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Reducing Lighting Energy Use in Controlled Agricultural Environments

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Abstract. **Photometric simulations using both daylight and electric lighting were performed to compare the energy use of conventional high-pressure sodium (HPS) greenhouse lighting to that of light-emitting diode (LED) lighting. Photometric simulations of a hypothetical greenhouse were performed in three different geographic locations in the United States with widely different annual daylight availability: Albany, NY, Fairbanks, AK, and Phoenix, AZ. Simulation conditions included summer and winter, overcast and clear skies, and several lighting layouts and distributions. The analysis showed that, while maintaining the criteria levels of photosynthetic photon flux density, lighting energy savings were primarily attributable to increased LED source efficacy rather than HPS. Secondary energy savings were attributable to the ability to continuously dim LED lighting in response to daily and seasonal changes in daylight. Despite options for LED luminaires with a slim form factor, reduced crop shading compared with larger conventional HPS luminaires did not result in significant lighting energy savings.**

The greenhouse as we know it dates as far back as the late 1700s in Europe, and it was used in commercial agriculture in England, France, and the United States by the late 1800s (Dalrymple 1973; Nemali 2022). Some of the crucial features of greenhouses, like transparent glazing and the generation of heat, date back to the Roman Empire and emerged again in the historical records of Renaissance Europe (Dalrymple 1973). The first recorded use of “artificial lighting” in greenhouses dates back to the mid-1800s (Dutta Gupta 2017; Wheeler 2008), but it was not until the early 20th century that supplemental electric lighting was used in commercial greenhouses for the promotion of plant growth (Pinho and Halonen 2014; van den Muijzenberg 1980).

Electric lighting technology in controlled horticulture environments initially consisted of incandescent filament sources, followed by fluorescent and high-intensity discharge (HID) sources such as high-pressure sodium (HPS) and metal-halide (MH) lamps (Dutta Gupta 2017). These fluorescent and discharge lamps had longer life spans, higher efficacies [photosynthetic photon flux (PPF) per watt ($PPF{\cdot}W^{-1}$)], and superior spectral output for the promotion of photosynthesis than the preceding incandescent sources, and they became the standard supplemental light source in commercial horticulture by the mid-20th century (Dutta Gupta 2017).

Light-emitting diode (LED) luminaires were first investigated as a photosynthetic radiation source in horticulture applications in the early 1990s (Bula et al. 1991). LEDs have since emerged as popular supplemental light sources for greenhouses, in large part because of their increased spectral control and greater efficacy. In horticulture, usable light from a luminaire is defined as PPF, which is measured in micromoles per second ($\mu mol{\cdot}s^{-1}$), or the total rate of the flow of photons within the photosynthetically active radiation (PAR) spectral region (between 400 and 700 nm) (Tibbitts 1993). LEDs can provide precise spectral control and, as such, the photosynthetic photon efficacy (PPE), which is measured in micromoles per joule ($\mu mol{\cdot}J^{-1}$), of some LED sources outperforms that of HPS or MH lamps. Some currently available LEDs produce a PPE $\geq 2.5\ \mu mol{\cdot}J^{-1}$, with some studies suggesting a theoretical upper limit of $>4\ \mu mol{\cdot}J^{-1}$ for LED luminaires (Kusuma et al. 2020; Stober 2017) compared with PPEs of 1.7 or 1.46 $\mu mol{\cdot}J^{-1}$ for HPS or MH luminaires, respectively (Stober 2017). Spectral tuning and high PPE have made LED luminaires an attractive option for growers who want to save lighting energy in horticultural applications. Moreover, the ease with which LED luminaires can be continuously dimmed in response to available daylight can provide additional energy savings.

Nelson and Bugbee (2014) were among the first to compare HPS and LED luminaires for controlled agriculture. Although the luminaire efficacies, energy costs, and equipment cost values have rapidly advanced since the publication of their work, the authors provided a solid framework for comparing some of the important differences between the two lighting technologies. Recent studies have taken an application-based approach to investigating the total energy savings potential of LED lighting in greenhouses when also considering the increase in heating energy required by switching to LEDs from HPS sources (Dieleman et al. 2016; Dueck et al. 2011; Katzin et al. 2021). Katzin et al. (2021) found that transitioning from HPS to LED sources in greenhouses saved 40% in lighting energy. However, total energy savings were reduced to 10% to 25% when accounting for the increased heating energy required by changing to LEDs, which emit much less heat energy than HPS sources, across a wide range of climactic conditions (Katzin et al. 2021).

Less prevalent in the literature are studies that have examined the potential energy savings of LED horticulture luminaires attributable to the optimization of the luminaire form factor and layout (Nelson and Bugbee 2014). Low-profile, linear LED luminaires have the potential to align better with greenhouse structural elements compared with bulky HPS luminaires, thus reducing the shadowing of daylight on the crop surface and reducing the overall amount of supplemental electric lighting required to maintain the grower’s target PPF density (PPFD), which is measured in spectrally weighted micromoles per second per square meter ($\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$).

Marcelis et al. (2006) demonstrated a linear relationship between average PPFD values and crop yield (up to a saturation point), suggesting that a 1% increase in the average PPFD will correlate with a 1% increase in crop yield; perhaps it is a small percentage, but on industrial scales, a 1% increase in yield can make a large difference in production output and growers’ profits (Marcelis et al. 2006). Additionally, improving the uniformity of the PPFD by tailoring the intensity distribution of LED luminaires within the greenhouse, for example, near the greenhouse perimeter, can ensure that a criterion PPFD will be met for the entire greenhouse crop. This strategy can reduce the overall electric lighting energy needed for growers to reach the target PPFD for crops in otherwise dimly illuminated areas of the greenhouse without overly lighting the rest of the crop. As an aside, tailoring the lighting intensity distribution for the geometry of a building space is a well-established practice in architectural applications; however, so far, it is one that is not widely exploited in horticulture lighting. Thus, supplemental electric lighting for greenhouses is potentially appealing to growers because it can, when properly designed and implemented, maintain photosynthetic activity in crops when daylight is absent, nonuniform, or simply insufficient to reach the criterion PPFD required for crop production.

The present study analyzed the interaction between daylight and two types of supplemental electric lighting needed to achieve a criterion PPFD uniformly in an exemplary virtual greenhouse located in three different

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cities in the United States during two different seasons of the year and under two different sky conditions. During these analyses, we also examined the potential energy savings of reduced shadowing from luminaires of different numbers, form factors, efficacies (PPF·W^{-1}), and intensity distributions for these 12 scenarios.

Materials and Methods

Photometric simulation model. An exemplary, arbitrarily constructed virtual greenhouse measuring 11 m × 9.1 m with a 4.6-m-high gabled ceiling was modeled using a photometric simulation software program (AGi32 version 20; Lighting Analysts, Littleton, CO, USA). Photometric simulation software programs are generally used to design luminaire layouts for architectural applications (e.g., classrooms, offices, roadways, etc.). These programs provide photopic illuminance values where the spectral power distributions of the light sources are weighted by the photopic luminous efficiency function, V(λ) (Commission Internationale de l'Éclairage 1924). These photopic illuminance values (in footcandles or lux) can be easily translated to values of PPFD by linear transformation of the V(λ)-weighted spectral irradiance values into PAR-weighted spectral irradiance values. All calculations performed during the present analysis used Imperial units and were converted to SI-compliant units for this contribution.

The AGi32 software uses a full radiosity calculation technique; after calculating direct irradiance, the software calculates interreflections. Each structure in the model is broken into small pieces ("patches") that are further subdivided ("elements"). Each patch reacts with the other elements that are visible to it by reflecting light toward them, which the software repeats, one step at a time, until the amount of light remaining unabsorbed in the model is very small. Then, the software adds the total amount of light reflected by each patch.

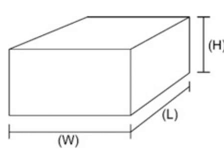
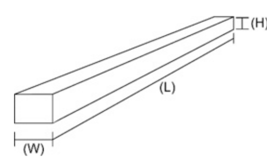
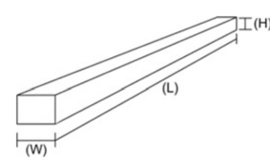
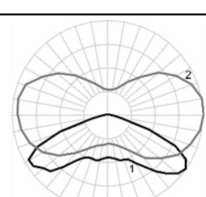
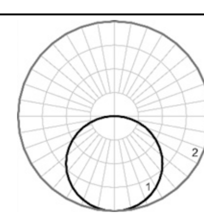
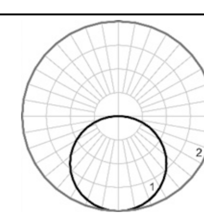
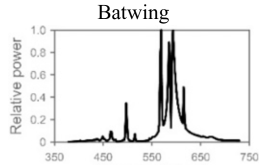
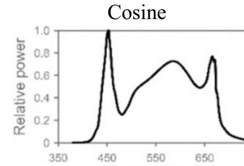
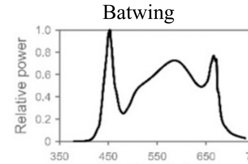
The software default subdivision is four elements per patch; because a shadow with a width of 8 cm is greater than half of a 15-cm calculation grid, the default element subdivision is expected to register such a shadow, both for direct and inter-reflected contributions.

The modeled greenhouse had an open structure with 10 trusses, 2.4 m above grade, spanning the width of the space for structural support and 5-cm-thick horizontal beams for mounting luminaires. The truss structure had a reflectance value of 0.5, and the greenhouse was skinned with transparent glass with a transmittance value of 0.9. The floor of the greenhouse had a reflectance value of 0.2. A uniform grid of horizontal PPFD calculation points spaced 15 cm × 15 cm apart and located 76 cm above grade was defined by the photometric software to quantify the optical performance (amount and distribution) of the lighting system for uniformly delivering an average PPFD to the crop surface. Figure 1 shows photometric software renderings of the greenhouse for the two sky conditions used during the analysis: clear and overcast.

Luminaire specifications. Three different virtual luminaires were evaluated for this study based on their photometric performance and any shading caused by their housing form factor. Two of the luminaires, an HPS luminaire and an LED linear luminaire (LED Luminaire 1), were based on commercially available products. The third luminaire (LED Luminaire 2) was a variation of LED Luminaire 1, with an intensity distribution optically modified to match that of the HPS luminaire. As discussed in greater detail, the PPF and wattage values of LED Luminaire 2 were mathematically adjusted, keeping the luminaire efficacy (PPF·W^{-1}) constant, to deliver a criterion PPFD for two different luminaire layouts. Again, the assumption was that the form factors and intensity distributions of these virtual luminaires were largely representative of the range of luminaires available for greenhouse horticulture. We further assumed that the form factor and intensity distribution of the HPS luminaire were common in greenhouse horticulture today and, consequently, this fixture type served as the base case for our analyses.

Table 1 provides the specifications of the three luminaires used during the analysis. The specifications include the PPF of each luminaire, the electrical power demand of each luminaire in watts, and the photosynthetic

Table 1. Specifications of the luminaires used for the analysis.

			LED Luminaire 2	
Attribute	HPS Luminaire	LED Luminaire 1	2a	2b
Photosynthetic photon flux (PPF)	941	679	831	961
Electric power (watts, W)	690	300	368	425
PPF·W^{-1}	1.36	2.26	2.26	2.26
Photosynthetic photon flux density (PPFD) factor (unitless)	11.7	15.4	15.4	15.4
Housing dimensions (cm)	 54.6 × 27.9 × 19 (L × W × H)	 121.9 × 8.3 × 7.6 (L × W × H)	 121.9 × 8.3 × 7.6 (L × W × H)	
Intensity distribution: (1) vertical (2) horizontal				
Relative spectral power distribution	Batwing 	Cosine 	Batwing 	

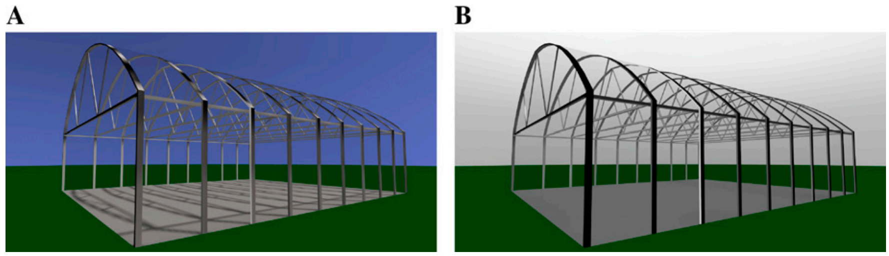


Fig. 1. Renderings of the greenhouse model using photometric simulation software AGi32 for the clear sky condition (**A**) and the overcast sky condition (**B**).

efficacy of each luminaire in terms of PPF per watt. The spectral PPFD factor for each luminaire indicates the conversion factor for each luminaire based on the spectral power distribution (SPD) of the source for translating photopic illuminance to the PPFD. The higher the PPFD factor, the more efficiently the light source stimulates photosynthesis in a plant. Table 1 also includes the intensity distribution and relative SPD of each luminaire's light source. Table 1 also provides the physical dimensions of the luminaires. The LED luminaires were chosen because of their slim design and relatively small form factor (7689 cm^3) to minimize shading. The selected larger HPS luminaire (28,943 cm^3) was neither the largest nor the smallest form factor available commercially.

Lighting conditions. The daylighting conditions used during the analysis were selected to encompass the wide range of daylight availability in the United States attributable to season, sky condition, geographical location, and time of day. Then, we assessed how these conditions affected the electric lighting energy requirements for the base case lighting layout and the three redesigned layouts, for a total of four layouts, as illustrated in Fig. 2. These layouts were chosen to represent ones that might be typically designed by a lighting specialist to provide supplemental lighting in a greenhouse.

To assess the impact of the greenhouse location in the United States, three different cities were selected for analysis: Albany, NY (42.6526°N, 73.7562°W); Fairbanks, AK (64.8401°N, 147.7200°W); and Phoenix, AZ (33.4484°N, 112.0740°W). To assess the effect of season, lighting calculations were conducted at the time of the summer solstice (when the sun is the highest in the sky and above the horizon for the longest period) and winter solstice (when the sun is lowest in the sky and above the horizon for the shortest period). Because they can both occur at any location, clear and overcast daytime sky conditions were used; both were predefined by the photometric software. Specifically, the software uses standard models for clear and overcast sky developed under a wide range of conditions, from the heavily overcast sky to cloudless weather. The purpose of these industry standards is to enable detailed calculations of extremes in daylight exposure (Commission Internationale de l'Éclairage 2004).

Two of the three selected cities in the United States represent extremes in terms of clear or partly sunny days (Climate-Zone.com 2023), seasonal daylength (Time and Date AS 2023), and solar altitude angle conditions. Fairbanks, AK, has both the fewest (≈4 h at the time of the winter solstice) and the most (≈20 h at the time of the summer solstice) daylight hours per day, as well as very few clear or partly sunny days (156 per year). At the other extreme, Phoenix, AZ, has many more daylight hours per day (≈10 h at the time of the winter solstice and ≈14 h at the time of the summer solstice), as well as the greatest number of clear or partly sunny

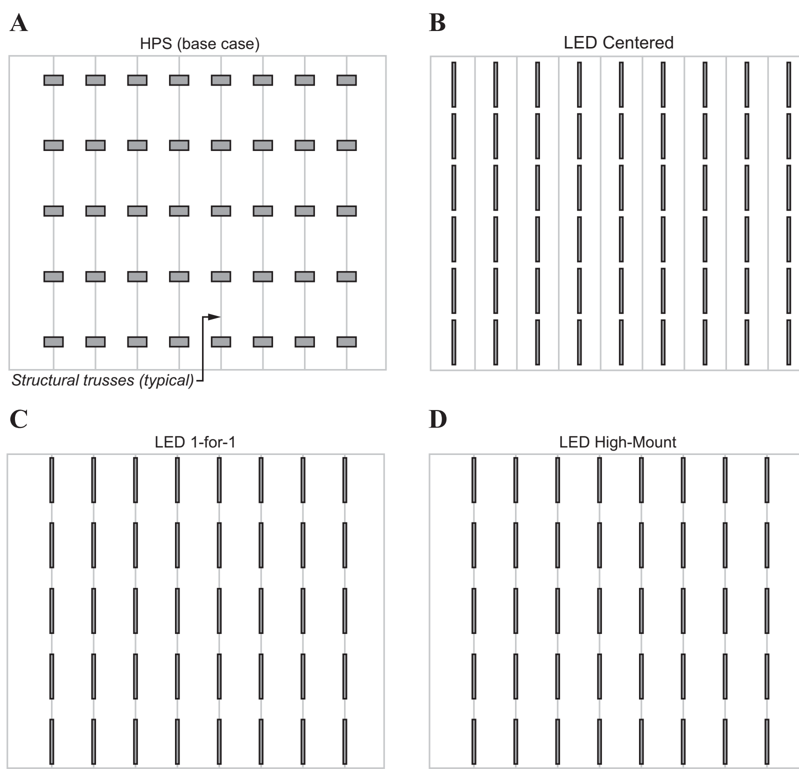


Fig. 2. The luminaire layouts used for the photometric simulations. (**A**) High-pressure sodium (HPS) base-case layout showing the HPS luminaire suspended 0.6 m from the greenhouse truss structure (1.6 m above grade) and spaced 1.2 m × 1.9 m on-center (OC) to deliver the target photosynthetic photon flux density (PPFD) value of 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$ on the crop plane. (**B**) Light-emitting diode (LED) Centered layout with luminaires (LED Luminaire 1) suspended 0.7 m from the greenhouse truss structure (1.6 m above grade) and spaced 1.2 m × 1.5 m OC. (**C**) Layout for the LED one-for-one HPS replacement layout with luminaires (LED Luminaire 2a) suspended 0.7 m from the greenhouse truss structure (1.6 m above grade) spaced 1.2 m × 1.9 m OC. (**D**) LED High-Mount layout (LED Luminaire 2b) with the same luminaire spacing as that used for LED one-for-one, but mounted directly to the overhead truss structure 2.3 m above grade.

days in the United States (296 per year). Albany, NY, was chosen because it has 180 clear or partly sunny days per year, which is close to the United States average (205 clear or partly sunny days per year). Albany experiences ≈9 h of daylight at the time of the winter solstice and ≈15 h of daylight at the time of the summer solstice, and it is also the location of our laboratory. For comparisons of location, sky condition, and season, the solar day was defined as a 12-h period with a total of 13 time points when daylighting calculations were performed. The 13 time points were centered around solar noon (the time point at which the sun is highest in the sky) for each geographical location. A total of 48 lighting simulations encompassing all combinations of the two seasons, two sky conditions, three geographic locations, and four luminaire layouts were performed.

The electric lighting layouts were designed to deliver a criterion mean value of 300 PPFD on the crop plane while maximizing the uniformity of flux density on the crop plane. The virtual luminaires were suspended from the virtual cross members of the greenhouse, and the spacing between luminaires was adjusted to provide maximum uniformity on the crop plane. This PPFD value was chosen because it is often recommended for lettuce (Kelly et al. 2020; Plant Light 2022; Stutte et al. 2009). Lettuce was chosen as the theoretical crop because it is primarily a horizontally distributed crop surface—unlike tomato plants, which are much taller and benefit from light incident on the entire vertical structure of the plant and often require lights positioned between the plants and emitting light horizontally. Importantly, 300 PPFD is toward the upper end of the linear operating range of photosynthetic activation for lettuce; nonetheless, its selection permits extrapolation of the present results to other crops where the operating range of photosynthetic activation is low and below saturation, as with shade plants, or high and above threshold, as with sun plants.

For the following simulations, the light output and wattage of the luminaires were mathematically adjusted to deliver the criterion mean value of 300 PPFD. Although it is technically possible to dynamically dim some luminaires more than others, all the luminaires were assumed to operate at the same output for these calculations. The base case lighting layout (Fig. 2A) used the HPS luminaire (with a wide "batwing" intensity distribution) to deliver the target PPFD value of 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$ on the crop plane within the structural confines of the greenhouse (luminaires were suspended from the trusses to a height of 1.6 m from the bottom of the luminaires to the ground and spaced as needed to reach the PPFD target evenly across the crop plane). When the base case layout was established, the next step was to redesign the greenhouse electric lighting with commercially available LED Luminaire 1 (with a typical "cosine" intensity distribution) to determine whether the target PPFD value could still be met (LED Centered) (Fig. 2B). For the LED lighting layout, the luminaires had to be spaced between the greenhouse trusses to deliver the criterion average PPFD to the crop surface as uniformly as possible (0.24 minimum/maximum). The target PPFD and uniformity requirement could be met with this layout, but more luminaires were required (54 LED luminaires compared with 40 HPS) because the total PPF generated by a given commercially available LED luminaire was less than that from an HPS luminaire. The added number of LED luminaires between the trusses implies more shadowing of daylight on the crop plane, but the LED luminaires have a smaller profile than the HPS luminaires, suggesting that the added number of fixtures might have no net effect on shadowing.

Results

Comparison between layouts for two commercially available luminaire types, HPS and LED Luminaire 1. The heights of the bars in all panels of Fig. 3 show how much each of the three factors (PPE, dimming, and shadowing) contributed to the mean electric lighting energy saved for each of the three LED luminaire layouts compared with the base-case HPS layout. Figure 3 also shows individual points that are the contributing sources to the mean electric energy saved (bar heights); each point represents one of the 12 combinations of season, sky condition, and geographic location.

Figure 3A indicates the mean electric lighting energy required (97.1 $kWh \cdot day^{-1}$) and saved, relative to the HPS (base case) luminaire layout (128.3 $kWh \cdot day^{-1}$), by the LED Luminaire 1 layout to deliver the criterion mean value of 300 PPFD with maximum uniformity. Also shown by the 12 individual points are the sources of the energy savings for each of the three factors.

On average, the LED Centered layout using the commercially available LED Luminaire 1 (cosine intensity distribution) required 55% less electric energy to reach the criterion 300 PPFD mean value on the crop surface with maximum uniformity compared with the HPS luminaire layout. This reduction in electric energy was primarily attributable to the higher PPE (efficacy) of the LED luminaire (2.26 $\mu mol \cdot J^{-1}$ for the LED luminaire compared with 1.36 $\mu mol \cdot J^{-1}$ for the HPS luminaire), resulting in 92.8 $kWh \cdot day^{-1}$ saved, on average (a 41% reduction), for the LED

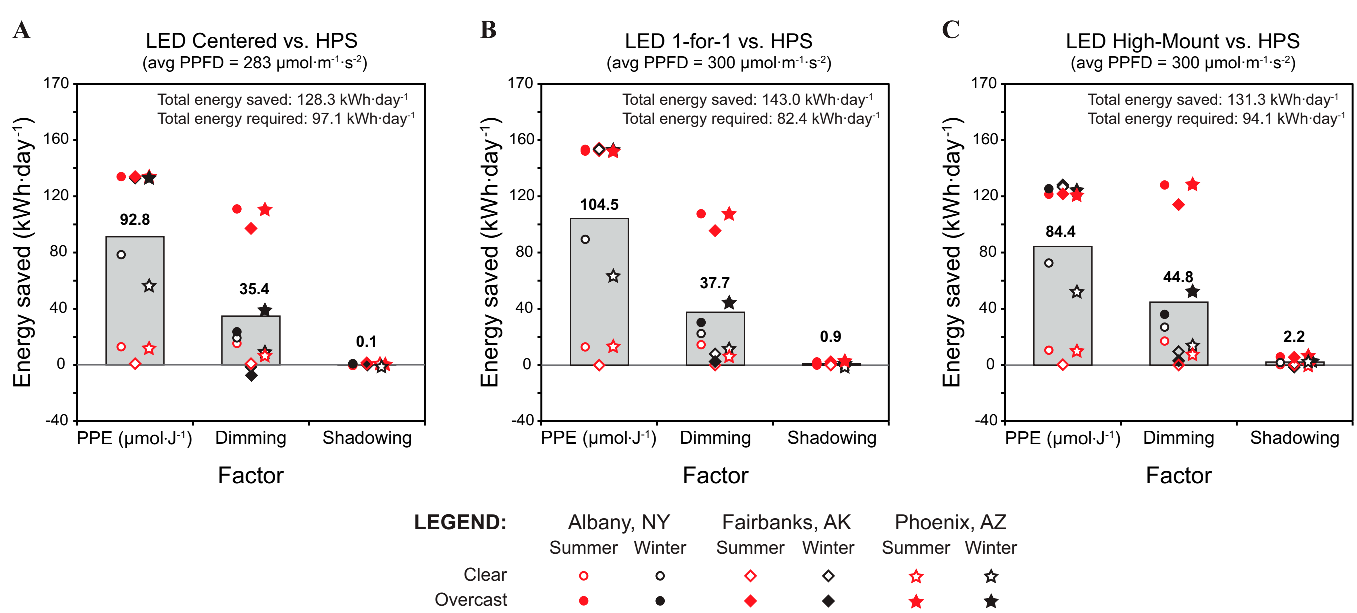


Fig. 3. Three factors (photosynthetic photon efficacy, dimming, and shadowing) contributing to the total average energy savings and bar heights of the three light-emitting diode (LED) luminaire layouts compared with the base-case high-pressure sodium (HPS) layout, as well as the 12 contributors (three cities, two seasons, and two sky conditions) to savings for each factor.

Centered layout. The additional average savings of 35.37 kWh·day^{-1} (a 14% reduction) was primarily a result of dimming the LED luminaires continuously in response to the presence of daylight; this is something HPS luminaires are not typically capable of achieving. Less than 1% of the net average energy savings from the LED Centered layout compared with the HPS layout resulted from a reduction in the amount of shadowing created by the greater number but slimmer LED luminaires. Again, the LED Centered layout required more luminaires (LED Luminaire 1) to reach the target 300 PPFD value on the crop surface (54 LED luminaires compared with 40 HPS), and the LED luminaires had to be spaced between the greenhouse truss structures to deliver the PPFD to the crop surface as uniformly as possible (0.24 min/max); therefore, these combined factors (amount and uniformity) negated the benefit of the slim LED luminaire profile in terms of shadow reduction.

Comparison between layouts for two luminaire types, HPS and LED Luminaire 2a, matched for both relative intensity distribution and location. In addition to the difference in luminaire efficacies, there were several differences between the commercially available HPS luminaire layout and commercially available LED Luminaire 1 layout. The commercially available LED Luminaire 1 layout (Fig. 2B) required more luminaires located between trusses, which are suboptimal locations for shadowing. During the next analysis, we minimized those differences by optically modifying the virtual LED luminaire intensity distribution to match the relatively wide batwing distribution of the HPS and locating the optically modified LED luminaires under the trusses at the same locations as the HPS luminaires. To provide the criterion mean value of 300 PPFD on the crop plane and retain uniformity on the crop plane, it was necessary to increase the PPF (flux output) and wattage of these optically modified luminaires (LED Luminaire 2a). Thus, there was a one-for-one replacement of optically modified LED luminaires with increased flux output (LED Luminaire 2a) (Fig. 2C).

As shown in Fig. 3B, the total energy saved (143.0 kWh·day^{-1}) was slightly larger for the layout in Fig. 2C with the optically modified LED luminaire (LED Luminaire 2a) relative to the LED Centered (LED Luminaire 1) luminaire layout in Fig. 2B (143.0 kWh·day^{-1} − 128.3 kWh·day^{-1} = 14.7 kWh·day^{-1} saved on average). Despite the higher wattage, this is primarily caused by the increased optical effectiveness of the LED one-for-one (LED Luminaire 2a) layout compared with the LED Centered (LED Luminaire 1) layout. In other words, compared with the LED Centered layout (and using the same locations as the HPS base-case layout), fewer LED luminaires with the same relative intensity distribution—but with a higher total PPF (flux) and associated wattage—were needed to deliver the criterion mean value of 300 PPFD. Combined, this resulted in lower overall power demand and, thus, greater energy savings than the HPS base case.

Comparison between the HPS layout and LED Luminaire 2b mounted directly to the greenhouse trusses. To determine the benefit of using the slim LED form-factor for reducing shadowing because it might affect lighting energy savings, we analyzed the impact of mounting the optically modified LED luminaires directly to the greenhouse trusses (Fig. 2D). As shown in Fig. 3C, to reach the criterion mean value of 300 PPFD, the energy savings for the LED Luminaire 2b, High-Mount layout was 131.3 kWh·day^{-1}, which is 11.7 kWh·day^{-1} lower than that of the LED one-for-one (LED Luminaire 2a) layout and approximately the same as the savings as the original LED Centered (LED Luminaire 1) layout. This is because, although there was a slight energy benefit from reduced shadowing by raising the luminaires up to the trusses, these energy savings were negated by the further increase in PPF (flux) needed, and thus wattage, by the LED luminaires (LED Luminaire 2b) to maintain the criterion mean value of 300 PPFD uniformly on the crop plane.

Table 2 shows the amount of energy saved solely because of reduced shadowing for the LED one-for-one (LED Luminaire 2a) and the LED High-Mount (LED Luminaire 2b) layouts relative to the HPS base-case layout. Also shown is the difference in savings between the LED Luminaire 2a (Fig. 2C) and LED Luminaire 2b (Fig. 2D) layouts because of shadowing. On overcast days in winter, when the sun is lower in the sky and provides some, but not all, of the light needed to reach the criterion mean value of 300 PPFD, raising the optically modified LED luminaires up against the trusses (Fig. 2D) to reduce shadowing in the greenhouse resulted in approximately 3.5 to nearly 4 more kWh·day^{-1} saved compared with the LED one-for-one layout (Fig. 2C). In most other cases, however, raising the LED luminaires to reduce shadowing made little difference in energy savings, and the gains in energy savings from reduced shadowing were not sufficient to compensate for the additional electric energy required to maintain the 300 PPFD target with the LED luminaires mounted higher in the greenhouse.

Intensity distribution analysis. To further assess the potential energy savings from improving the distribution of photosynthetic flux from the luminaires, LED Luminaire 1, with the typical cosine distribution, was compared with LED Luminaire 2, with the wide batwing distribution. Both luminaires were placed in the one-for-one replacement configuration shown in Fig. 2C. The light output and wattage of the luminaires were mathematically adjusted to deliver the criterion mean value of 300 PPFD as well as the minimum value of 300 PPFD to assess the difference in electric energy required to reach these targets solely as a function of the intensity distribution of the luminaires.

Changing the optics of the LED luminaires from a typical cosine (LED Luminaire 1) to a wide batwing intensity distribution (LED Luminaire 2a) increased the uniformity of the PPFD on the crop surface from 0.15:1 (minimum:average) to 0.23:1, and it increased the minimum PPFD value from 44 μmol·m^{-2}·s^{-1} (LED Luminaire 1) to 70 μmol·m^{-2}·s^{-1} (LED Luminaire 2a) (Fig. 4A). The improvement in PPFD uniformity resulted in a mean 3% energy savings for the LED lighting layout with the batwing intensity distribution luminaire (LED Luminaire 2a) relative to the layout with the cosine intensity distribution (LED Luminaire 1). However, it should be noted that this estimate does not account for the optical losses that would, in practice, result from the use of refractors or reflectors to redistribute light. Practically, then, any energy savings from the batwing distribution during this study would likely be negligible.

When targeting a minimum PPFD value of 300 μmol·m^{-2}·s^{-1} on the crop plane, however, the impact of the intensity distribution on energy savings may be great enough to counteract optical losses. It should be recognized that a grower would not set a minimum PPFD value of 300 μmol·m^{-2}·s^{-1} for the crop plane of lettuce because higher flux densities would simply saturate photosynthetic activation of this crop. Rather, the analysis was performed to show that setting a minimum PPFD value changes the interpretation of the importance of luminaire optics.

The LED layout with LED Luminaire 2a required 39% less energy to reach the minimum

Table 2. Energy (kWh·day^{-1}) saved from reduced shadowing for the optically modified light-emitting diode (LED) one-for-one layout with Luminaire 2a (Fig. 2C) and the optically modified LED High-Mount layout with Luminaire 2b (Fig. 2D) relative to the base-case HPS layout for each geographic location, season, and sky condition. Also shown is the difference in the amount of energy saved (LED High-Mount savings minus the LED one-for-one savings) for each condition.

	Albany, NY				Fairbanks, AK				Phoenix, AZ				
	December		June		December		June		December		June		
Layout	OVC	CLR	OVC	CLR	OVC	CLR	OVC	CLR	OVC	CLR	OVC	CLR	Avg
LED one-for-one	2.25	−0.01	0.97	0.71	2.02	0	0.22	0.35	2.25	0.02	1.02	0.75	0.88
LED High-Mount	5.78	0.13	1.76	1.7	5.45	0	0.20	0.52	6.12	0.28	2.55	1.33	2.15
Difference	3.53	0.14	0.79	0.99	3.43	0	−0.02	0.17	3.87	0.26	1.53	0.58	1.27

AVG = average; CLR = clear; OVC = overcast.

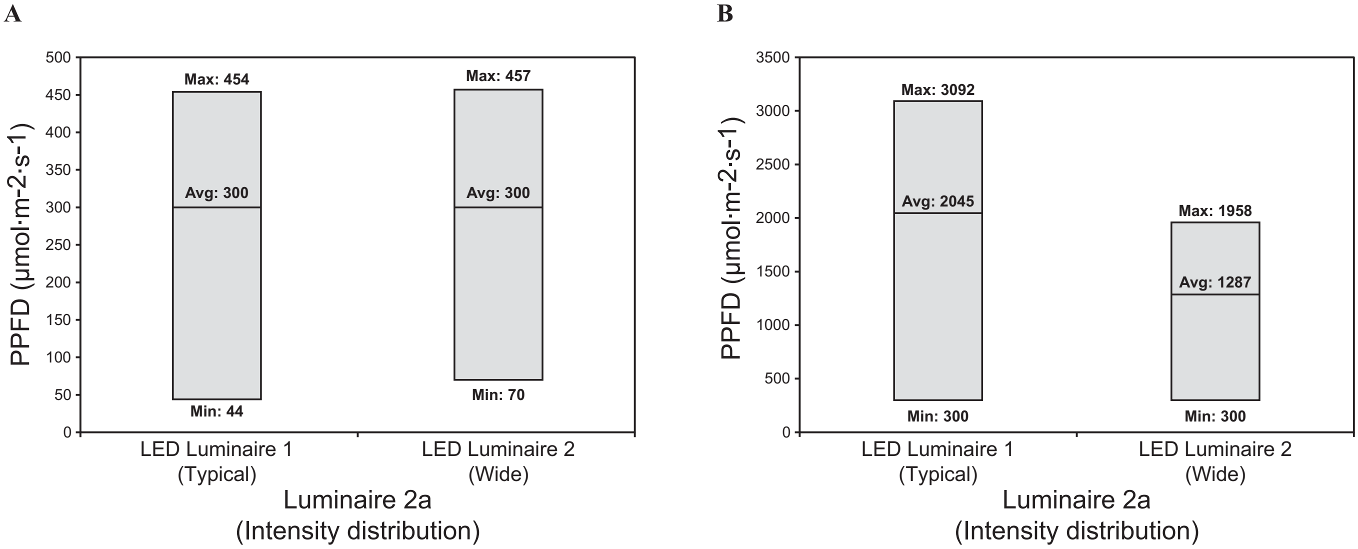


Fig. 4. Box plots comparing the commercially available light-emitting diode (LED) Luminaire 1 to the optically modified batwing distribution LED Luminaire 2a in terms of the criterion mean photosynthetic photon flux density (PPFD) value of 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (**A**) and a target minimum PPFD value of 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (**B**).

value of 300 PPFD compared with the LED layout with LED Luminaire 1 (Fig. 4B). More importantly, however, the desire to set a minimum criterion of PPFD provides a dramatic improvement for the batwing distribution. As previously noted, photosynthetic activation will saturate with some plants, meaning there is no benefit on yield from PPFD values greater than the point of photosynthetic activation saturation. With lettuce, this saturation occurs at approximately 350 to 500 PPFD (Zhou et al. 2022); therefore, higher PPFD levels will not produce more lettuce. Because the maximum (1958) and average (1287) PPFD levels are lower for the batwing distribution than for the cosine distribution maximum (3092) and average (2045) PPFD levels, the former is much more effective in terms of lettuce yield. By lowering the minimum criterion PPFD, much more electric energy from the luminaires could be used to improve crop yield. In general, growers should always be cognizant of photosynthetic activation threshold and saturation levels when optimizing the amount and distribution of PPFD and, therefore, lighting electric energy.

Discussion

Figure 3 clearly shows that the factor with the greatest impact on lighting energy use was simply upgrading the lighting system from HPS to LED technology. Relative to the HPS base case, LEDs offer superior photosynthetic photon flux efficacy (PPE, $\mu mol \cdot J^{-1}$) because of greater wall-plug efficiency and, in part, because of superior spectral efficiency. In this regard, our findings were nearly identical to those of Katzin et al. (2021). Of particular note, the energy savings attributable to higher LED PPE was almost always realized on overcast days, both summer and winter. In contrast, during the summer in Fairbanks, AK, when the sky is clear, PPE has no effect because the lighting system would not be operated.

Again, as shown in Fig. 3, the second priority for achieving lighting energy savings would be dimming the LED lighting at times when daylight is admitted through the greenhouse glazing. Dimming was found to be especially helpful under overcast summer conditions, when daylight contributed a portion, but not all, of the lighting need. Under clear sky conditions (especially during summer), daylight levels were high enough that electric lighting could be turned off entirely, rather than partially dimmed. Growers should consider the typical local sky conditions, balanced with the PPFD needs of the specific crop, to decide whether dimming might be valuable. For example, a greenhouse grower in Fairbanks, AK, will not have much use for dimming in winter, when full illumination would be required most of the time; conversely, under clear summer conditions, so much daylight is available that electric lighting can be switched off entirely. Importantly, dimming can be quite important for seasonally adjusting the PPFD to avoid both photosynthetic activation threshold and saturation levels, thereby maximizing yield. Again, dimming is common for LED systems, but not readily available for HPS systems.

Although LED efficacy and LED dimming are promising for lighting energy savings and crop production in greenhouses, optimization of the luminaire form factor and mounting location had minimal impact on energy savings, especially when the illumination criterion was based on the mean PPFD (as opposed to a minimum PPFD). The amount of electric light required to maintain the criterion mean value of 300 PPFD on the crop plane in the best-case scenario was reduced only approximately 6% using a slimmer luminaire and having it mounted high against the greenhouse truss structures. Although luminaires mounted higher in the greenhouse improved uniformity and reduced shadowing, this also resulted in greater energy use because of the increased flux and wattage required from the optically modified LED luminaires to compensate for the greater distance from the crop plane compared with the LED one-for-one replacement option. Of course, this issue could be resolved by raising the crop bed to maintain the same distance between the luminaires and the crops, as established with the other lighting configurations; however, having the crops located higher and closer to the overhead structures in the greenhouse (as well as luminaires) has the potential to increase shadowing, particularly when the sun is entering the greenhouse at shallow angles, such as in Fairbanks, AK, or during the early morning or late afternoon hours of the day.

We further determined whether the impact of luminaire shadowing interacted with luminaire intensity distribution, or if it can be considered an independent factor. Figure 5 shows the $kWh \cdot day^{-1}$ values needed to reach the criterion mean value of 300 PPFD for the different seasons and geographic locations averaged together (for clear and overcast sky conditions) for each lighting configuration. Also shown is the clear sky condition-to-overcast sky condition ratio of the $kWh \cdot day^{-1}$ needed for each lighting configuration. Except for one case, this ratio was the same for the different LED lighting configurations, indicating that the effect of the luminaire form factor on the shadowing of daylight is independent of the effect of the intensity distribution on energy savings. The one case in which this ratio was not applicable was the HPS base-case lighting configuration. Much higher wattage values at certain times of day are required from the luminaire type and layout (HPS in Fig. 2A), increasing thus the ratio, because of a lack of continuous dimming ability with that lighting technology.

It is also important to consider the optical effectiveness of LEDs. As shown in Fig. 3B, a

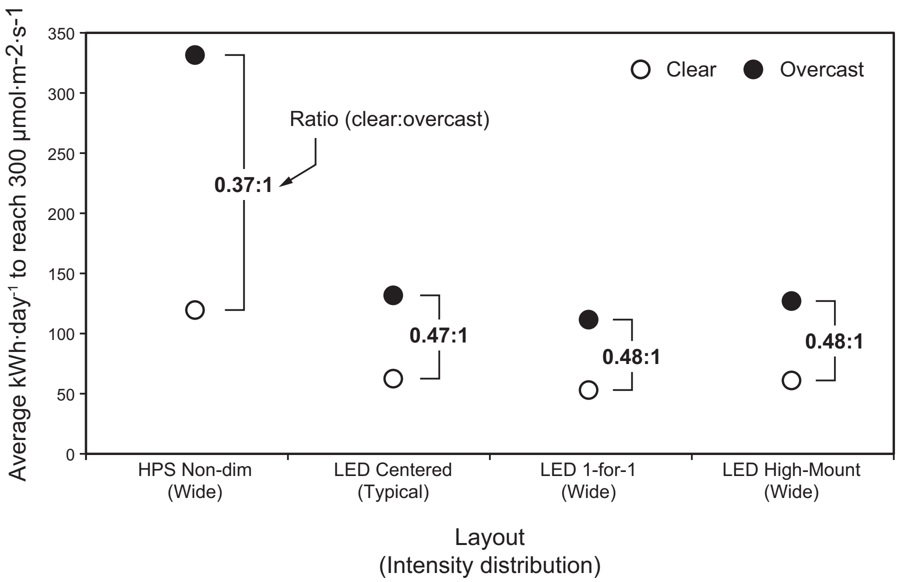


Fig. 5. The average kWh·day^{-1} needed to reach the criterion mean photosynthetic photon flux density (PPFD) value of 300 μmol·m^{-2}·s^{-1} for the different luminaire layouts broken down by two sky conditions. The average kWh·day^{-1} value for each point is derived from the three geographic locations and two seasons. Also shown are the ratios of the clear sky condition mean values to the overcast sky condition mean values for each luminaire layout in Fig. 2.

more uniform distribution of PPFD on the crop plane from a batwing distribution (LED Luminaire 2a) results in greater energy savings than that achieved with a luminaire cosine distribution (LED Luminaire 1), with all other factors being the same. More importantly, Fig. 4B shows that a more uniform distribution of PPFD on the crop plane reduces the PPFD minimum-to-maximum ratio. A lower ratio is quite important to growers because it is more likely to keep PPFD levels across the crop plane above the photosynthetic activation threshold and below saturation. Combined with LED dimming, for which the criterion PPFD can be adjusted according to season and sky conditions, growers can continuously maximize the effectiveness of the electrical lighting system, thereby increasing both energy savings and crop yield.

This study had limitations. The shadowing analysis involved a specific set of geometric factors such as the size and shape of the greenhouse, the luminaire and truss heights, and the orientation and geographic locations of the greenhouse itself. Therefore, the results of the shadowing analysis were derived from a limited set of data, and there may be scenarios in which shadowing is more of a factor for energy savings than the findings of this analysis would suggest. Certain scenarios could include a taller greenhouse in which the trusses and luminaires are mounted higher than the 2.3-m height we used during our analysis, which would further reduce shadowing compared with the best-case scenario we calculated. Although, again, we found that this would require more electric energy for the lighting to compensate for the greater distance from the crop plane, likely counteracting the advantage of reduced shadowing. Compared with other strategies aimed at minimizing lighting energy and maximizing crop yield, those aimed at reducing shadowing from the luminaires have very little impact.

Another limitation of this research was the assumption that crops are grown from wall to wall in the greenhouse; in reality, growers may incorporate walkways and access spaces that would not require illumination to the same levels as their crops, thus providing a benefit for different luminaire intensity distributions near the greenhouse walls.

Finally, the combined characteristics of LED Luminaires 2a and 2b (i.e., batwing intensity distribution, spectral power distribution, dimming, form factor, and photosynthetic efficacy) do not necessarily reflect those of current products that have been developed for the horticulture market. Nevertheless, the energy impacts of the characteristics examined during this study can help growers more accurately choose among actual products. As suggested, it is possible that asymmetric distributions could be used for lighting the perimeter of the greenhouse to enable the desired uniformity. Regarding conventional area lighting (e.g., parking lots and roadways), lighting manufacturers have developed a wide range of lighting distributions that are tailored to meet specific geometric needs.

Overall, compared with conventional HPS greenhouse lighting, LED lighting offers many energy advantages, primarily from increased efficacy and, for some luminaires, the ability to dim. However, efforts should be made to increase luminaire optical efficiency (i.e., to increase uniformity on the crop plane) and promote dimming, both of which can significantly increase energy savings and crop yield.

References Cited

Bula RJ, Morrow RC, Tibbitts TW, Barta DJ, Ignatius RW, Martin TS. 1991. Light-emitting diodes as a radiation source for plants. HortScience. 26(2):203–205. https://doi.org/10.21273/HORTSCI.26.2.203.

Climate-Zone.com. 2023. United States. Grand Rapids, MI: MBH Media, Inc. https://www.climate-zone.com/climate/united-states/. [accessed 3 Jan 2023].

Commission Internationale de l'Éclairage. 1924. Commission Internationale de l'Éclairage Proceedings. Cambridge University Press, Cambridge.

Commission Internationale de l'Éclairage. 2004. Spatial Distribution Of Daylight — CIE Standard General Sky. ISO 15469:2004(E)/CIE S 011/E:2003. Commission Internationale de l'Éclairage, Vienna.

Dalrymple DG. 1973. Controlled Environtment Agriculture: A Global Review of Greenhouse Food Production. Foreign Agricultural Economic Report (FAER) 145622. US Department of Agriculture, Washington, DC.

Dieleman JA, Visser P, Vermeulen P. 2016. Reducing the carbon footprint of greenhouse grown crops: Re-designing LED-based production systems. Acta Hortic. 1134:395–402. https://doi.org/10.17660/ActaHortic.2016.1134.51.

Dueck T, Janse J, Eveleens-Clark B, Kempkes F, Marcelis LFM. 2011. Growth of tomatoes under hybrid LED and HPS lighting. Acta Hortic. 952:335–342. https://doi.org/10.17660/ActaHortic.2012.952.42.

Dutta Gupta S. 2017. Light emitting diodes for agriculture smart lighting. Springer Singapore, Singapore.

Katzin D, Marcelis LFM, van Mourik S. 2021. Energy savings in greenhouses by transition from high-pressure sodium to LED lighting. Energy. 281:116019. https://doi.org/10.1016/j.apenergy.2020.116019.

Kelly N, Choe D, Meng Q, Runkle ES. 2020. Promotion of lettuce growth under an increasing daily light integral depends on the combination of the photosynthetic photon flux density and photoperiod. Scientia Hortic. 272:109565. https://doi.org/10.1016/j.scienta.2020.109565.

Kusuma P, Pattison PM, Bugbee B. 2020. From physics to fixtures to food: Current and potential LED efficacy. Hortic Res. 7:56. https://doi.org/10.1038/s41438-020-0283-7.

Marcelis LFM, Broekhuijsen AGM, Meinen E, Nijs EMFM, Raaphorst MGM. 2006. Quantification of the growth response to light quantity of greenhouse grown crops. Acta Hortic. 711:97–104. https://doi.org/10.17660/ActaHortic.2006.711.9.

Nelson JA, Bugbee B. 2014. Economic analysis of greenhouse lighting: Light emitting diodes vs. high intensity discharge fixtures. PLoS One. 9(6):e99010. https://doi.org/10.1371/journal.pone.0099010.

Nemali K. 2022. History of controlled environment horticulture: Greenhouses. HortScience. 57(2):239–246. https://doi.org/10.21273/hortsci16160-21.

Pinho P, Halonen L. 2014. Agricultural and horticultural lighting, p 1–14. In: Karlicek R, Sun C-C, Zissis G, Ma R (eds). Handbook of advanced lighting technology. Springer International Publishing, Cham, Switzerland.

Plant Light. 2022. Plant light: The Internet's source of plant light requirements. Plant Light. https://plantlightdb.com/#adjusting-light. [accessed 1 Nov 2022].

Stober K. 2017. Energy savings potential of ssl in horticultural applications. US Department of Energy, Washington, DC.

Stutte GW, Edney S, Skerritt T. 2009. Photoregulation of bioprotectant content of red leaf lettuce with light-emitting diodes. HortScience. 44(1):79–82. https://doi.org/10.21273/HORTSCI.44.1.79.

Tibbitts TW. 1993. Terminology for photosynthetic active radiation for plants. Report 106/8. Vienna, Austria: Commission Internationale de l'Eclairage.

Time and Date AS. 2023. Sunrise & sunset. Stavanger, Norway: Time and Date AS. https://www.timeanddate.com/sun/. [accessed 3 Jan 2023].

van den Muijzenberg EWB. 1980. A history of greenhouses. Institute of Agricultural Engineering: Wegeningen, Netherlands.

Wheeler RM. 2008. A historical background of plant lighting: An introduction to the workshop. HortScience. 43(7):1942–1943. https://doi.org/10.21273/hortsci.43.7.1942.

Zhou J, Li P, Wang J. 2022. Effects of light intensity and temperature on the photosynthesis characteristics and yield of lettuce. Horticulturae. 8(2):178. https://doi.org/10.3390/horticulturae8020178.