# Achieving Controllable and Optimal Photosynthetic Photon Flux Density (PPFD): A Methodological Approach Using COB LEDs for Generating Near-Optimal Uniformity in Photon Distribution

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## Introduction:

Presented is a novel methodology for generating a controllable density of photosynthetically active radiation (PAR) with near-optimal uniformity for any size space. This method employs a patented COB LED configuration that works with a wireless lighting control system and predictions made by proprietary lighting simulation software to generate controllable photosynthetic photon flux density (PPFD) levels with near-optimal uniformity in any size space for crops with any DLI requirement.

## 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.

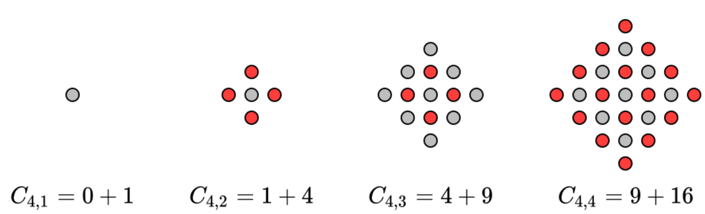



**Figure 1**. Diamond pattern logic based on the centered square number integer sequence (source: Wikipedia, URL: https://en.wikipedia.org/wiki/Centered_square_number).

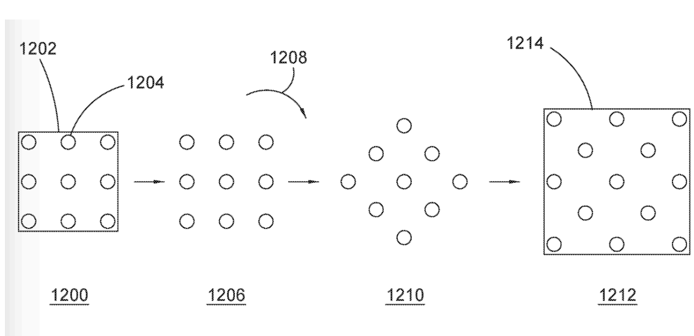


**Figure 2**. Transformation of diamond pattern logic into a completed square array (source: USPTO, URL:https://uspto.report/patent/grant/10,687,478).

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.

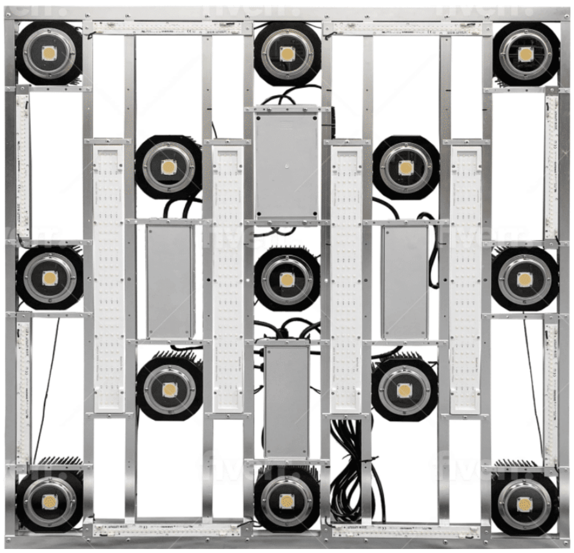


**Figure 3**. One embodiment of the patented COB LED arrangement (13 COBs - lights off) (source: LED Cultivation, URL: https://ledcultivation.com/product/synergy-series-elite/).

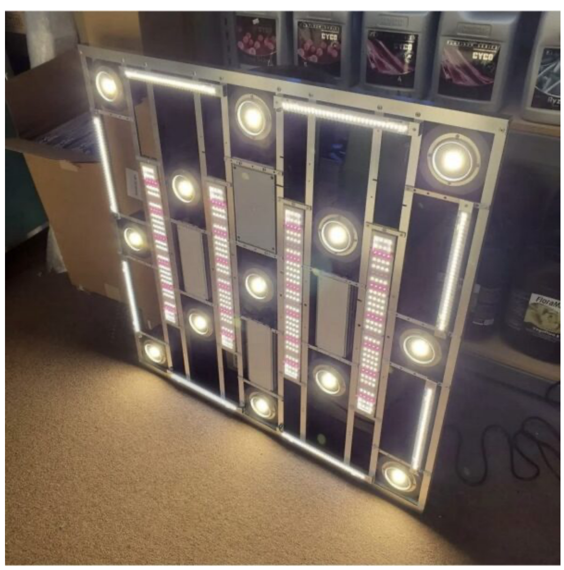


**Figure 4**. One embodiment of the patented COB LED arrangement (13 COBs - lights on) (source: LED Cultivation, URL: https://ledcultivation.com/product/synergy-series-elite/).

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

## Modular Diamond Pattern Arrangement System:

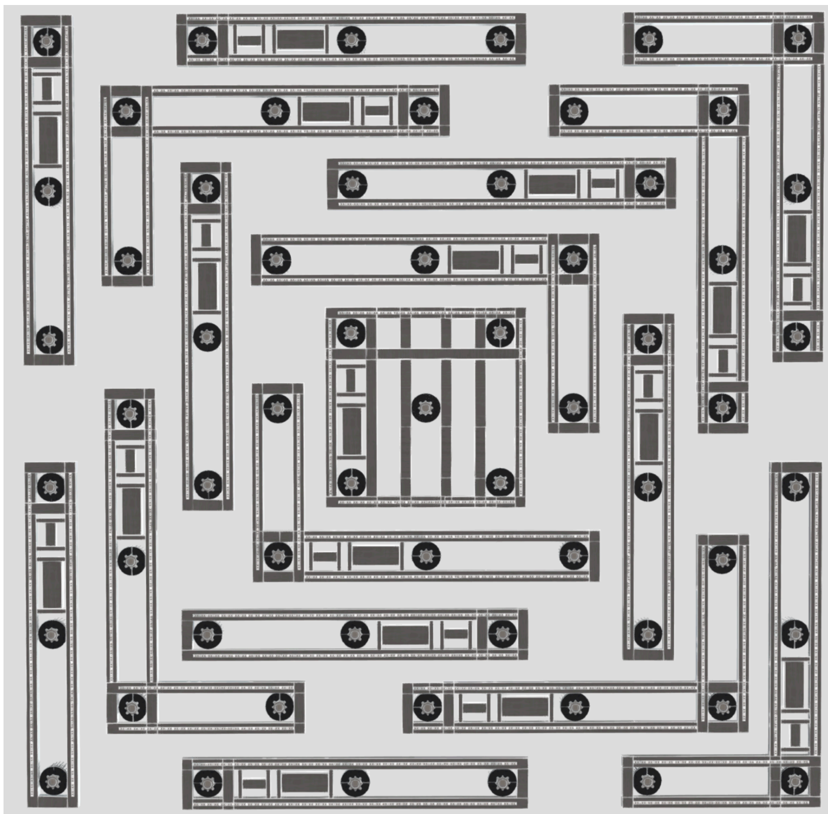


**Figure 5.** Another embodiment of the patented COB LED arrangement logic (61 COBs).

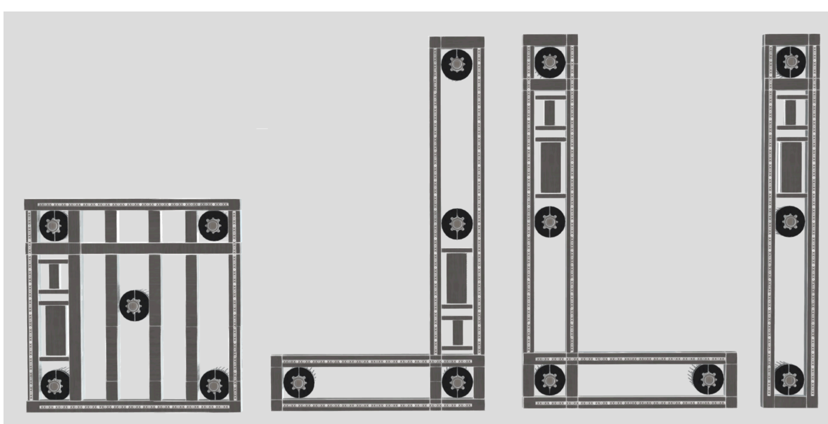


**Figure 6.** The four fixtures which comprise all embodiments of the patented COB LED arrangement logic.

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.

## Wireless Lighting Control System:

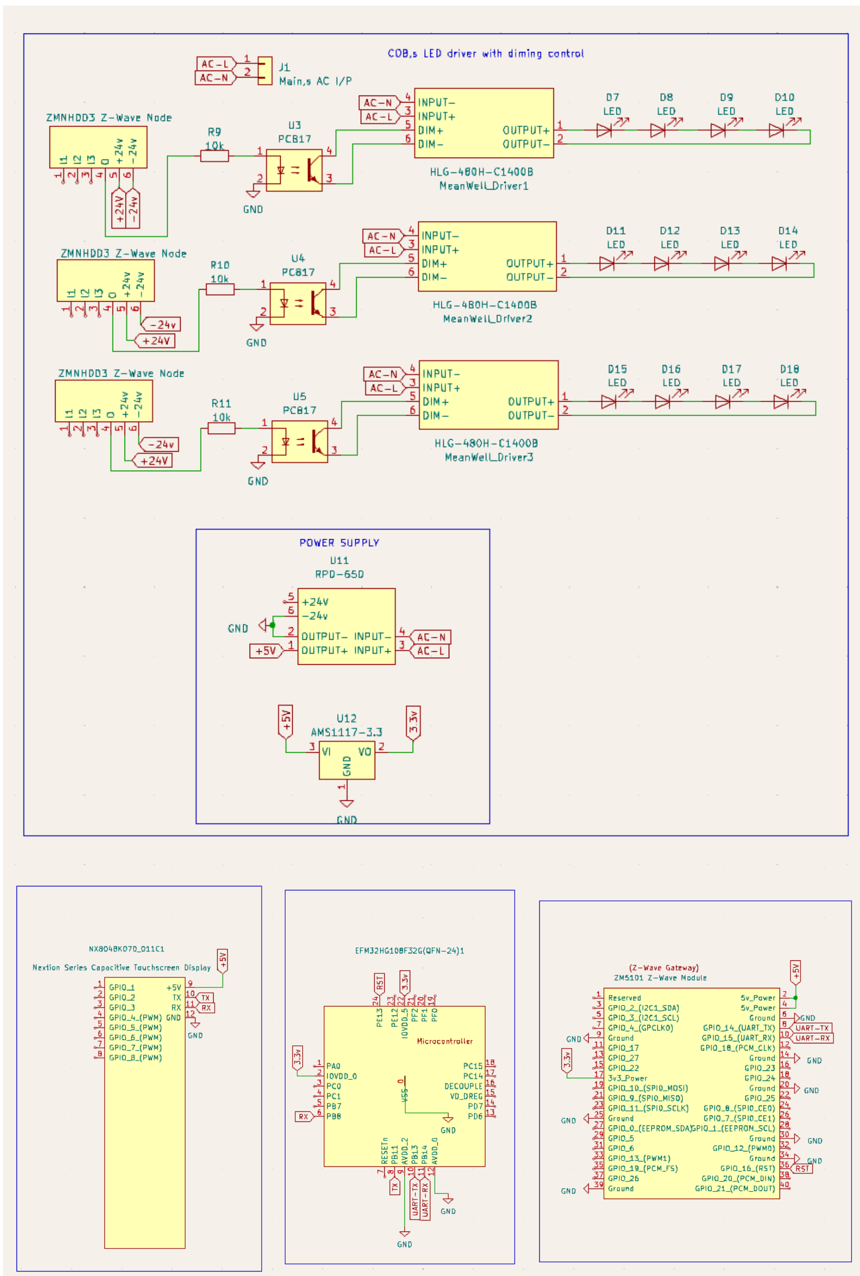


**Figure 7.** Schematic for the wireless lighting control system.

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.

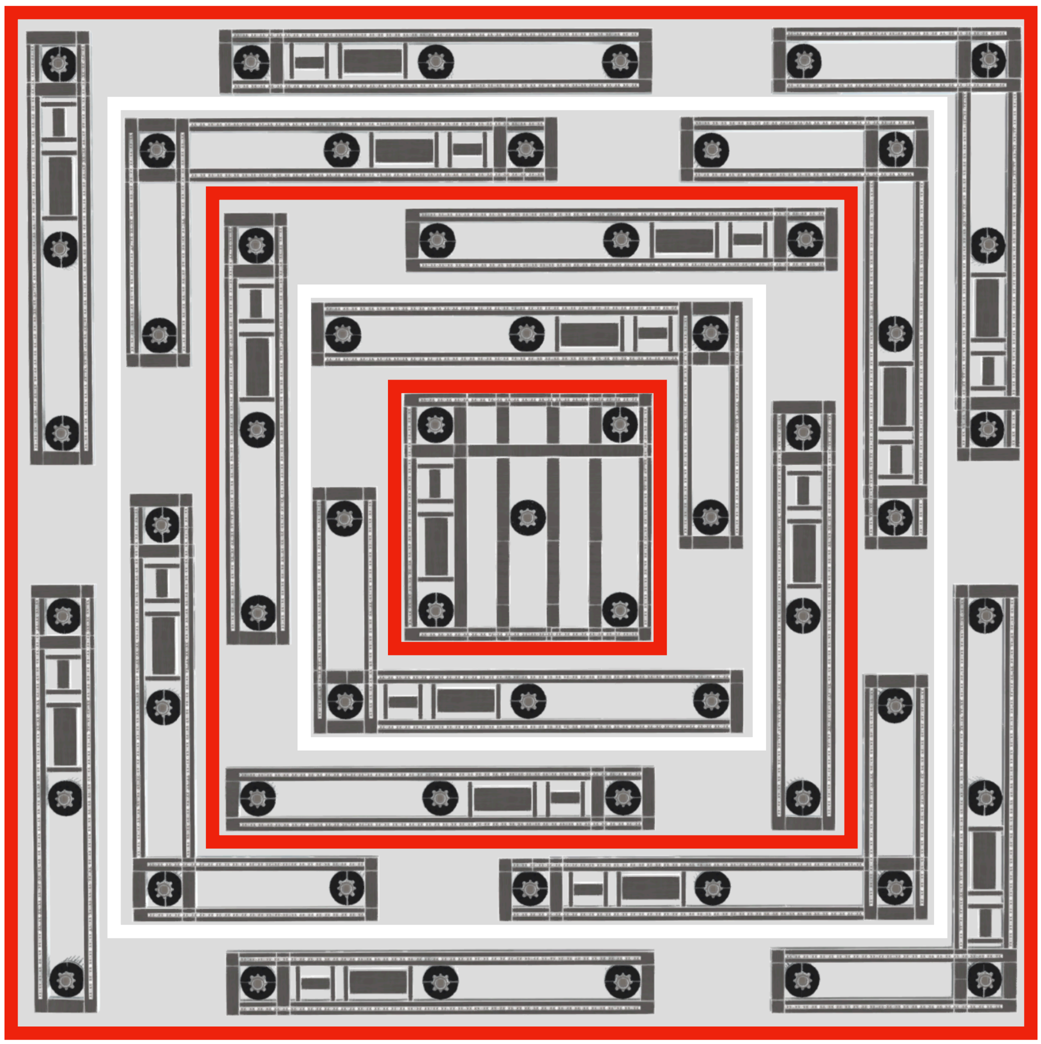


**Figure 8.** Illustration for concentric square layer intensity modulation.

In Figure 8 there are red / white 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.

## Proprietary Lighting Simulation Software:

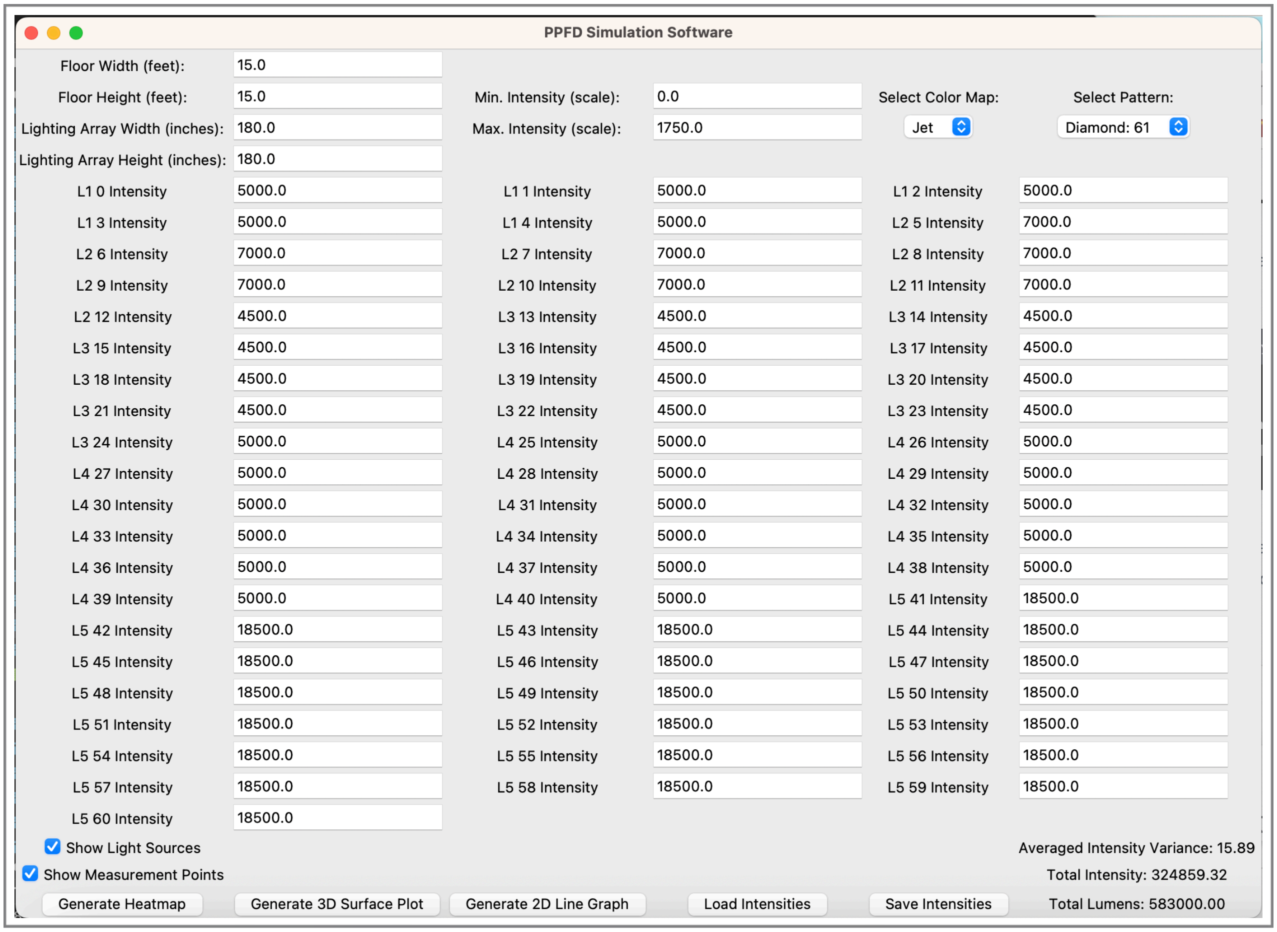
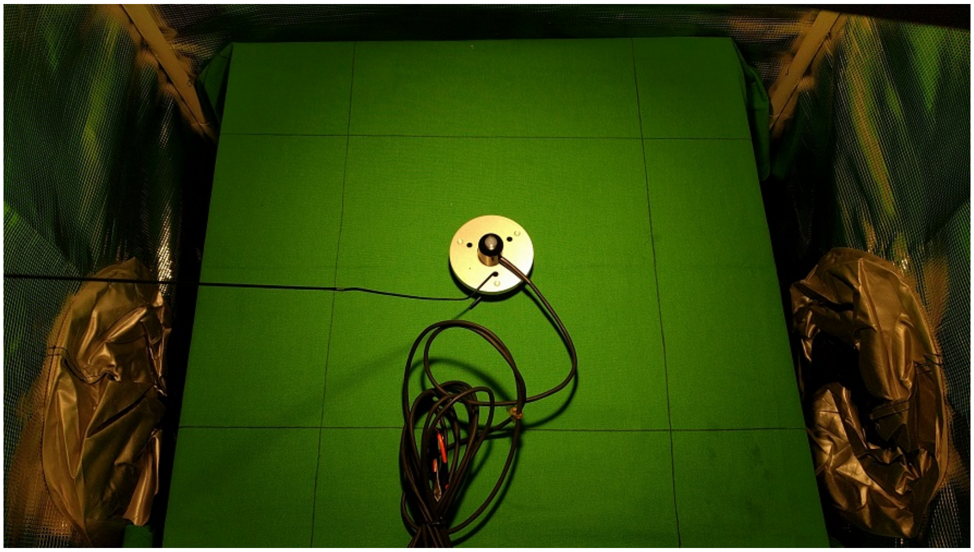
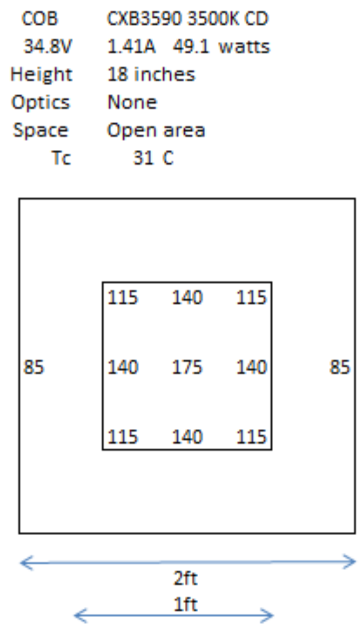



**Figure 9**. Graphical User Interface (GUI) for our proprietary lighting simulation software.

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.






**Third-party physical test of a single CXB3590 3500K CD COB**

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

**Figure 10.** Third-party measurements of a single COB in an open area (source: RollItUp, URL: https://www.rollitup.org/t/lens-and-reflector-optics-for-cob.893660/).

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.

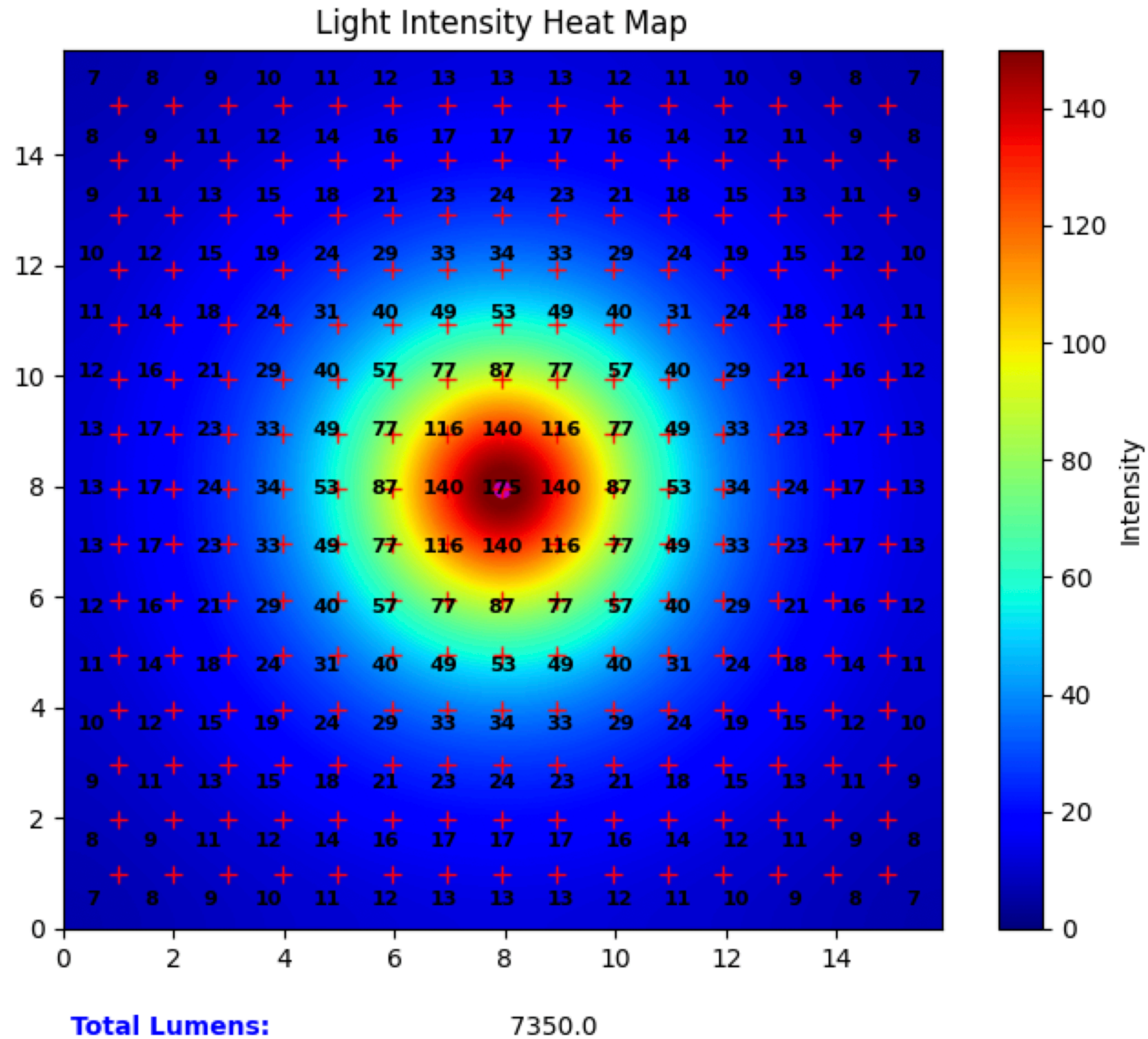



**Figure 11.** Simulation of a single COB in an open area

## Simulation of a single CXB3590 3500K CD COB with same conditions as third-party test

Performed 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.

Figure 11 shows a simulation of a single COB that has the same electrical characteristics and testing conditions as used in the third-party measurements referenced above. It can be seen that the intensity values produced by the simulation are nearly identical to those in the third-party test.

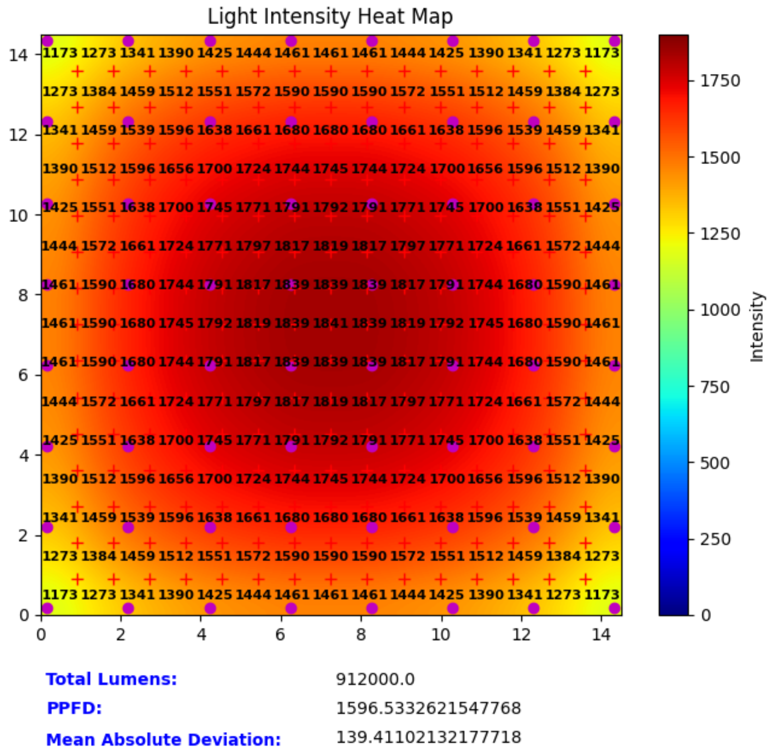



**Figure 12**. Heatmap generated for simulation of an 8x8 grid of 64 COBs arranged in a uniform matrix of straight rows and columns, with the same intensity value assigned to each COB.

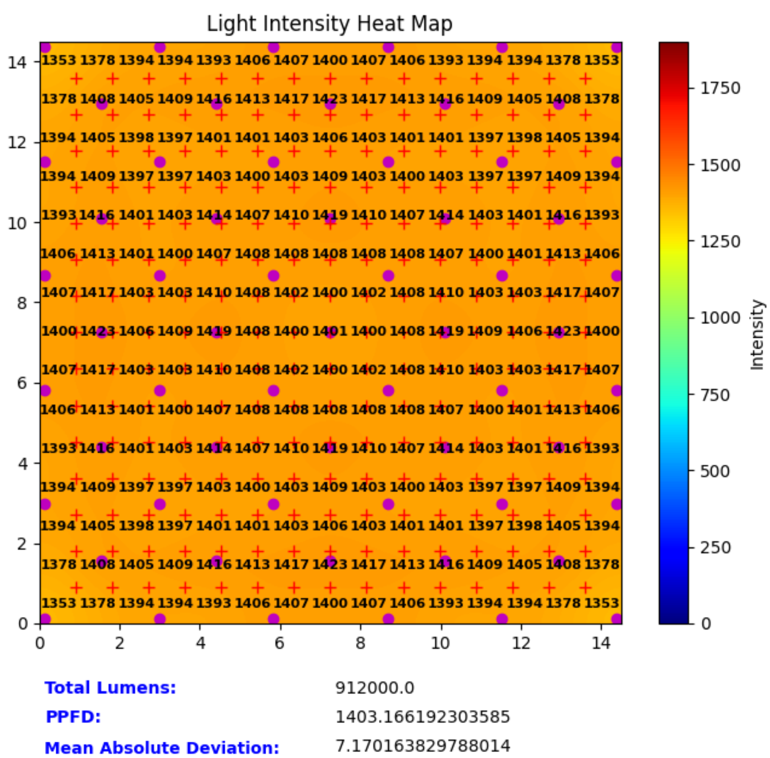



**Figure 13**. Heatmap generated for simulation of 61 COBs arranged in the diamond pattern with varying intensities assigned to the COBs, according to their positions within the concentric square layers.

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**:

I. An 8x8 grid of 64 COBs arranged in a uniform matrix of straight rows and columns
II. 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.

Here's a step-by-step breakdown of the calculations:

I. **Variables**: The script uses several variables that are 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.

II. **Distance Calculation**: The Euclidean distance $d$ between a light source and a measurement point is calculated as:

$$d = \sqrt{(light_x - point_x)^2 + (light_y - point_y)^2 + (light_z - point_z)^2}$$

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

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

IV. **Lambertian Distribution**: The Lambertian distribution 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:

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

A. **Intensity Modification**: 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:

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

V. **Total Intensity**: The total intensity $I_{total}$ at a measurement point is calculated as the sum of $I'$ from all light sources:

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

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 in virtual environments.

Finally, the entire process can be expressed with the following equation:

$$I_{total} = \sum_{i=1}^{n} I_i' = \sum_{i=1}^{n} I_i \cdot \frac{\cos^2\left(\arccos\left(\frac{(light_{x,i} - point_x)\cdot 0 + (light_{y,i} - point_y)\cdot 0 + (light_{z,i} - point_z)\cdot 1}{\sqrt{(light_{x,i} - point_x)^2 + (light_{y,i} - point_y)^2 + (light_{z,i} - point_z)^2}}\right)\right)}{\pi \cdot \max(\sin\left(\arccos\left(\frac{(light_{x,i} - point_x)\cdot 0 + (light_{y,i} - point_y)\cdot 0 + (light_{z,i} - point_z)\cdot 1}{\sqrt{(light_{x,i} - point_x)^2 + (light_{y,i} - point_y)^2 + (light_{z,i} - point_z)^2}}\right)\right), \epsilon)}$$

Where $light_{x,i}$, $light_{y,i}$, and $light_{z,i}$ are the coordinates of the $i^{\text{th}}$ light source, and the sum is over all light sources.

**Quantifying Uniformity:**

The Degree of Uniformity ($DOU$) value is calculated to quantify the uniformity of light distribution. It is determined as follows:

I. **Variables**: The script uses several variables that are worth defining:

- $PAR_k$: The Photosynthetically Active Radiation intensity value at the $k^{\text{th}}$ measurement point on the heatmap.
- $PPFD$: The Photosynthetic Photon Flux Density 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 $PPFD$.
- $MAD$: 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 $PPFD$.

II. **PPFD**: The PPFD is computed by averaging the $PAR_k$ values:

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

III. **Intensity Variance**: The intensity variance $V_k$ at each measurement point is determined by calculating the absolute difference between each $PAR_k$ measurement and the $PPFD$ value, as expressed in the equation:

$$V_k = |PAR_k - PPFD|$$

IV. **Mean Absolute Deviation**: The $MAD$ is then computed by averaging these variance values $V_k$:

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

V. **Degree of Uniformity**: 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 $PPFD$ from 1, and then multiplying by 100:

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

The entire process can be expressed with the following equation:

$$DOU = 100 \times \left(1 - \frac{\frac{1}{225} \sum_{k=1}^{225} |PAR_k - \frac{1}{225} \sum_{k=1}^{225} PAR_k|}{\frac{1}{225} \sum_{k=1}^{225} PAR_k}\right)$$

For example:

A simulation resulting in a $PPFD$ of 1596.53 and a $MAD$ of 139.41 (see: Figure 12) would yield a $DOU$ of 91.26%.

A simulation resulting in a $PPFD$ of 1403.17 and a $MAD$ of 7.17 (see: Figure 13) would yield 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.

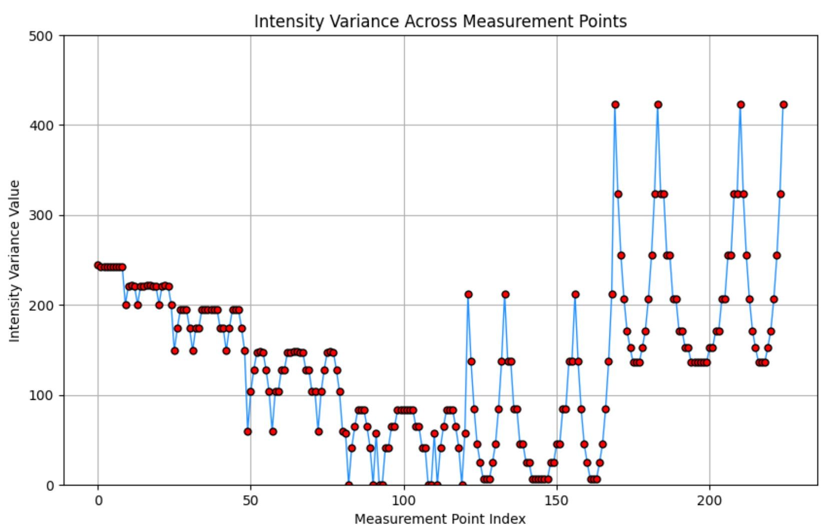


**Figure 14**. Variance ($V_k$) values for an 8x8 grid of 64 COBs arranged in a uniform matrix of straight rows and columns, with the same intensity value assigned to each COB.

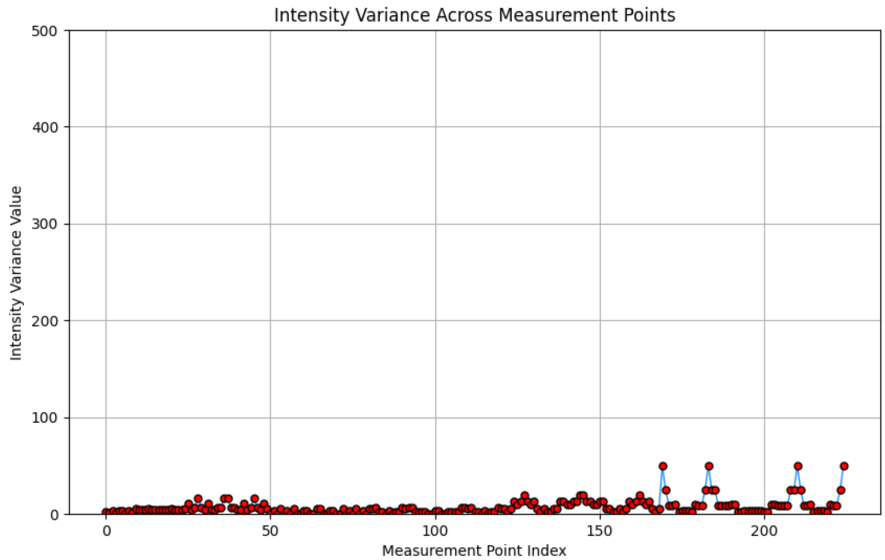



**Figure 15**. Variance ($V_k$) values for 61 COBs arranged in the diamond pattern with varying intensities assigned to the COBs, according to their positions within the concentric square layers.

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 $PPFD$, as expressed in the equation:

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

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

$$V_k = |PAR_k - PPFD|$$

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. This reordering 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.

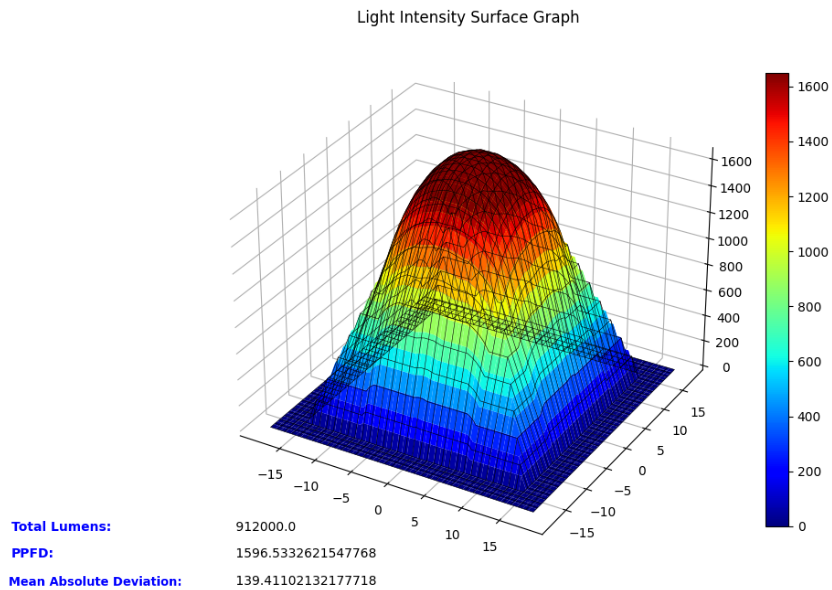



**Figure 16**. PPFD surface plot for an 8x8 grid of 64 COBs arranged in a uniform matrix of straight rows and columns, with the same intensity value assigned to each COB.

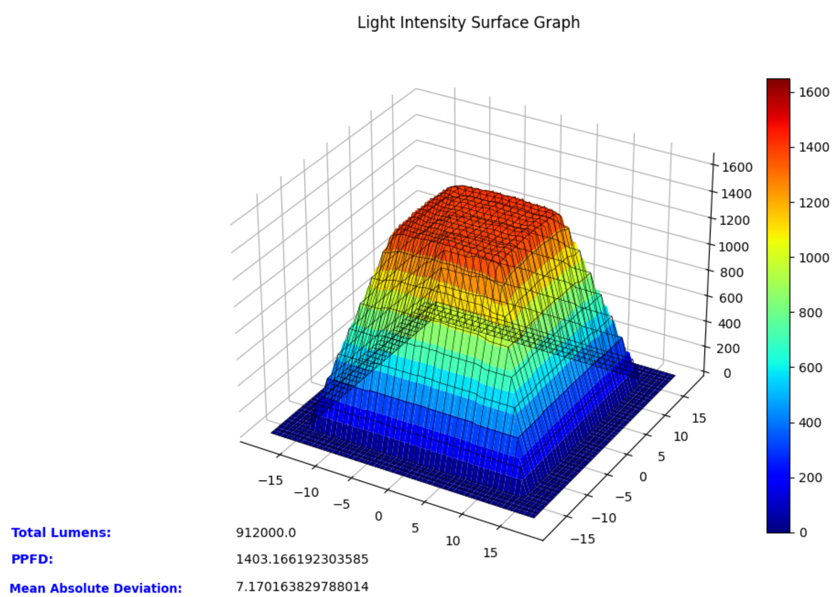



**Figure 17**. PPFD surface plot for 61 COBs arranged in the diamond pattern with varying intensities assigned to the COBs, according to their positions within the concentric square layers.

To generate the 3D surface plots showcased in Figures 16 and 17, the process begins with the calculation of intensity at each measurement point, which is stored in the variable ‘z’. The ‘x’ and ‘y’ coordinates represent the 225 measurement points in a 15x15 grid, with each of these points having a corresponding light intensity value, ‘z’. The surface plot is generated by raising each z-value along the z-axis to a height relative to that value, creating a 3D mesh grid.

## Conclusion:

By utilizing the patented COB LED configuration and modulating the intensity of each concentric square layer to a specified degree based on the dimensions of the space, the desired PPFD, and the predictions made by our lighting simulation software, near-optimal PPFD uniformity can be achieved in any size space while achieving any desired intensity.

In the realm of LED technology, Chip-On-Board (COB) LEDs have emerged as a superior choice over Surface-Mounted Device (SMD) LEDs, particularly in the context of indoor farming. The COB LEDs, with their unique design where LED chips are directly mounted onto a circuit board with high thermal conductivity, offer exceptional thermal management. This feature not only enhances the lifespan and stability of the LED but also contributes to a more efficient operation, a critical aspect for indoor farming where energy efficiency is paramount. Moreover, the COB LEDs are distinguished by their ability to provide a higher light density from a single light source. This results in a more intense and uniform light output, a feature that is of utmost importance in indoor farming. The uniformity of light distribution ensures that all parts of all leaves of all plants receive an equal amount of light, thereby promoting consistent growth across the entire indoor farming setup.

> If the PPFD is spatially uniform at an appropriate level in a plant canopy regardless of the canopy's depth, the net photosynthetic rate of the whole plant canopy should increase significantly, and the decrease in net photosynthetic capacity of lower leaves due to their senescence may be prevented (Zhang et al., 2015; Joshi et al., 2017).
>
> A uniform light environment in a plant canopy has the following effects:
> **(1)** Geometrical relationships between the source (photosynthesizing parts) and sink (accumulating parts of translocated carbohydrates) of plants are changed; **(2)** All leaves of a plant canopy relatively equally act as producers of carbohydrates; **(3)** Senescence of lower leaves due to low PPFD is suppressed; and **(4)** Phytohormone balances in individual plants are changed. (Kozai, 2022).

This paper presents a comprehensive methodology for achieving optimal saturation of PAR in a defined space, with potential applications in other fields that require precise control of light distribution. The patented COB LED configuration, the wireless lighting control method, and the proprietary lighting simulation software form the core of this methodology, providing a robust and versatile system that serves as an excellent, cutting-edge lighting solution for plant factories with artificial lighting (PFAL).

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9. Rouse, A. (2023). Graphical User Interface (GUI) for LED Cultivation's proprietary lighting simulation software [Figure].
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13. Rouse, A. (2023). 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 [Figure].
14. Rouse, A. (2023). Variance () 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 [Figure].
15. Rouse, A. (2023). Variance () 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 [Figure].
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