

Supplementary Materials

Uniform lighting of high-power LEDs at a short distance to plants for energy-saving and high-density indoor farming

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S1. Lighting uniformities for a 48 cm×48 cm red LED panel based on the LED distribution on an Osram PHYTOFY® panel

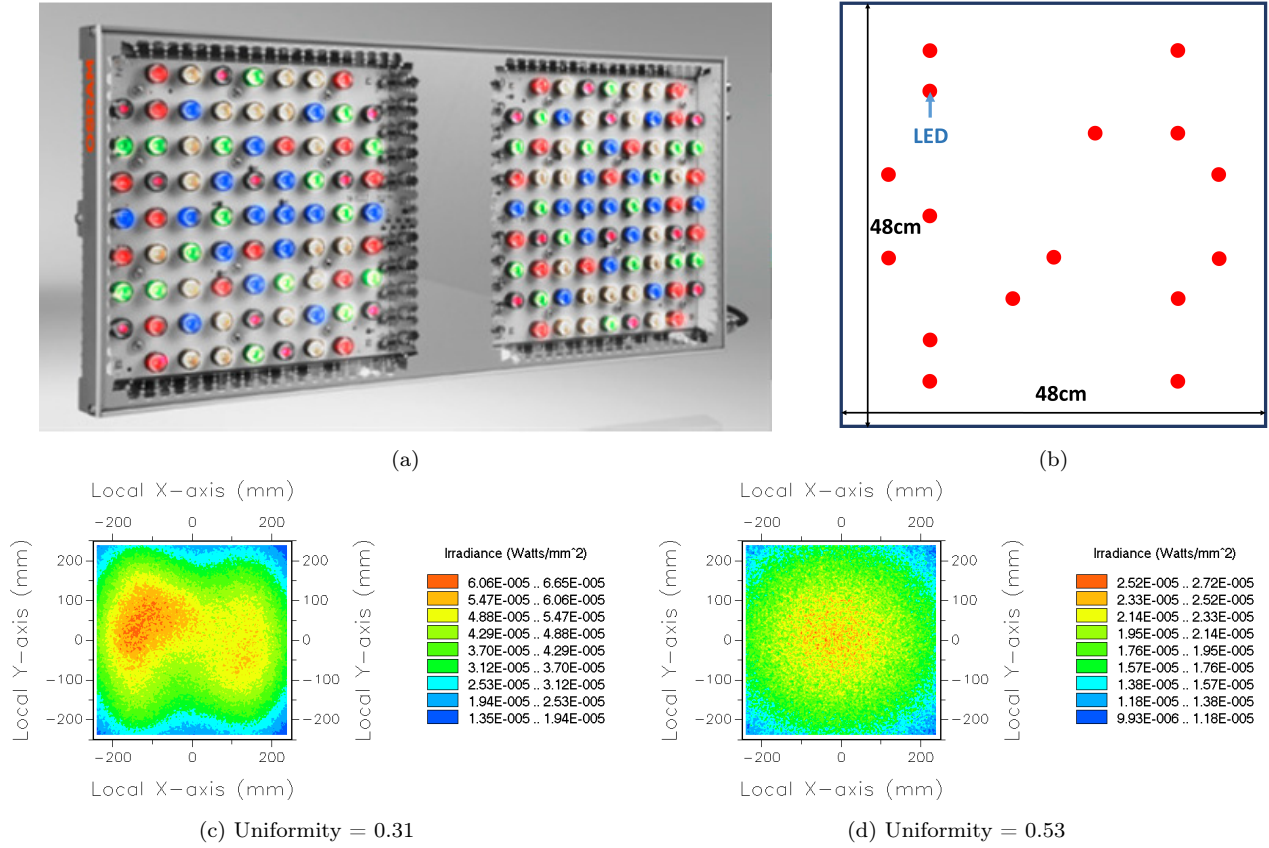


Figure S1: (a) LED arrangement on OSRAM PHYTOFY® RL LED panel (at a size of 66.7 cm×30 cm). (b) Red LEDs arranged on a 48 cm×48 cm LED panel, based on red LEDs' locations in a PHYTOFY® RL LED panel. (c) and (d) are simulated irradiance of (b) on a 48 cm x 48 cm illuminated area at 15 cm and 40 cm distances from the LED panel to plants, respectively. The LEDs are Osram GH CSSRM4.24 at the wavelength of 660 nm with 120° view angle, and light uniformity is calculated as the ratio of minimum to average irradiance in the illuminated area.

As can be seen from Figure S1(a), there are 77 LEDs (16 red LEDs, 19 white LEDs, 10 infrared LEDs, 16 blue LEDs and 16 green LEDs) on the Osram PHYTOFY® panel, and the LEDs at different wavelengths are arranged on the panel randomly. We believe such an arrangement was carefully designed by optical engineers for the LED panel to accommodate LEDs in multiple wavelengths. According to the positions of red LEDs arranged on the Osram PHYTOFY® RL panel (at a size of 30 cm×30 cm at each side), the panel is proportionally expanded to 48 cm×48 cm as drawn in Figure S1(b).

By ray tracing simulations, at a distance of 15 cm from the LED panel to plants, the light uniformity (calculated by the ratio of minimum to average irradiance) is only 0.31 on a 48 cm×48 cm illuminated area, as presented in Figure S1(c); while at the distance of 40 cm, the uniformity is increased to 0.53 as shown in Figure S1(d).

S2. Light uniformities simulated for a 24 cm×24 cm LED panel with a 2×2 LED array and reflectors

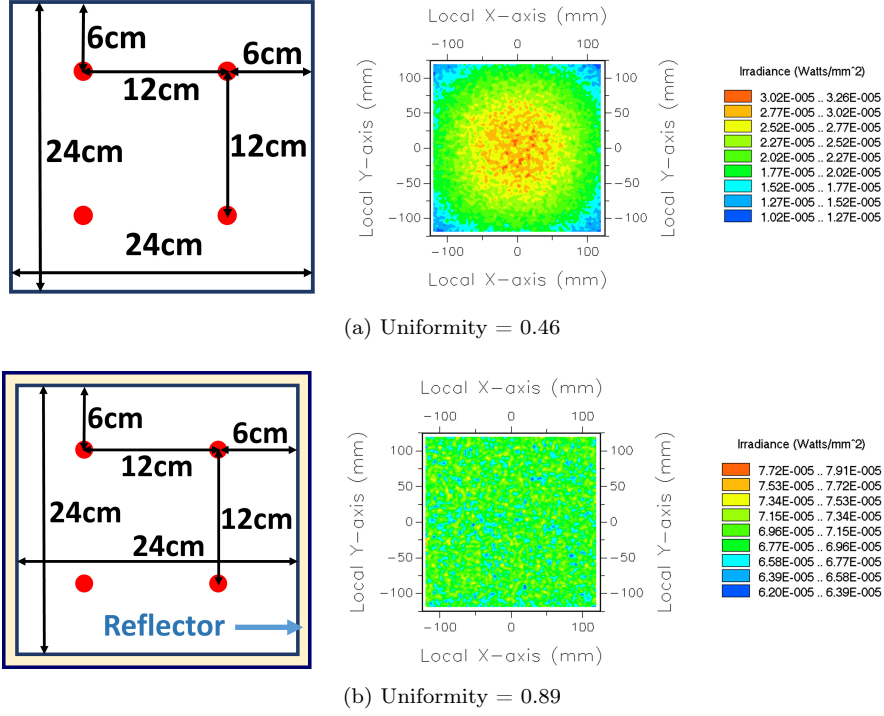


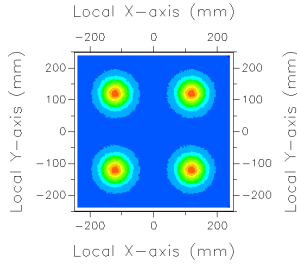
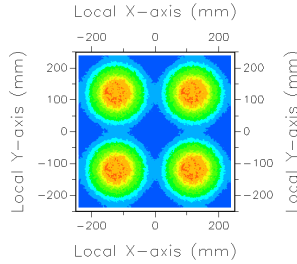
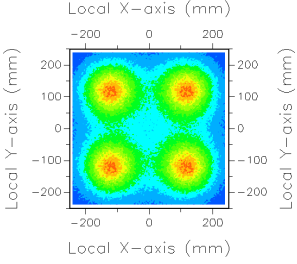
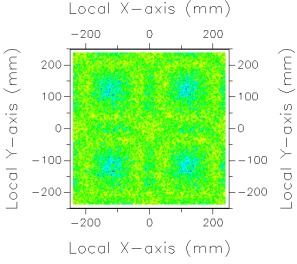
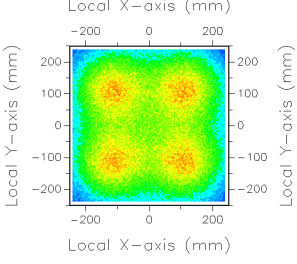
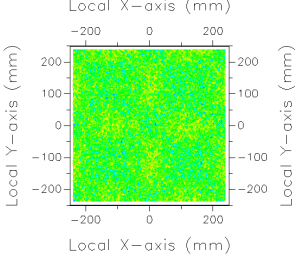
Figure S2: To verify the functions of reflectors placed vertically at the sides for uniformity improvement, 2×2 SST-10-DR LED array with 120° view angle is arranged on a 24 cm×24 cm panel. The irradiance patterns on a 24 cm×24 cm illuminated area at a distance of 15cm below the LEDs are presented for the LED panel (a) without reflectors and (b) having four 15 cm high reflectors with 100% reflectance at the sides.

To check the effectiveness on uniformity improvement by reflectors, we simulated 4 Luminus deep red SST-10-DR LEDs (with 120° view angle) arranged on a 24 cm×24 cm LED panel as illustrated in Figure S2, with the 2×2 LED array having a pitch of 12 cm. When there are only 4 LEDs on the panel, the side effect will be strong at the sides and corners, and the light uniformity is 0.46 in a 24 cm×24 cm illuminated area which is 15 cm away from the LED panel (Figure S2(a)). By placing four 15 cm high reflectors with 100% reflectance at the sides of the panel, the light uniformity on the same illuminated area reaches 0.89 (Figure S2(b)), and the average irradiance on the illuminated area of 24 cm×24 cm is tripled.

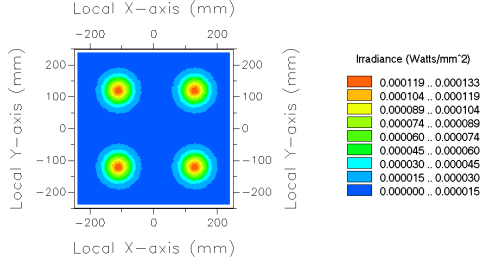
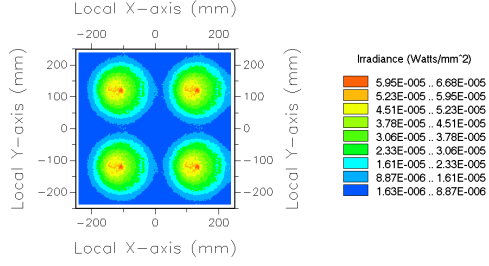
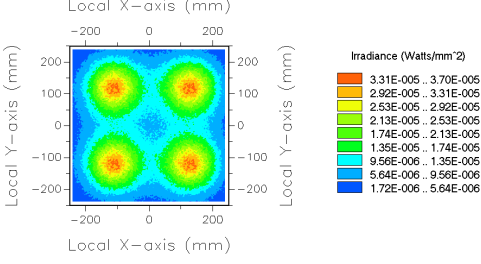
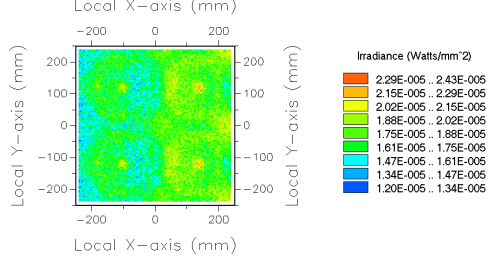
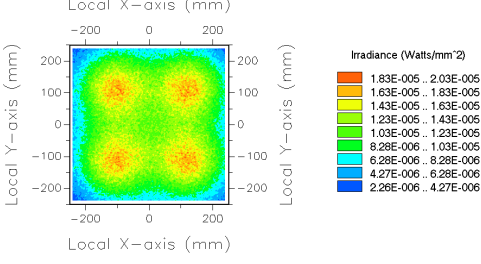
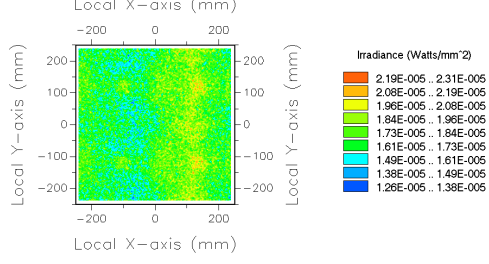
S3. Light uniformities of the 48 cm×48 cm LED panel with different numbers of LEDs

The irradiance for 2×2, 3×3 and 5×5 LED arrays are simulated in Table S1, S2 and S3, for a 48 cm×48 cm LED with Luminus SST-10-B blue LEDs and Osram GH CSSRM4.24 red LEDs. The pitches of the 2×2, 3×3, 4×4 and 5×5 LED arrays on the panel are 24, 16, 12 and 9.6 cm, respectively.

Table S1: Simulations of a 2×2 LED array on a 48 cm×48 cm sized LED panel. (a) shows the light uniformities of blue LEDs and (b) shows the light uniformities of red LEDs, when the LED panel is at a distance of 5, 10, and 15 cm to a plant area of 48 cm×48 cm, respectively. The LEDs are Luminus SST-10-B blue LEDs and Osram GH CSSRM4.24 red LEDs at 120° view angle.

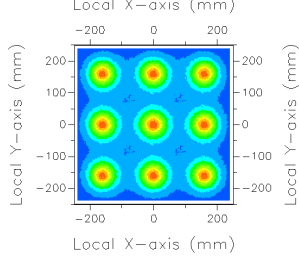
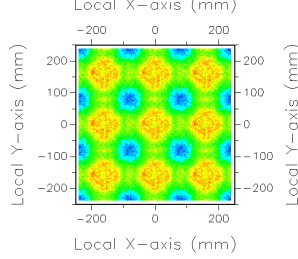
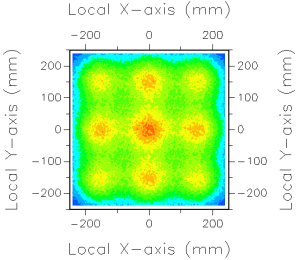
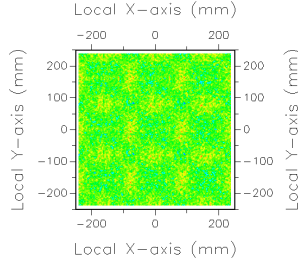
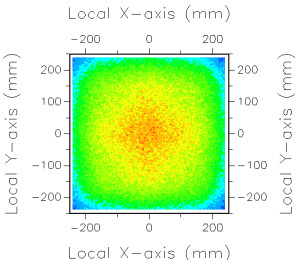
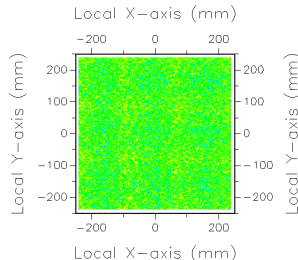
Condition	4 blue LEDs without our solution	4 blue LEDs with our solution
Lighting at 5 cm from LED panel	 <p>Uniformity = 0.04</p>	 <p>Uniformity = 0.22</p>
Lighting at 10 cm from LED panel	 <p>Uniformity = 0.15</p>	 <p>Uniformity = 0.75</p>
Lighting at 15 cm from LED panel	 <p>Uniformity = 0.24</p>	 <p>Uniformity = 0.78</p>

(a)

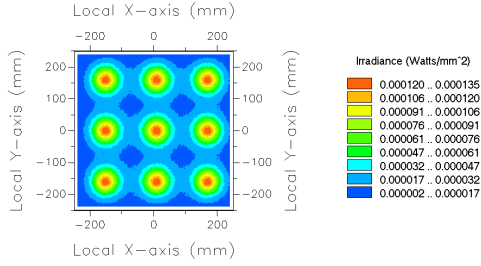
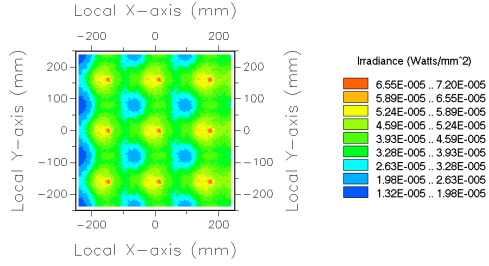
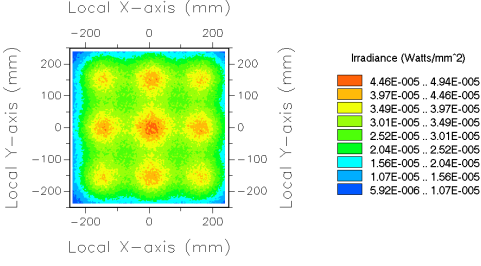
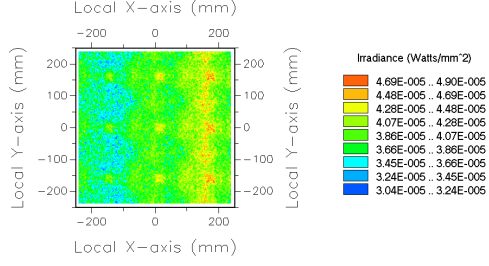
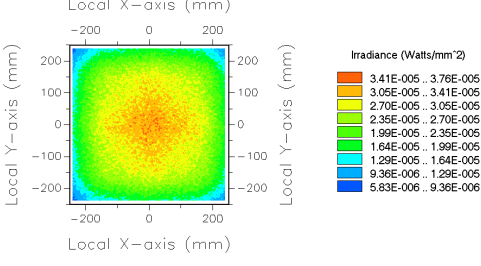
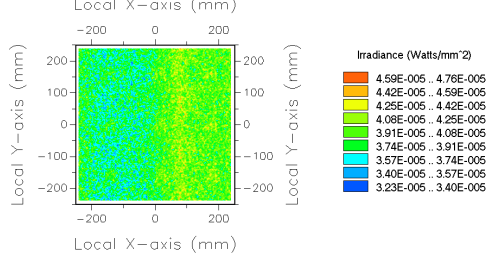
Condition	4 red LEDs without our solution	4 red LEDs with our solution
Lighting at 5 cm from LED panel	 <p>Uniformity = 0.02</p>	 <p>Uniformity = 0.09</p>
Lighting at 10 cm from LED panel	 <p>Uniformity = 0.12</p>	 <p>Uniformity = 0.69</p>
Lighting at 15 cm from LED panel	 <p>Uniformity = 0.19</p>	 <p>Uniformity = 0.73</p>

(b)

Table S2: Simulations of a 3×3 LED array on a $48 \text{ cm} \times 48 \text{ cm}$ sized LED panel. (a) shows the light uniformities of blue LEDs and (b) shows the light uniformities of red LEDs, when the LED panel is at a distance of 5, 10, and 15 cm to a plant area of $48 \text{ cm} \times 48 \text{ cm}$, respectively. The LEDs are Luminus SST-10-B blue LEDs and Osram GH CSSRM4.24 red LEDs at 120° view angle.

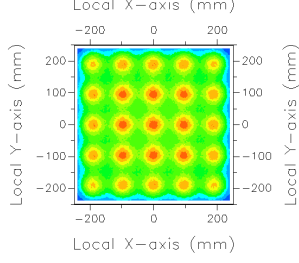
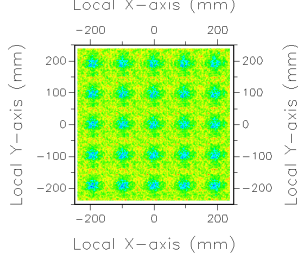
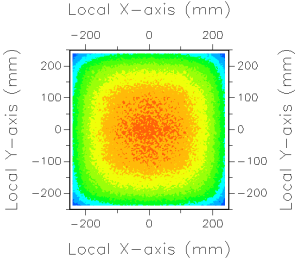
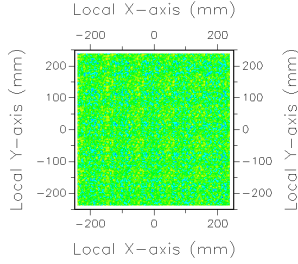
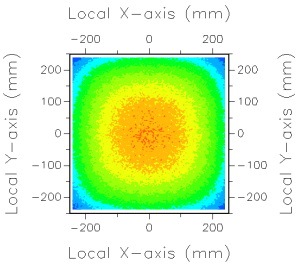
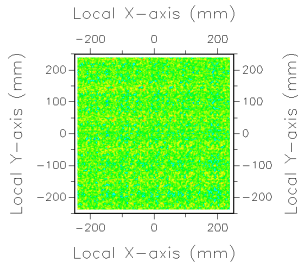
Condition	9 blue LEDs without our solution	9 blue LEDs with our solution
Lighting at 5 cm from LED panel	 <p>Uniformity = 0.13</p>	 <p>Uniformity = 0.60</p>
Lighting at 10 cm from LED panel	 <p>Uniformity = 0.26</p>	 <p>Uniformity = 0.83</p>
Lighting at 15 cm from LED panel	 <p>Uniformity = 0.32</p>	 <p>Uniformity = 0.83</p>

(a)

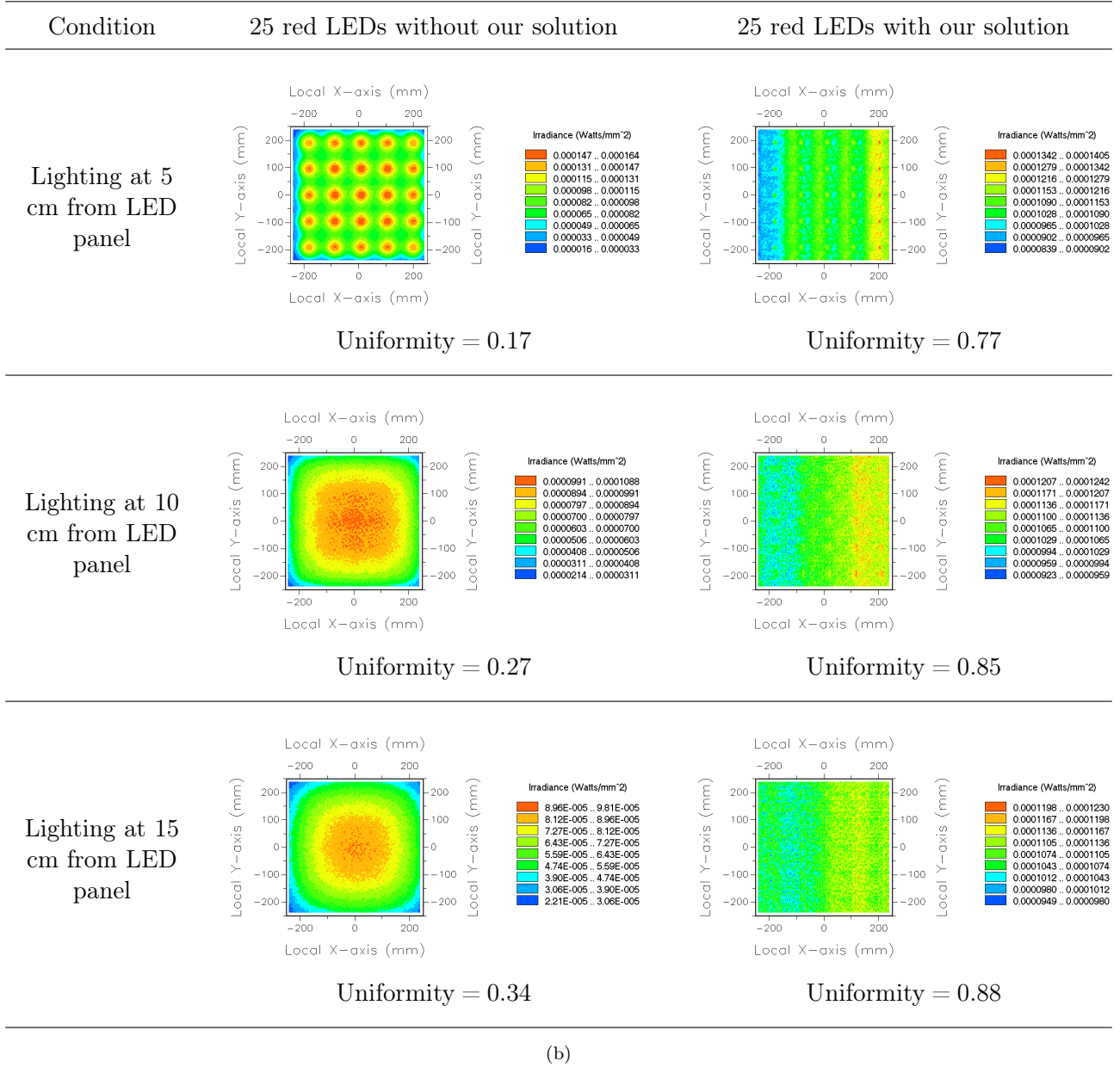
Condition	9 red LEDs without our solution	9 red LEDs with our solution
Lighting at 5 cm from LED panel	 <p>Uniformity = 0.06</p>	 <p>Uniformity = 0.34</p>
Lighting at 10 cm from LED panel	 <p>Uniformity = 0.20</p>	 <p>Uniformity = 0.78</p>
Lighting at 15 cm from LED panel	 <p>Uniformity = 0.24</p>	 <p>Uniformity = 0.83</p>

(b)

Table S3: Simulations of a 5×5 LED array on a $48 \text{ cm} \times 48 \text{ cm}$ sized LED panel. (a) shows the light uniformities of blue LEDs and (b) shows the light uniformities of red LEDs, when the LED panel is at a distance of 5, 10, and 15 cm to a plant area of $48 \text{ cm} \times 48 \text{ cm}$, respectively. The LEDs are Luminus SST-10-B blue LEDs and Osram GH CSSRM4.24 red LEDs at 120° view angle.

Condition	25 blue LEDs without our solution	25 blue LEDs with our solution
Lighting at 5 cm from LED panel	 <p>Local X-axis (mm) -200 0 200 Local Y-axis (mm) -200 0 200</p> <p>Irradiance (Watts/mm²)</p> <p>0.000134 .. 0.000148 0.000119 .. 0.000134 0.000105 .. 0.000119 0.000091 .. 0.000105 0.000077 .. 0.000091 0.000062 .. 0.000077 0.000048 .. 0.000062 0.000034 .. 0.000048 0.000020 .. 0.000034</p> <p>Uniformity = 0.22</p>	 <p>Local X-axis (mm) -200 0 200 Local Y-axis (mm) -200 0 200</p> <p>Irradiance (Watts/mm²)</p> <p>0.0001163 .. 0.0001190 0.0001136 .. 0.0001163 0.0001109 .. 0.0001136 0.0001082 .. 0.0001109 0.0001055 .. 0.0001082 0.0001028 .. 0.0001055 0.0001001 .. 0.0001028 0.0000975 .. 0.0001001 0.0000948 .. 0.0000975</p> <p>Uniformity = 0.87</p>
Lighting at 10 cm from LED panel	 <p>Local X-axis (mm) -200 0 200 Local Y-axis (mm) -200 0 200</p> <p>Irradiance (Watts/mm²)</p> <p>8.95E-005 .. 9.79E-005 8.11E-005 .. 8.95E-005 7.27E-005 .. 8.11E-005 6.44E-005 .. 7.27E-005 5.60E-005 .. 6.44E-005 4.76E-005 .. 5.60E-005 3.92E-005 .. 4.76E-005 3.08E-005 .. 3.92E-005 2.24E-005 .. 3.08E-005</p> <p>Uniformity = 0.32</p>	 <p>Local X-axis (mm) -200 0 200 Local Y-axis (mm) -200 0 200</p> <p>Irradiance (Watts/mm²)</p> <p>0.0001176 .. 0.0001199 0.0001154 .. 0.0001176 0.0001132 .. 0.0001154 0.0001109 .. 0.0001132 0.0001087 .. 0.0001109 0.0001065 .. 0.0001087 0.0001042 .. 0.0001065 0.0001020 .. 0.0001042 0.0000998 .. 0.0001020</p> <p>Uniformity = 0.92</p>
Lighting at 15 cm from LED panel	 <p>Local X-axis (mm) -200 0 200 Local Y-axis (mm) -200 0 200</p> <p>Irradiance (Watts/mm²)</p> <p>7.79E-005 .. 8.49E-005 7.09E-005 .. 7.79E-005 6.39E-005 .. 7.09E-005 5.69E-005 .. 6.39E-005 4.99E-005 .. 5.69E-005 4.28E-005 .. 4.99E-005 3.58E-005 .. 4.28E-005 2.88E-005 .. 3.58E-005 2.18E-005 .. 2.88E-005</p> <p>Uniformity = 0.38</p>	 <p>Local X-axis (mm) -200 0 200 Local Y-axis (mm) -200 0 200</p> <p>Irradiance (Watts/mm²)</p> <p>0.0001162 .. 0.0001184 0.0001140 .. 0.0001162 0.0001117 .. 0.0001140 0.0001095 .. 0.0001117 0.0001073 .. 0.0001095 0.0001050 .. 0.0001073 0.0001028 .. 0.0001050 0.0001005 .. 0.0001028 0.0000983 .. 0.0001005</p> <p>Uniformity = 0.91</p>

(a)



S4. Simulations and analyses of light uniformities for the fabricated LED panel

Comparisons between simulations and experiments can be found on Figure S3 and S4.

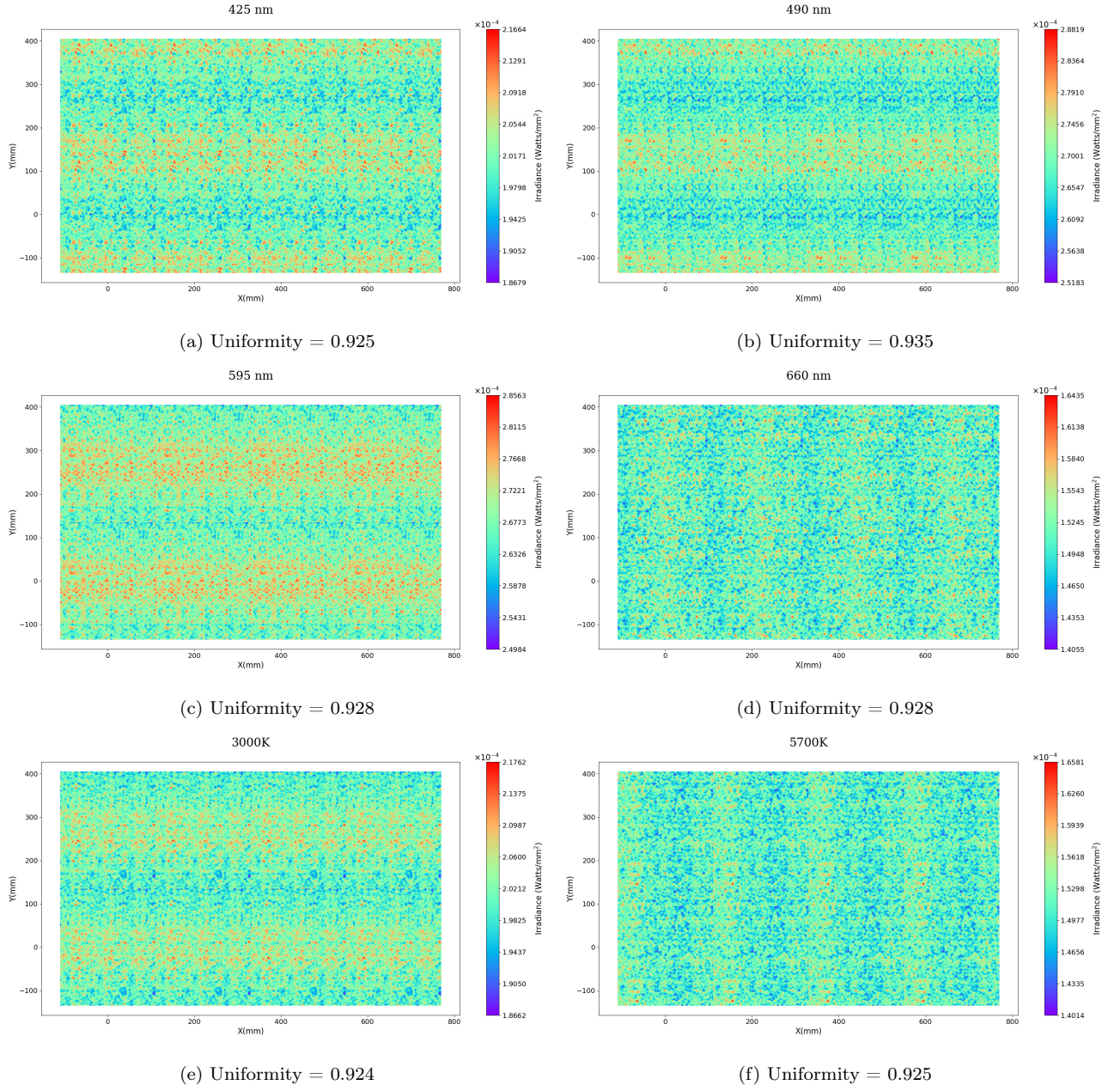


Figure S3: Simulations of light uniformities for 3000k white LEDs (SST-20-W30H-A120 at a view angle of 120°) at the locations of (a) 425 nm LEDs, (b) 495 nm LEDs, (c) 595 nm LEDs, (d) 660 nm LEDs, (e) 3000K LEDs and (f) 5700K LEDs, on the fabricated LED panel. The fabricated LED panel is at a size of 88 cm×54 cm and a distance of 15 cm to an 88 cm×54 cm illuminated area. The four sides of the LED panel are installed with 15cm high reflectors with 100% reflectance.

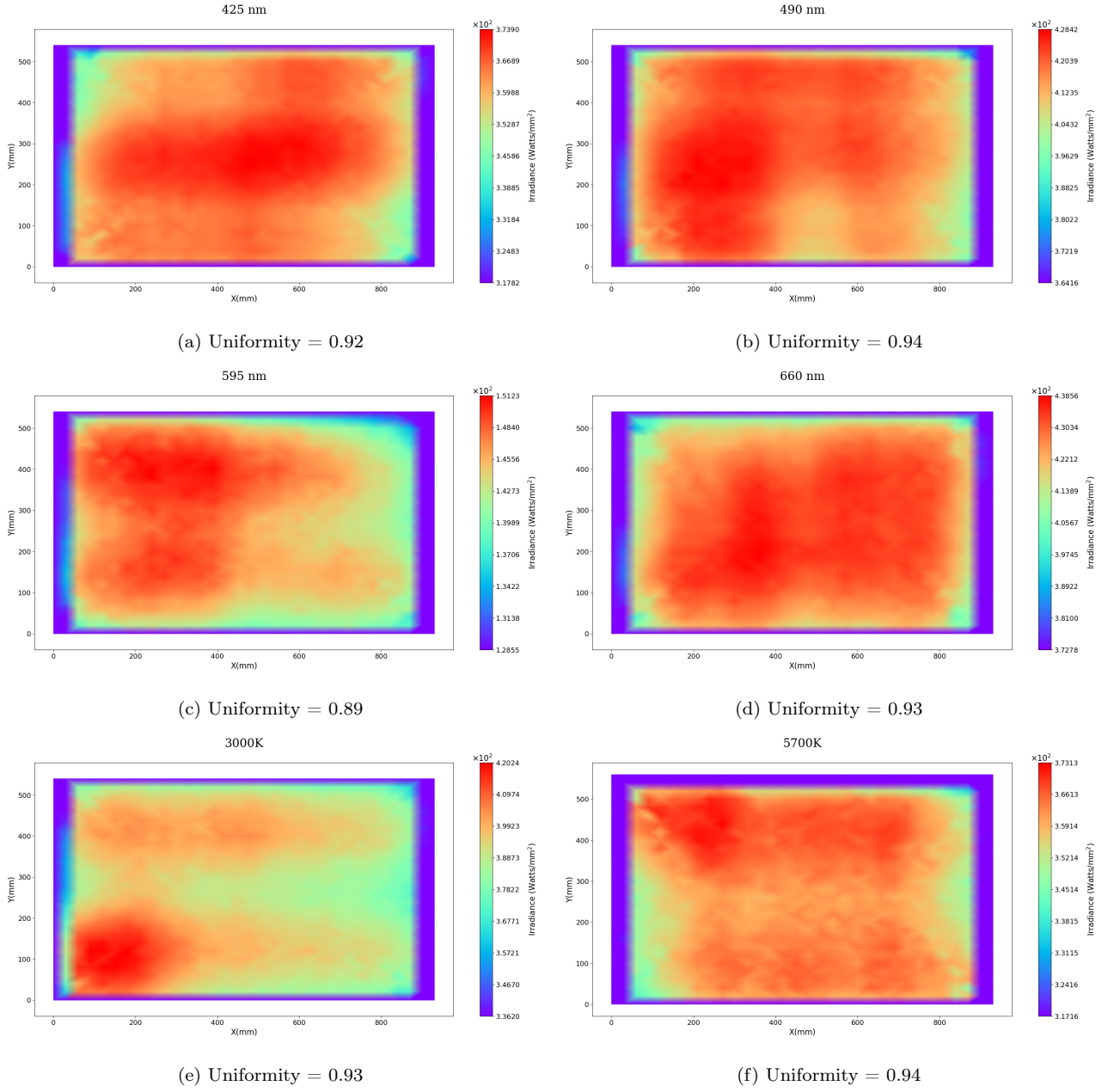


Figure S4: Analyses of light uniformities characterized for the fabricated 88 cm \times 54 cm LED panel within an 88 cm \times 54 cm illuminated area 15 cm below the LEDs, for the LEDs at wavelengths of (a) 425, (b) 495, (c) 595, (d) 660 nm, and white LEDs at color temperatures of (e) 3000K and (f) 5700K. Four 15cm high mirrors were installed at the sides of the LED panel during the characterization.