# Optimizing Photosynthetic Photon Flux Density (PPFD) through Advanced LED Arrangements: A Comprehensive Analysis of Uniformity and the Integrated Photosynthetic Performance Metric (IPP)

Austin Rouse, Founder at LED Cultivation

***Abstract*—Traditional plant lighting systems, while effective, have been constrained by an emphasis on raw power and luminous output, often leading to the 'hot spot' phenomenon - a significant non-uniformity in photon distribution. This paper introduces an innovative methodology that resolves these limitations. By employing a patented COB LED configuration, integrated with a novel wireless lighting control system and advanced lighting simulation software, we achieve a controllable photosynthetic photon flux density (PPFD) with a near-optimal degree of uniformity (DOU) across any spatial dimension. Central to our approach is the novel Integrated Photosynthetic Performance (IPP) metric, which redefines the conventional understanding and calculation of photosynthetic photon efficacy (PPE) and the daily light integral (DLI). With a demonstrated DOU exceeding 99.49%, our system not only addresses the challenges of traditional lighting but also underscores the profound benefits of uniform photon distribution. Drawing insights from recent academic research, we highlight the transformative impact near-optimal uniformity could have on plant growth, from enhancing photosynthetic rates to preserving the vitality of lower leaves. This convergence of technology and horticulture paves the way for a new era in horticultural lighting, setting a diamond standard for future innovations.**

***Index Terms*—Plant Growth, Lighting Measurement, Uniformity Analysis, Daily Light Integral (DLI), Photosynthetic Photon Flux Density (PPFD), Plant Factories with Artificial Lighting (PFAL)**

## I. Introduction

Plant lighting systems have long been a cornerstone in horticultural practices, facilitating controlled growth environments independent of natural light conditions. Historically, these systems have prioritized raw power and luminous output, metrics that, while important, overlook the nuanced intricacies of light distribution. The prevalent 'hot spot' phenomenon, characterized by a concentration of photons in the center of the coverage area, has been a persistent challenge. Coupled with this is the 'canopy penetration' issue, where traditional approaches have sought to overcome the shielding effect of upper leaves on lower foliage, often with suboptimal results. The non-uniformity associated with the 'hot spot' phenomenon not only compromises plant growth but also underscores the limitations of traditional lighting systems. In this paper, we delve into a transformative methodology that addresses these challenges head-on, leveraging cutting-edge technology and novel metrics to redefine horticultural lighting.

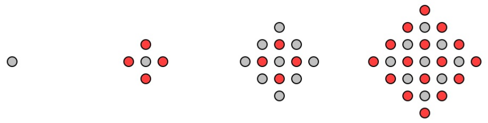
## II. Methodology

At the heart of our approach is the patented COB LED configuration. This unique arrangement, when integrated with our innovative wireless lighting control system and proprietary lighting simulation software, allows for unprecedented control over PPFD. The system's ability to modulate LED intensities based on their positions within concentric square layers of the array, combined with predictive insights from our software, ensures a near-optimal degree of uniformity (DOU) across any spatial dimension.

Central to our discourse is the introduction of the Integrated Photosynthetic Performance (IPP) metric. This novel metric offers a fresh perspective on photosynthetic photon efficacy (PPE) and the daily light integral (DLI), challenging conventional understandings and establishing a paradigm shift for how the efficacy of plant lighting systems is measured and represented.

## II.1 Patented Chip-on-Board (COB) LED Configuration

The arrangement logic for the patented COB LED configuration, protected under Patent #US10687478B2 - "Optimized LED Lighting Array for Horticultural Applications," is predicated on the centered square number integer sequence. This sequence forms the mathematical foundation for the diamond pattern, which is the core of the LED arrangement logic. The established claims in this patent cover any order of the centered square number integer sequence, and therefore every embodiment of the diamond pattern with COBs for horticultural applications.



$C_{4,1} = 0 + 1$ $C_{4,2} = 1 + 4$ $C_{4,3} = 4 + 9$ $C_{4,4} = 9 + 16$

Fig. 1: Diamond pattern logic based on the centered square number integer sequence [1].

The pattern logic is illustrated in Figure 1, while Figure 2 depicts the transformation of the diamond pattern into a completed square array of equidistantly arranged COBs. This pattern logic is infinitely expandable, continuing ad infinitum. The patent protects any order of COBs in this specific LED arrangement strategy for horticultural applications, facilitating the coverage of any size space using this method.

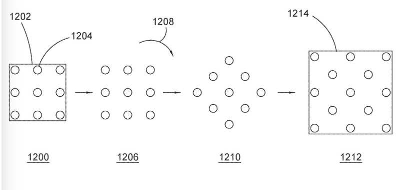


Fig. 2: Transformation of diamond pattern logic into a completed square array [2].

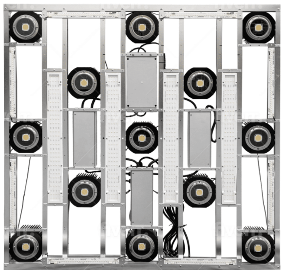


Fig. 3: One embodiment of the patented COB LED arrangement - Lights Off [3].

Fig. 4: One embodiment of the patented COB LED arrangement - Lights On [4].

Figures 3 and 4 demonstrate an embodiment of the patented COB LED arrangement logic.

## II.2 Modular Diamond Pattern Arrangement System

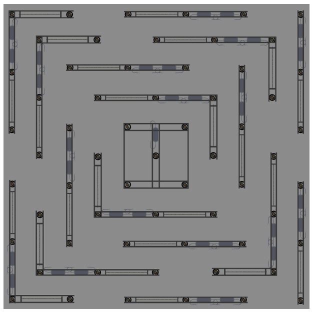


Fig. 5: Another embodiment of the patented COB LED arrangement logic (61 COBs) [5].

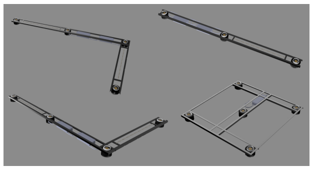


Fig. 6: The four fixtures which comprise all embodiments of the patented COB LED arrangement logic [6].

Figure 6 shows the set of modular pieces needed to create the modular diamond pattern arrangement system in any size with any amount of COBs. The fixtures are comprised of COBs with heatsinks and the driver that powers them, mounted to an aluminum frame, which serves as the primary light output for the array. There is also a smaller driver that powers SMD LED strips, which are positioned along the frame. These SMD LED strips can comprise different color configurations (e.g. '660nm Red = R', '730nm Infrared = IR', '437nm Blue = B' → 'B-R-R-B-IR-B-R-R-B-IR…') to output desired spectrums, depending on the specific horticultural application requirements. The system is installed by simply hanging these light fixtures with a specified degree of spacing between each other and distance from the floor surface. Then they are plugged in / setup with the wireless lighting control system and the install is complete.

## II.3 Wireless Lighting Control System

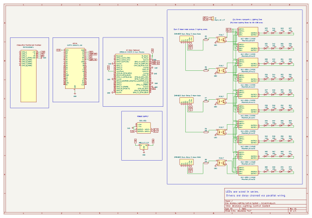


Fig. 7: Schematic for the wireless lighting control system [7].

Figure 7 shows a schematic for the wireless lighting control system, which is critical for achieving the results that this methodology produces. Each driver that powers the LED fixtures is paired with a Z-Wave node that communicates with a Z-Wave module. The Z-Wave module serves as the network gateway and enables control of all of the LED fixtures' intensities via a capacitive touchscreen display that serves as the central control hub for the system.

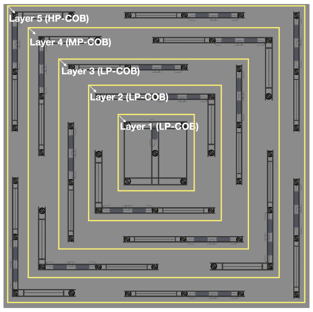
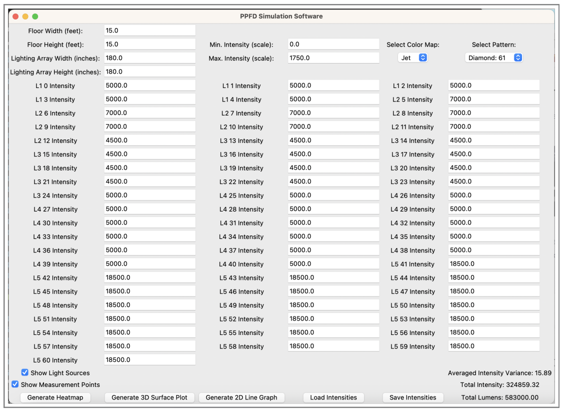


Fig. 8: Illustration for concentric square layer intensity modulation [8].

In Figure 8 there are yellow squares forming successive concentric squares around the midpoint of the COB array. The fixtures within each of these layers are separately controlled, and the intensity of each layer is modulated to a specified degree based on predictions made by our proprietary lighting simulation software. The specified intensity modulations of each concentric square layer of LEDs around the midpoint of the COB array result in near-optimal uniformity for any desired density of PAR in any size space.

## II.4 Proprietary Lighting Simulation Software



PPFD Simulation Software

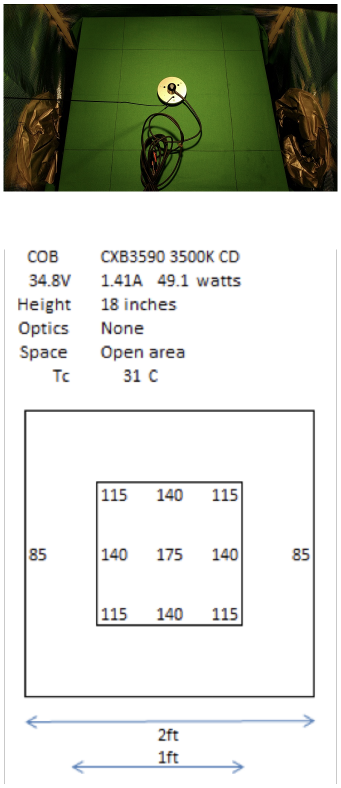
| | | | | | |
|---|---|---|---|---|---|
| Floor Width (feet): | 15.0 | | | | |
| Floor Height (feet): | 15.0 | Min. Intensity (scale): | 0.0 | Select Color Map: | Select Pattern: |
| Lighting Array Width (inches): | 180.0 | Max. Intensity (scale): | 1750.0 | Jet | Diamond: 61 |
| Lighting Array Height (inches): | 180.0 | | | | |
| L1 0 Intensity | 5000.0 | L1 1 Intensity | 5000.0 | L1 2 Intensity | 5000.0 |
| L1 3 Intensity | 5000.0 | L1 4 Intensity | 5000.0 | L2 5 Intensity | 7000.0 |
| L2 6 Intensity | 7000.0 | L2 7 Intensity | 7000.0 | L2 8 Intensity | 7000.0 |
| L2 9 Intensity | 7000.0 | L2 10 Intensity | 7000.0 | L2 11 Intensity | 7000.0 |
| L2 12 Intensity | 4500.0 | L3 13 Intensity | 4500.0 | L3 14 Intensity | 4500.0 |
| L3 15 Intensity | 4500.0 | L3 16 Intensity | 4500.0 | L3 17 Intensity | 4500.0 |
| L3 18 Intensity | 4500.0 | L3 19 Intensity | 4500.0 | L3 20 Intensity | 4500.0 |
| L3 21 Intensity | 4500.0 | L3 22 Intensity | 4500.0 | L3 23 Intensity | 4500.0 |
| L3 24 Intensity | 5000.0 | L4 25 Intensity | 5000.0 | L4 26 Intensity | 5000.0 |
| L4 27 Intensity | 5000.0 | L4 28 Intensity | 5000.0 | L4 29 Intensity | 5000.0 |
| L4 30 Intensity | 5000.0 | L4 31 Intensity | 5000.0 | L4 32 Intensity | 5000.0 |
| L4 33 Intensity | 5000.0 | L4 34 Intensity | 5000.0 | L4 35 Intensity | 5000.0 |
| L4 36 Intensity | 5000.0 | L4 37 Intensity | 5000.0 | L4 38 Intensity | 5000.0 |
| L4 39 Intensity | 5000.0 | L4 40 Intensity | 5000.0 | L5 41 Intensity | 18500.0 |
| L5 42 Intensity | 18500.0 | L5 43 Intensity | 18500.0 | L5 44 Intensity | 18500.0 |
| L5 45 Intensity | 18500.0 | L5 46 Intensity | 18500.0 | L5 47 Intensity | 18500.0 |
| L5 48 Intensity | 18500.0 | L5 49 Intensity | 18500.0 | L5 50 Intensity | 18500.0 |
| L5 51 Intensity | 18500.0 | L5 52 Intensity | 18500.0 | L5 53 Intensity | 18500.0 |
| L5 54 Intensity | 18500.0 | L5 55 Intensity | 18500.0 | L5 56 Intensity | 18500.0 |
| L5 57 Intensity | 18500.0 | L5 58 Intensity | 18500.0 | L5 59 Intensity | 18500.0 |
| L5 60 Intensity | 18500.0 | | | | |

☑ Show Light Sources
☑ Show Measurement Points

Averaged Intensity Variance: 15.89
Total Intensity: 324859.32
Total Lumens: 583000.00

Fig. 9: Graphical User Interface (GUI) for our proprietary lighting simulation software [9].

Physics-based lighting simulation software was developed with several features. In the GUI the user can define the floor width / floor height of the simulated space, lighting array width / lighting array height for the simulated COB array, min. / max. intensity scale of the heatmap / 3D surface plot, color scheme of the heatmap / 3D surface plot, different diamond pattern / standard grid size options for the arrangement of simulated light sources, and the ability to assign specific luminous intensities to each LED in the simulated COB array. They then have the option to generate a heatmap or 3D surface plot to visualize the PPFD distribution and they can also generate a 2D line graph to visualize the intensity variance between each measurement point.



| | |
|---|---|
| COB | CXB3590 3500K CD |
| 34.8V | 1.41A 49.1 watts |
| Height | 18 inches |
| Optics | None |
| Space | Open area |
| Tc | 31 C |

Fig. 10: Third-party measurements of a single COB in an open area [10].

**Height from floor surface** = 18 inches
**Optics** = none
**Space type** = open area
**Beam angle** = 115-degrees
**Lumens** = 7,350
**Tc** = 31 celsius

Figure 10 shows measurements taken by a third-party of a single CXB3590 3500K COB in a 2-foot by 2-foot space with an SQ-120 quantum sensor from Apogee Instruments.

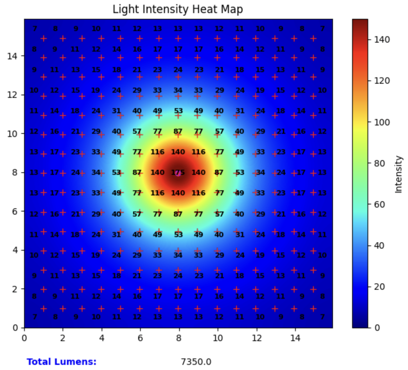


Fig. 11: Simulation of a single CXB3590 3500K CD COB with same conditions as third-party test [11].

The heatmap shown in Figure 11. was generated by employing a Lambertian distribution function. This function takes into account the specific beam angle of the light source and the distance to each measurement point, enabling a realistic and precise calculation of light intensity throughout the modeled space. It can be seen that the intensity values produced by the simulation are nearly identical to those in the third-party test.

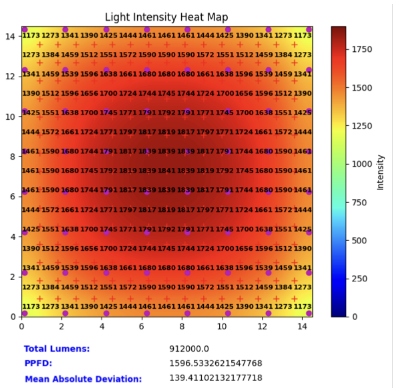


Fig. 12: Heatmap generated for simulation of an 8x8 grid of 64 COBs arranged in a uniform matrix of straight rows and columns, with the same intensity value assigned to each COB [12].

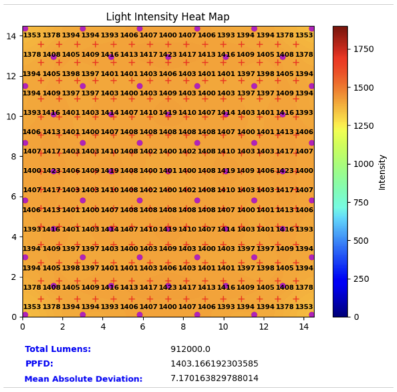


Fig. 13: Heatmap generated for simulation of 61 COBs arranged in the diamond pattern with varying intensities assigned to the COBs, according to their positions within the concentric square layers [13].

Figures 12 and 13 show heatmaps for two different simulations of a 15-foot by 15-foot space with 225 measurement points spanned across the space in a 15x15 grid, with each LED array being positioned 18-inches from the floor surface.

**Simulations**:
**1.** An 8x8 grid of 64 COBs arranged in a uniform matrix of straight rows and columns
**2.** A 61 COB array in the diamond pattern arrangement with specified intensities assigned to the COBs according to their position within the concentric square layers of the array, as determined by our lighting simulation software.

Each purple dot on the heatmap represents a single COB in the array, and each red '+' sign represents one of the 225 measurement points that span the simulated space in a 15x15 grid, and are illuminated by the simulated COB array.

## Calculating Intensity

The light intensity at each measurement point is calculated based on the luminous intensity assigned to each light source, the distance between each light source and each measurement point, the beam angle of the COB, the sum total of each individual contribution of all the COBs in the array, and an intensity modification based on the Lambertian distribution of light. The following is a step-by-step breakdown of the calculations.

There are several variables worth defining:

- $(light_x, light_y, light_z)$: The position of a light source in 3D space.
- $(point_x, point_y, point_z)$: The position of a measurement point in 3D space.
- $I$: The original luminous intensity of a light source.
- $\alpha$: The beam angle of a COB LED, initially given in degrees and converted to radians for the calculations.
- $d$: the Euclidean distance between a light source at $(light_x, light_y, light_z)$ and a measurement point at $(point_x, point_y, point_z)$.
- $\theta$: The angle between the direction of maximum intensity (normal to the LES) and the direction towards the measurement point.
- $I'$: The intensity at a measurement point due to a single light source, before summing up the contributions from all light sources.
- $I_{total}$: The total intensity at a measurement point due to all light sources.
- $\epsilon$: A small positive constant used to avoid division by zero in the intensity modification calculation.

The Euclidean distance $d$ between a light source and a measurement point is calculated as:

$$\begin{aligned}\Delta x &= light_x - point_x \\ \Delta y &= light_y - point_y \\ \Delta z &= light_z - point_z \\ d &= \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}\end{aligned}$$

The beam angle $\alpha$ of a COB LED is given in degrees (e.g. '115-degrees') and converted to radians:

$$\alpha = \frac{\alpha_{\text{degrees}} \cdot \pi}{180}$$

The Lambertian distribution function is used to model the intensity of light emitted by the COB LEDs. This model is appropriate for simulating COB LEDs because they typically have a circular Light Emitting Surface (LES), meaning that the light emission is more uniform across all angles in the plane perpendicular to the LES. The Lambertian distribution accurately captures this behavior by ensuring that the intensity of light is strongest at normal incidence (the angle perpendicular to the surface) and gradually decreases as the angle of emission deviates from the surface normal.

The angle $\theta$ for the Lambertian distribution is calculated based on the beam angle $\alpha$ and the distance $d$ between the light source and the measurement point. It represents the angle between the direction of maximum intensity (normal to the LES) and the direction towards the measurement point. The equation for $\theta$ is:

$$\theta = \arccos\left(\frac{point_z - light_z}{d}\right)$$

The modified intensity of light $I'$ at a measurement point due to a single light source is calculated from the original luminous intensity $I$ and the angle $\theta$. To avoid division by zero, a small positive constant $\epsilon$ is used:

$$I' = I \cdot \frac{\cos^2(\theta)}{\pi \cdot \max(\sin(\theta), \epsilon)}$$

The total intensity $I_{\text{total}}$ at a measurement point is calculated as the sum of $I'$ from all light sources:

$$I_{\text{total}} = \sum_{i=1}^{n} I'_i$$

Where $n$ is the total number of light sources, and $I'_i$ is the modified intensity from the $i^{\text{th}}$ light source. This total intensity represents the cumulative light intensity at each measurement point, considering the individual contribution from all of the COBs in the array.

This method of calculating light intensity provides a scientifically sound approach for simulating the light emitted by COB LEDs and allows for accurate predictions of illumination levels.

### Quantifying Uniformity

There are several variables that are worth defining:

- $PAR_k$: The Photosynthetically Active Radiation intensity value at the $k^{\text{th}}$ measurement point on the heatmap.
- $PPFD_{avg}$: The Photosynthetic Photon Flux Density Average is the average of all intensity values $PAR_k$.
- $V_k$: The intensity variance at the $k^{\text{th}}$ measurement point, calculated as the absolute difference between $PAR_k$ and $PPFD_{avg}$.
- $MAD$: The Mean Absolute Deviation, calculated as the average of all $V_k$ values.
- $DOU$: The Degree of Uniformity, calculated as a percentage based on $MAD$ and $PPFD_{avg}$.

The $PPFD_{avg}$ is computed by averaging the $PAR_k$ values:

$$PPFD_{avg} = \frac{1}{225} \sum_{k=1}^{225} PAR_k$$

The intensity variance $V_k$ at each measurement point is determined by calculating the absolute difference between each $PAR_k$ measurement and the $PPFD_{avg}$ value, as expressed in the equation:

$$V_k = |PAR_k - PPFD_{avg}|$$

The $MAD$ is then computed by averaging these variance values $V_k$:

$$MAD = \frac{1}{225} \sum_{k=1}^{225} V_k$$

The $DOU$ is calculated as a percentage that represents the uniformity of the light intensity distribution. It's determined by subtracting the ratio of $MAD$ to $PPFD_{avg}$ from 1, and then multiplying by 100:

$$DOU = 100 \times \left(1 - \frac{MAD}{PPFD_{avg}}\right)$$

For example:

A simulation resulting in a $PPFD_{avg}$ of 1596.53 and a $MAD$ of 139.41 yields a $DOU$ of 91.26%.

A simulation resulting in a $PPFD_{avg}$ of 1403.17 and a $MAD$ of 7.17 yields a $DOU$ of 99.49%.

This indicates a near-optimal degree of uniformity in the distribution of light intensity generated by our system, which is a significant achievement in the horticultural lighting space.

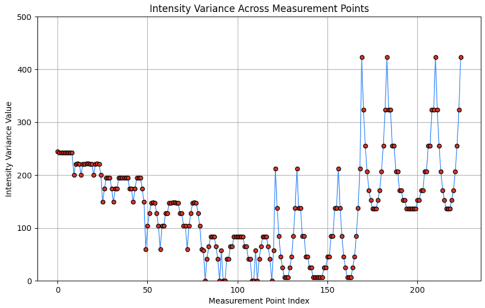


Fig. 14: Variance $V_k$ values for an 8x8 grid of 64 COBs arranged in a uniform matrix of straight rows and columns, with the same intensity value assigned to each COB [14].

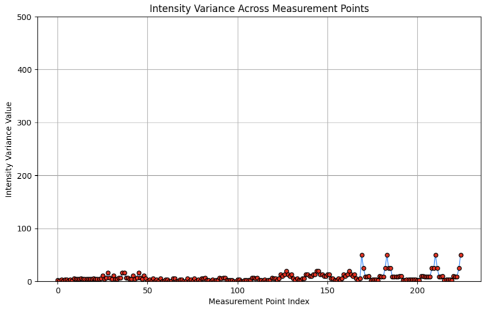


Fig. 15: Variance $V_k$ values for 61 COBs arranged in the diamond pattern with varying intensities assigned to the COBs, according to their positions within the concentric square layers [15].

Figures 14 and 15 showcase 2D line graphs for the same simulations that produced the heatmaps in Figures 12 and 13. These line graphs showcase the intensity variance between measurement points and they are generated in the following way:

The intensity values at each measurement point in the simulation are denoted as $PAR_k$, where $k$ is the 225 measurement points on the grid, and is used to determine $PPFD_{avg}$, as expressed in the equation:

$$PPFD_{avg} = \frac{1}{225}\sum_{k=1}^{225} PAR_k$$

The intensity variance values are determined by calculating the absolute difference between each $PAR_k$ measurement and the $PPFD_{avg}$ value, as expressed in the equation:

$$V_k = |PAR_k - PPFD_{avg}|$$

This calculation provides a measure of the variance in light intensity across the grid of measurement points.

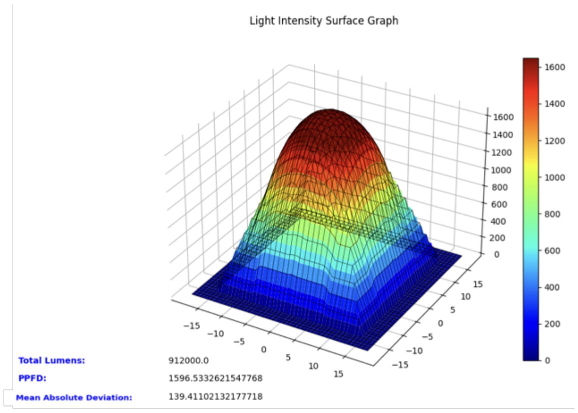
The $V_k$ values are then reordered to be plotted on the line graph, based on their spatial relationship to the center point of the measurement grid. The following Python function illustrates the process used to reorder these variance values:

```
def reorder_dps(dps, measurement_points,
    ↪ center_point):
    # Calculate coordinates relative to the
        ↪ central point
    relative_coords = [(x - center_point
        ↪ [0], y - center_point[1]) for x,
        ↪  y, _ in measurement_points]

    # Create a list of tuples, where each
        ↪ tuple is (dps, relative
        ↪ coordinate)
    dps_coords = list(zip(dps,
        ↪ relative_coords))

    # Sort by the maximum absolute
        ↪ coordinate
    dps_coords.sort(key=lambda x: max(abs(x
        ↪ [1][0]), abs(x[1][1])))

    # Extract and return the sorted dps
        ↪ values
    sorted_dps = [dps for dps, coord in
        ↪ dps_coords]
    return sorted_dps
```

*Note: A red hook arrow (↪) indicates the continuation of a wrapped line.*

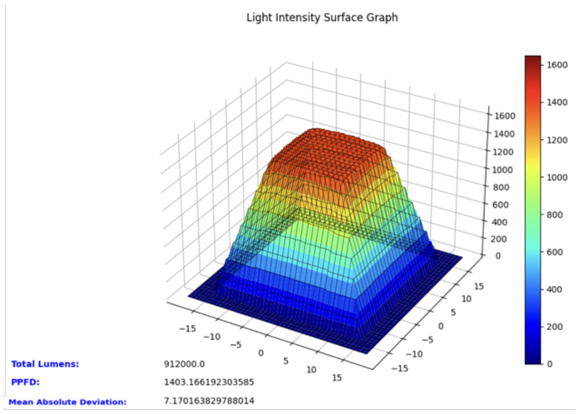
This reordering function is a critical step as it allows for a more meaningful interpretation of the data when it is plotted. Specifically, it ensures that the $V_k$ values are not plotted in an arbitrary sequence but rather in a manner that reflects their spatial distribution across the grid. This is important because the spatial distribution of light intensity is a key factor in understanding the performance of a lighting system for horticulture.

To generate the 3D surface plots illustrated in Figures 16 and 17, we commence with the previously detailed method for calculating light intensity at each measurement point, denoted as 'z'. In our 15x15 grid, the 'x' and 'y' coordinates correspond to 225 distinct measurement points, with each coordinate paired with a 'z' value reflecting the light intensity at that location. The surface plot is constructed by elevating each 'x' and 'y' coordinate to a height proportional to its 'z' value. This process creates a three-dimensional mesh grid, an effective tool for visualizing the propagation and distribution of light within the entire cubic coverage area. Such a graphical representation is instrumental in elucidating the spatial dynamics of light intensity, highlighting the efficacy and uniformity of our lighting system's photon distribution capabilities.



**Total Lumens:** 912000.0
**PPFD:** 1596.5332621547768
**Mean Absolute Deviation:** 139.41102132177718

Fig. 16: PPFD surface plot for an 8x8 grid of 64 COBs arranged in a uniform matrix of straight rows and columns, with the same intensity value assigned to each COB [16].



**Total Lumens:** 912000.0
**PPFD:** 1403.166192303585
**Mean Absolute Deviation:** 7.170163829788014

Fig. 17: PPFD surface plot for 61 COBs arranged in the diamond pattern with varying intensities assigned to the COBs, according to their positions within the concentric square layers [17].

## II.5 Beyond Averages: Reframing PPFD and DLI through the Lens of Uniformity and the Integrated Photosynthetic Performance Metric (IPP)

In the intricate landscape of plant lighting systems, the quest for optimal performance has traditionally been guided by metrics that emphasize raw power and luminous output, typically described as the ‘photosynthetic photon efficacy’ (PPE) of a system, or less commonly (but more appropriately), the ‘photosynthetic photon efficiency’ (PPE) of a system.

However, a deeper exploration into the nuances of light distribution reveals a compelling narrative; the uniformity of light, often overshadowed, emerges as a cornerstone in determining a system’s true efficacy. Through this lens, we introduce Integrated Photosynthetic Performance (IPP), a pioneering metric which crystallizes the profound influence of uniformity on plant lighting efficacy.

**Defined Variables**:

- $PPFD_{avg}$ represents the average PPFD value (in $\mu\mathrm{mol\,m^{-2}\,s^{-1}}$).
- $L$ represents the Luminous Output (in lumens, $lm$).
- $P$ represents the Power Consumption (in watts, $W$).
- $DOU$ represents the Degree of Uniformity.
- $PPFD_{max}$ represents the maximum PPFD value on the measurement grid (in $\mu\mathrm{mol\,m^{-2}\,s^{-1}}$).
- $PPFD_{min}$ represents the minimum PPFD value on the measurement grid (in $\mu\mathrm{mol\,m^{-2}\,s^{-1}}$).

The Uniformity Factor (UF) is a metric which captures the essence of light distribution.

$$UF = \frac{PPFD_{min}}{PPFD_{max}}$$

Energy Efficiency (EE) is the ratio of useful energy output to the total energy input.

$$EE = \frac{L}{P}$$

The Integrated Photosynthetic Performance (IPP) metric, a fusion of energy efficiency, photosynthetic photon production, and uniform light distribution.

$$IPP = EE \times UF \times DOU \times PPFD_{avg}$$

Now, a comparative analysis between our patented system and an alternative system is carried out to showcase the IPP metric.

**Defined Variables for the Comparative Analysis**:

- $P = 5364.70w$
- $DOU_{comp} = 0.9126$
- $DOU_{pat} = 0.9949$
- $L = 912,000_{lm}$
- $PPFD_{min.comp} = 1173\ \mu\mathrm{mol\,m^{-2}\,s^{-1}}$
- $PPFD_{max.comp} = 1841\ \mu\mathrm{mol\,m^{-2}\,s^{-1}}$
- $PPFD_{min.pat} = 1353\ \mu\mathrm{mol\,m^{-2}\,s^{-1}}$
- $PPFD_{max.pat} = 1401\ \mu\mathrm{mol\,m^{-2}\,s^{-1}}$
- $EE = 170_{lm/W}$
- $PPFD_{avg.comp} = 1596.5332\ \mu\mathrm{mol\,m^{-2}\,s^{-1}}$
- $PPFD_{avg.pat} = 1403.1661\ \mu\mathrm{mol\,m^{-2}\,s^{-1}}$

Substitute the given values into the IPP formula to determine the IPP of both systems:

**Competitor System**:

$$\mathrm{IPP} \approx 157,816.37 \left( \frac{\mathrm{lm} \times \mu\mathrm{mol\,m^{-2}\,s^{-1}}}{\mathrm{W}} \right)$$

**Patented System**:

$$\mathrm{IPP} \approx 229,191.01 \left( \frac{\mathrm{lm} \times \mu\mathrm{mol\,m^{-2}\,s^{-1}}}{\mathrm{W}} \right)$$

Equation to determine the hypothetical efficiency increase required for the competitor system to match the IPP of the patented system:

$$\begin{aligned} IPP_{comp} = & \frac{L}{P(1-f)} \\ & \times UF_{comp} \\ & \times DOU_{comp} \\ & \times PPFD_{avg.comp} \end{aligned}$$

Solving for $f$:

$$f \approx 0.3115$$

This means the competitor system would need to increase its efficiency by approximately 31.15% just to match the IPP of the patented system.

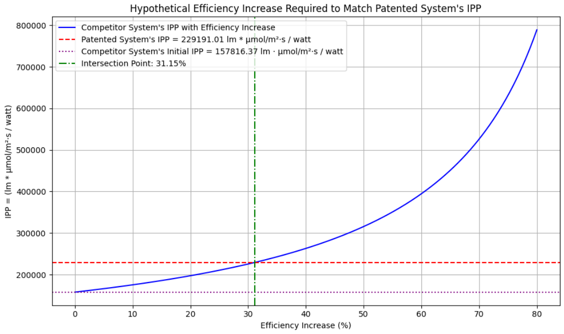


Fig. 18: Line graph showing the hypothetical efficiency increase that would be required for the competitor's IPP to match the patented system's IPP [18].

It should be noted that in the hypothetical scenario illustrated in Figure 18., although mathematically the competitor system could reach the patented system's IPP via increasing efficiency by ≈ 31%, this is only presented for illustration purposes to highlight the importance of uniformity, as in reality a raw efficiency increase of 31% would further exacerbate the uniformity issues. It is also unrealistic to expect that a competing system could achieve becoming 31% more efficient than the patented system, as COB and SMD LED efficiencies typically differ by just 3-5%, and the patented system is a COB-SMD hybrid plant lighting system, so the slight efficiency disadvantage that is typical of COBs is partially offset by the slight efficiency benefit offered by the SMD aspect of our hybrid system.

### Revised DLI Calculations Incorporating the IPP Metric

The conventional method for calculating DLI assumes a constant PPFD across a given area. However, real-world lighting systems exhibit variations in PPFD due to differences in the uniformity of light distribution emitted by a lighting system. To provide a more accurate representation of the light intensity experienced by plants, we introduce a revised method for calculating DLI that incorporates insights from the Integrated Photosynthetic Performance (IPP) metric.

**Defined Variables**:

- $PPFD_{avg}$: Photosynthetic Photon Flux Density, traditionally measured in $\mu\mathrm{mol}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}$.
- $K(h)$: A constant that accounts for the conversion from $\mu\mathrm{mol}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}$ to $\mathrm{mol}\,\mathrm{m}^{-2}\,\mathrm{d}^{-1}$ and the number of light-hours per day $h$ during which active photons are delivered to the target area.
- $DOU$: Degree of Uniformity, a measure of how uniformly light is distributed across the measurement area.
- $h$: Number of light-hours per day, tailored to the specific horticultural application.

**Revised DLI Calculation**

The conventional DLI calculation assumes a constant PPFD, which does not account for variations in light distribution. Our revised formula introduces the Degree of Uniformity (DOU) and incorporates a conversion factor $K(h)$ to better represent real-world conditions.

The revised DLI is calculated as follows:

$$DLI_{revised} = K(h) \times PPFD_{avg} \times DOU$$

Where:

$$K(h) = \frac{h}{277.78}$$

The factor 277.78 in $K(h)$ facilitates the conversion from PPFD (measured in $\mu\mathrm{mol}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}$) to DLI (measured in $\mathrm{mol}\,\mathrm{m}^{-2}\,\mathrm{d}^{-1}$), considering the number of light-hours per day $h$.

For example, with 12 hours of light per day ($h = 12$), the conversion factor becomes:

$$K(12) = \frac{12}{277.78} \approx 0.0432$$

This revised method, incorporating DOU and the adjusted DLI formula, provides a more accurate assessment of light intensity and photon distribution for horticultural applications.

# III. Results

The performance of our system is epitomized by a DOU surpassing 99.49%, serving as a compelling testament to its unparalleled efficacy. This achievement in near-optimal uniformity transcends the conventional challenges of 'hot spots' inherent in traditional systems. Furthermore, it heralds a new paradigm in plant lighting, fostering enhanced photosynthetic rates and adeptly addressing the 'canopy penetration' conundrum by preserving the vitality of the lower leaves through precise uniformity in photon distribution.

# IV. Discussion

The implications of achieving such a high degree of uniformity are profound. Drawing from contemporary academic literature, we elucidate the multifaceted advantages of this uniformity. Enhanced photosynthetic rates, preservation of lower leaf vitality, and alterations in plant geometrical relationships are but a few of the myriad benefits. Furthermore, the impact on phytohormone balances within plants offers promising avenues for future research.

Our research emphasizes the significance of incorporating uniformity into measurement calculations through the Integrated Photosynthetic Performance (IPP) metric. This metric highlights uniformity as a critical factor in assessing a plant lighting system's operational effectiveness. Achieving near-optimal uniformity has widespread implications for plant lighting systems, including the system operating at a near-optimal degree of energy utilization. Additionally, the inherent design of COBs results in them emitting a superior quality beam of light compared with SMD systems. The novel methodology by which we employ COBs in an intelligent COB-SMD hybrid system truly sets a new benchmark in plant lighting system design.

Our system combines the strengths of both COB and SMD LEDs to produce a synergistic effect. By modulating the light intensity of specific areas in the coverage area to specified degrees based on room dimensions, target PPFD, and predictions made by our proprietary lighting simulation software, near-optimal PPFD uniformity for any size space and with any desired intensity can be achieved.

Addressing the 'canopy penetration' issue, certain competitors have proposed solutions utilizing tight cluster arrangements of high-powered SMD LEDs. Their aim is to generate 'laser-like' beams powerful enough to 'penetrate' the top of the plant canopy. This strategy, however, can be detrimental to plants. Uniform light distribution across the leaf is more beneficial than concentrating intensity on a small area. Contrary to the competitors' approach, literature suggests that a spatially consistent PPFD at an appropriate level in a plant canopy, irrespective of its depth, can significantly elevate the net photosynthetic rate of the entire canopy and potentially prevent the decline in net photosynthetic capacity of the lower leaves due to their senescence [19]. Furthermore, a uniform light environment in a plant canopy can transform the geometrical relationships between the source and sink of plants, ensure all leaves act as equal carbohydrate producers, suppress the senescence that occurs in lower leaves due to low PPFD, and alter the phytohormone balances in individual plants [20].

Our analysis heralds a transformative shift in how we measure and comprehend plant lighting systems. The traditional metrics of luminous output and efficiency are now seamlessly integrated into our advanced IPP metric, poised to become the industry standard for defining PPFD. As the agricultural sector evolves, this intricate understanding, encapsulated by the IPP metric, will be instrumental in optimizing plant growth and championing sustainable practices.

## V. Conclusion

The fusion of advanced patented LED technology with a cutting-edge plant lighting system measurement algorithm, has birthed a new era in Plant Factories with Artificial Lighting (PFALs). Our methodology, characterized by its patented COB-SMD hybrid LED configuration, proprietary lighting simulation software, innovative lighting control strategy, and novel approach to measuring the effectiveness of plant lighting systems, sets a diamond standard in the field. As we stand on the cusp of this transformative approach, the future of horticultural lighting promises incredible innovations and advancements that will undoubtedly reshape the way plants are grown.

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