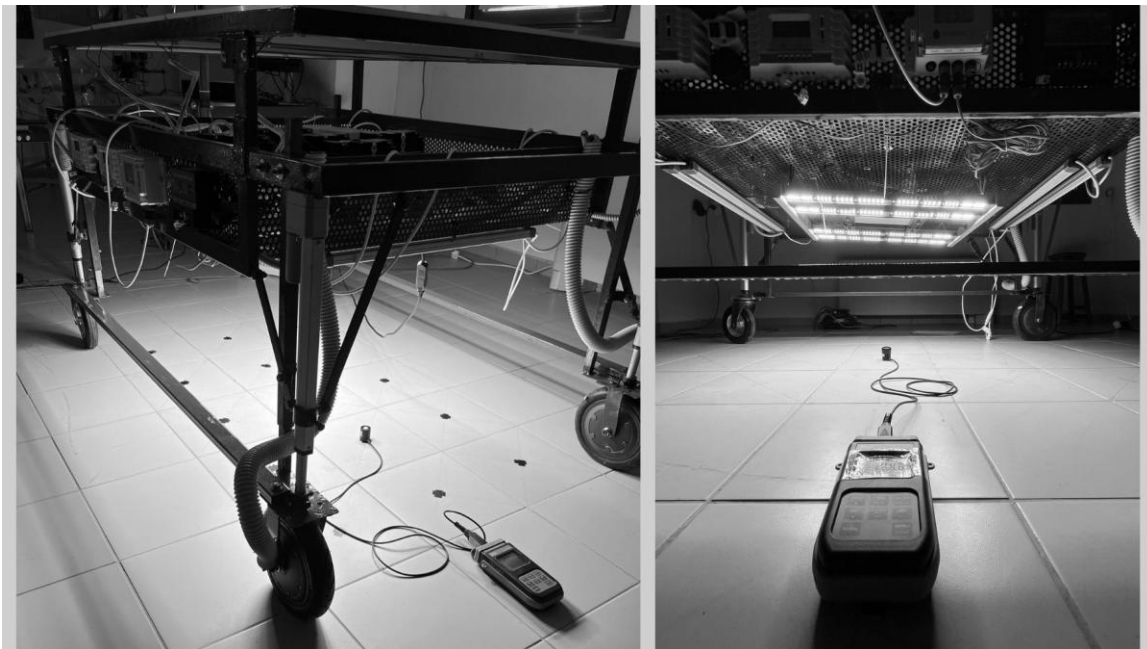
platform may be effectively utilized to enhance crop productivity. By analyzing the spatial distribution of PAR under different operational configurations, the aim is to inform improved management practices for artificial lighting systems applicable not only to open-field agriculture but also to urban and vertical farming contexts.

**MATERIALS AND METHODS**

This study evaluated the distribution and intensity of Photosynthetically Active Radiation (PAR) emitted by an artificial lighting system integrated into a mobile robotic platform (Figure 1), under various operational configurations. PAR measurements were conducted over a surface area of 1.35 m<sup>2</sup>, subdivided into 15 equal quadrants of 30×30cm. Data collection was performed at three different heights of the robotic platform (53, 68, and 83 cm above the measurement surface) and across multiple power settings. The power output ranged from 36 W (10% of the system’s rated power) up to 299 W (100% of rated power), incrementally increased during the measurements. To ensure consistency and eliminate measurement bias, the robotic platform remained stationary throughout all experimental trials.

The artificial lighting system used was a full-spectrum LED fixture emitting in the 400–700 nm range, corresponding to the PAR spectrum. It offers precise intensity regulation between 10% and 100% of its maximum power and is designed to support all stages of plant growth, from germination to flowering and fruiting. It includes broad-spectrum white light for overall photosynthetic support, blue light (400–500 nm) to promote leaf and root development (Terfa et al., 2012), green light (500–600 nm) to penetrate deeper into the plant canopy and enhance photosynthesis (Shafiq et al., 2021), and red light (635–665 nm), which is critical for flowering and fruit production (Aliniaiefard et al., 2018).

PAR intensity was recorded using equipment from the Italian manufacturer Senseca, consisting of a quantum radiometric probe (LP471PAR02) with a spectral sensitivity of 400–700 nm, accuracy of ±5%, and resolution of 0.1 μmol/m<sup>2</sup>/s, paired with a data logger (HD2102.1). At each measurement point, the sensor was allowed to stabilize for two minutes to minimize transient errors, and each reading was repeated three times. The quantum sensor was placed at the center of each section to ensure uniform data collection. All measurements were conducted under controlled environmental conditions, with the exclusion of external light sources, to guarantee measurement accuracy and repeatability. Data were stored in an Excel file and later processed using Python, specifically the Pandas, Matplotlib, and Seaborn libraries.



**Fig. 1** Mobile robotic platform with integrated artificial lighting system.

Photosynthetic Photon Flux Density (PPFD) is a key measured parameter for evaluating the intensity of photosynthetically active radiation (PAR) reaching the surface of plants. It is expressed in units of

$\mu\text{mol}/\text{m}^2/\text{s}$  and refers to the number of photons within the 400–700 nm spectrum that strike a unit of surface area per second (Ge *et al.*, 2011; Nelson & Bugbee, 2014a; Ritchie, 2010). PPF is critical for understanding photosynthetic activity, as plants primarily respond to the quantity of photons rather than the energy of light. In controlled agriculture applications, PPF is used to adjust the intensity of artificial lighting in order to ensure optimal photosynthetic efficiency depending on the plant's growth stage (Kozai *et al.*, 2016). PPF is measured using quantum sensors, which have a spectral response tailored to the PAR spectrum. PPF values vary depending on the plant species and developmental stage, with typical values ranging from 100–300  $\mu\text{mol}/\text{m}^2/\text{s}$  for seedlings and up to 600–1000  $\mu\text{mol}/\text{m}^2/\text{s}$  for mature plants (Ouzounis *et al.*, 2015)

To evaluate the performance of the lighting system, two key parameters were calculated: the coefficient of uniformity ( $C_U$ ) and the system's photon efficiency (PE). Uniformity was calculated using equation (1).

$$C_U = \frac{E_{\min}}{E_{\text{avg}}} \quad (1)$$

where  $E_{\min}$  is the minimum measured PAR value across the 15 points, and  $E_{\text{avg}}$  is the average PAR. This index evaluates the spatial distribution of the radiation.

The energy efficiency of the artificial lighting system is assessed using the Photosynthetic Photon Efficacy (PPE) index, which expresses the amount of photosynthetically active photons (PPF) emitted per unit of electrical power consumed (Kozai *et al.*, 2016; Nelson & Bugbee, 2014). Photosynthetic Photon Flux (PPF) refers to the total rate of photon emission in the photosynthetically active radiation (PAR) range of 400–700 nm, measured in  $\mu\text{mol}/\text{s}$ . In experimental settings where PPF (photosynthetic photon flux density) is measured at multiple points, the total PPF can be estimated using the equation (2).

$$PPF \approx PPF_{\text{avg}} \times A \quad (2)$$

where  $PPF_{\text{avg}}$  is the average photosynthetic photon flux density (in  $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ ), derived from  $n$  point measurements across the cultivation surface and  $A$  is the total illuminated area ( $\text{m}^2$ ). Once the PPF has been calculated, PPE is determined as equation (3):

$$PPE = \frac{PPF}{P} \quad (3)$$

The resulting unit  $\mu\text{mol}/\text{J}$  (or equivalently  $\mu\text{mol}/\text{W} \cdot \text{s}$ ) allows for comparing the photosynthetic performance of different lighting systems regardless of their total power input. Higher PPE values indicate greater efficiency in delivering useful light for photosynthesis.

## RESULTS AND DISCUSSION

The energy efficiency of the artificial lighting system, as expressed by the PPE index ( $\mu\text{mol}/\text{J}$ ), is strongly influenced by both the electrical power input and the distance between the light source and the target surface. According to the results, as shown in Figure 2, the maximum efficiency was achieved at a height of 53 cm and a power level of 94 W, yielding a PPE of 1.83  $\mu\text{mol}/\text{J}$ . However, when the power input exceeded 150 W, the PPE values consistently declined across all tested height levels, indicating reduced energy efficiency at higher power settings. Furthermore, increasing the height of the light source from 53 cm to 68 cm and subsequently to 83 cm resulted in a consistent decline in PPE, confirming the impact of distance in accordance with the inverse square law. This finding is consistent with the results reported by Sheibani *et al.* (2023), who demonstrated that reducing the distance between the LED source and the plant canopy significantly improved energy efficiency, as plant growth was achieved with lower energy consumption. Their study highlights that increasing the distance of the light source tends to reduce the overall effectiveness of energy use in crop lighting systems. Additionally, Sheibani *et al.* (2023) highlight light losses associated with the wide emission angle of LEDs, which follow a Lambertian distribution, resulting in a significant portion of photons being lost outside the cultivation zone. In addition to energy efficiency, light uniformity also plays a crucial role. Light uniformity, as expressed by the Coefficient of Uniformity ( $C_U$ ), increases steadily with the height of the lighting system. As shown in Figure 2, at a low height of 53 cm,  $C_U$  remains low at 0.33, indicating significant non-uniformity. At a medium height of 68 cm,  $C_U$  reaches approximately 0.47, offering a balance between light intensity and distribution. At the highest level of 83 cm,  $C_U$  reaches its maximum value of 0.59, indicating high uniformity independent of power level. Therefore,

the optimal selection of lighting height and power depends on the application requirements: if energy efficiency is prioritized, a height of 53 cm with 94 W is preferred, while for enhanced light uniformity, 83 cm is recommended. For a combination of efficiency and uniformity, the 68 cm height with 154 W provides the most balanced option. These findings are also supported by the study of *Hwa-Soo et al. (2014)*, in which optimization of lighting arrangement parameters (including the mounting height of the light sources) resulted in a 15% increase in lighting uniformity. Moreover, it was observed that increasing the height was associated with improved uniformity, despite a reduction in the average light intensity on the target surface.

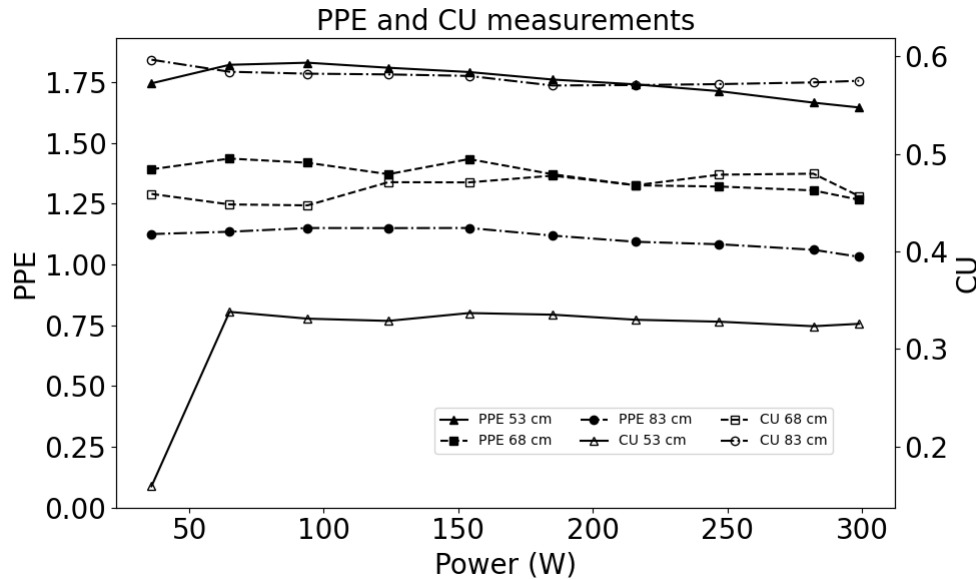


Fig. 2 diagram of PPE and CU measurements

To better understand the spatial distribution of radiation across the analyzed surface, 3D plots were generated for each combination of height and power of the artificial lighting system. Figure 3 illustrates the three-dimensional distribution of PPFD for all heights at 124 W and 217 W. At a height of 53 cm, the measurements exhibit prominent central peaks in the central region, indicating high radiation intensity, but with considerable non-uniformity, as the intensity decreases sharply toward the edges. At 83 cm, the surface shows a much more gradual distribution, with reduced overall intensity but improved uniformity across the entire area. The intermediate height of 68 cm presents a more balanced distribution, with smoother transitions in intensity that reflect a trade-off between strength and uniformity. The use of such graphical tools has been recognized as a valuable methodology in crop lighting studies, as it enables a direct and qualitatively comparable interpretation of light diffusion, as also demonstrated in the study by *Hwa-Soo et al. (2014)*.

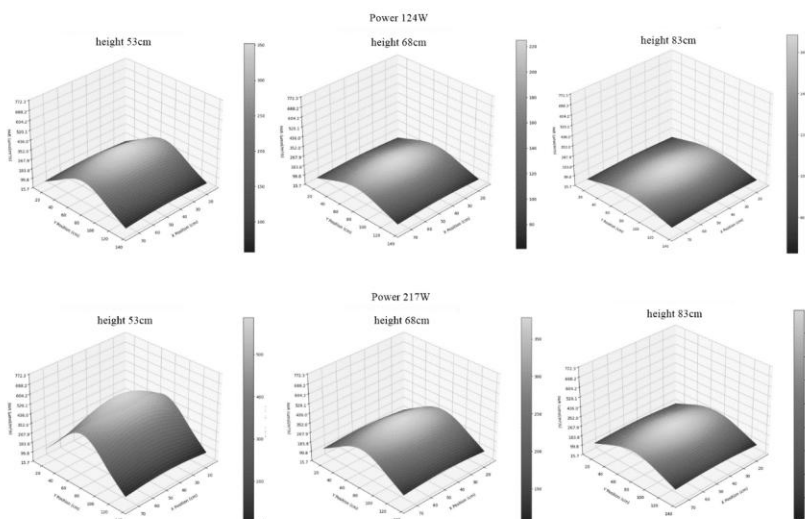


Fig. 3 3D PPFD distribution map for 124 W, 217 W and different heights.

## CONCLUSION

This study demonstrates the technical and operational reliability of the mobile robotic platform equipped with a full-spectrum artificial lighting system. The maximum Photosynthetic Photon Efficacy (PPE) value  $1.83 \mu\text{mol/J}$  was achieved at a height of 53 cm and power of 94 W, indicating that optimal efficiency is attained at intermediate power levels and short distances from the target surface. Increasing the height of the light source from the measurement surface progressively improved the uniformity of illumination ( $C_U$ ), with the highest value of 0.59 recorded at 83 cm. This finding underscores the importance of the platform's geometric configuration of the robotic platform in achieving uniform PAR distribution across the measurement surface. The platform's ability to adjust height and modify electrical power offers significant advantages in extending the photoperiod for long-day plants, and the technical analysis presented herein may serve as a guide for the deployment of such technologies in precision agriculture and controlled environment applications

## REFERENCES

- Adams, S. R., & Langton, F. A. (2005). Photoperiod and plant growth: A review. In *Journal of Horticultural Science and Biotechnology* (Vol. 80, Issue 1, pp. 2–10). Headley Brothers Ltd. <https://doi.org/10.1080/14620316.2005.11511882>.
- Aliniaiefard, S., Seif, M., Arab, M., Mehrjerdi, M. Z., Li, T., & Lastochkina, O. (2018). Growth and Photosynthetic Performance of *Calendula Officinalis* under Monochromatic Red Light. *International Journal of Horticultural Science and Technology*, 5(1), 123–132 <https://doi.org/10.22059/ijhst.2018.261042.248>.
- Ge, S., Smith, R. G., Jacovides, C. P., Kramer, M. G., & Carruthers, R. I. (2011). Dynamics of photosynthetic photon flux density (PPFD) and estimates in coastal northern California. *Theoretical and Applied Climatology*, 105(1), 107–118 <https://doi.org/10.1007/s00704-010-0368-6>.
- Hwa-Soo, L., Sook-Youn, K., & Jae-Hyun, L. (2014). Improvement of light uniformity by lighting arrangement for standardized crop production. *Journal of Central South University*, 21(11), 4311-4319.
- Kozai, T., Fujiwara, K., & Runkle, E. S. (2016). LED lighting for Urban agriculture. In *LED Lighting for Urban Agriculture*. Springer Singapore <https://doi.org/10.1007/978-981-10-1848-0>.
- Kuniga, T. (2020). Modification of the Light Environment Influences the Production of Horticultural Crops <https://doi.org/10.6090/jarq.54.285>.
- Lozano-Castellanos, L. F., Navas-Gracia, L. M., Lozano-Castellanos, I. C., & Correa-Guimaraes, A. (2025). Technologies Applied to Artificial Lighting in Indoor Agriculture: A Review. In *Sustainability* (Switzerland) (Vol. 17, Issue 7). Multidisciplinary Digital Publishing Institute (MDPI). <https://doi.org/10.3390/su17073196>

8. Nelson, J. A., & Bugbee, B. (2014). Economic analysis of greenhouse lighting: Light emitting diodes vs. high intensity discharge fixtures. *PLoS ONE*, 9(6). <https://doi.org/10.1371/journal.pone.0099010>
9. Ouzounis, T., Rosenqvist, E., & Ottosen, C. O. (2015). Spectral effects of artificial light on plant physiology and secondary metabolism: A review. In *HortScience* (Vol. 50, Issue 8). <https://doi.org/10.21273/hortsci.50.8.1128>.
10. Serrano-Bueno, G., Romero-Campero, F. J., Lucas-Reina, E., Romero, J. M., & Valverde, F. (2017). Evolution of photoperiod sensing in plants and algae. In *Current Opinion in Plant Biology* (Vol. 37, pp. 10–17). Elsevier Ltd. <https://doi.org/10.1016/j.pbi.2017.03.007>
11. Shafiq, I., Hussain, S., Raza, M. A., Iqbal, N., Asghar, M. A., Raza, A., ... & YANG, F. (2021). Crop photosynthetic response to light quality and light intensity. *Journal of Integrative Agriculture*, 20(1), 4-23. [https://doi.org/10.1016/S2095-119\(20\)63227-0](https://doi.org/10.1016/S2095-119(20)63227-0)
12. Sheibani, F., Bourget, M., Morrow, R. C., & Mitchell, C. A. (2023). Close-canopy lighting, an effective energy-saving strategy for overhead sole-source LED lighting in indoor farming. *Frontiers in Plant Science*, 14, 1215919
13. Terfa, M., Poudel, M., Roro, A., Gislerød, H., Olsen, J., & Torre, S. (n.d.). Light Emitting Diodes with a High Proportion of Blue Light Affects External and Internal Quality Parameters of Pot Roses Differently than the Traditional High Pressure Sodium Lamp.
14. Wenxiong, Y., & Chengwei, M. (2019). Design and Development of Light Radiation Testing Equipment for Solar Greenhouse. In *E3S Web of Conferences* (Vol. 136, p. 02042). EDP Sciences. Zhang, X., Zhang,
15. Zou, J., Wang, Z., Huang, H., Huang, X., & Shi, M. (2025). A Low-Energy Lighting Strategy for High-Yield Strawberry Cultivation Under Controlled Environments. *Agronomy*, 15(5). <https://doi.org/10.3390/agronomy15051130>

**Corresponding author:**

Athanasios Makris, Ph.D Candidate, Department of Agrotechnology, Faculty of Agricultural Science, University of Thessaly, Gaiopolis Campus, Larissa - Trikala Ring - Road, Larissa, Greece, 41500, phone: +30 2410684286, e-mail: [athanmakris@uth.gr](mailto:athanmakris@uth.gr)