Artificial Lighting Technologies and Light Delivery in Controlled Environment Horticulture

Grant Kinkead
Independent Researcher, Melbourne, VIC, Australia
grant@kinkead.au

***Abstract*—Controlled environment agriculture (CEA) and hydroponic production systems depend on artificial lighting to supplement or replace solar radiation, yet the utility of a given fixture cannot be assessed from photon output alone. The technology family selected determines spectral composition, photon efficacy, thermal load, and the degree of controllability available to the operator. Fixture geometry, optics, and mounting position govern how photons are distributed through the canopy volume and whether the delivered light environment matches crop demand. This paper synthesises peer-reviewed evidence to compare the major horticultural artificial-lighting technology families, with emphasis on high-pressure sodium discharge lamps and light-emitting diode systems as the dominant commercial options. The analysis covers operating characteristics relevant to crop use, scientifically meaningful performance comparisons, the role of fixture geometry and inter-lighting placement in canopy light distribution, controllability and dimming as determinants of practical flexibility, and the thermal differences that constrain mounting options and climate interaction. The distinction between supplemental lighting in greenhouse settings, where solar radiation provides the baseline photon environment, and sole-source artificial lighting in fully enclosed systems is maintained throughout, because the criteria for technology selection differ substantially between these two production paradigms. The evidence indicates that LED technology offers advantages in photon efficacy, spectral flexibility, thermal profile, and dimming range, while inter-lighting geometry provides measurable agronomic benefits in tall-vine crops with deep canopies.**

I. Introduction

Artificial lighting has become a fundamental input in controlled environment horticulture, and the range of available technology families has expanded considerably over the past two decades. Horticultural lighting encompasses high-pressure sodium (HPS) discharge lamps, fluorescent and compact fluorescent sources, light-emitting diodes (LEDs), and, in earlier commercial practice, metal halide lamps. Each technology generates photons through a distinct physical mechanism, which determines spectral output, photon efficacy, thermal load, and optical controllability. A comprehensive review of lighting conditions in CEA confirms that operating characteristics of the selected technology directly shape the photon environment available to the crop and constrain the flexibility available to growers adjusting light conditions across crop stages or seasonal periods [1]. The implication is that fixture selection is not a secondary decision: it sets the boundaries within which all subsequent light management operates.

The commercial transition from HPS to LED technology has been the dominant development in horticultural lighting over the past decade, and comparative research has quantified the performance and thermal differences that matter practically to growers. HPS lamps generate light through a gas discharge arc, producing a spectral distribution weighted toward yellow and orange wavelengths with substantial infrared radiation as a thermal byproduct. LEDs use semiconductor junctions to convert electricity directly to photons, enabling spectral composition to be engineered at the point of manufacture. A comparative performance and economic analysis of LED and HPS greenhouse lighting identified differences in photon efficacy and heat load that influence both electricity costs and the thermal environment presented to the crop canopy [2]. The pace of LED adoption in commercial greenhouse operations has been shaped by the magnitude of that efficacy advantage relative to the capital cost premium of LED fixtures.

Beyond lamp technology, fixture placement geometry determines how effectively photons are delivered through the canopy volume. Overhead placement directs light downward from above, which creates steep photosynthetically active radiation (PAR) gradients between the upper and lower canopy in dense or tall-vine crops. Inter-lighting, in which fixtures are positioned between crop rows or within the canopy, addresses this limitation by delivering photons closer to leaves that would otherwise be most constrained by shading. Research on supplemental LED inter-lighting demonstrates that geometric placement interacts with available solar radiation to determine whether artificial light compensates adequately for periods of low natural irradiance and how effectively the delivered photons are distributed across the canopy volume [3]. This body of evidence establishes that technology choice and fixture geometry must be evaluated together, not as independent variables.

II. Background and Scope

Horticultural lighting research has a substantial history rooted in greenhouse supplemental practice, where HPS technology held a near-dominant commercial position for several decades owing to its relatively high photon output per unit of electrical input and its availability in large-wattage configurations suited to commercial greenhouse structures. The entry of LED technology into horticultural use prompted a period of direct comparative evaluation, with studies examining photon efficacy, spectral breadth, operational longevity, and fixture capital cost. Nelson and Bugbee's comparative analysis of LED and HPS greenhouse lighting provides a foundational

performance benchmark, and the LED horticultural systems market subsequently expanded substantially, with commercial adoption accelerating as fixture efficacies improved and capital costs declined [2]. The commercial trajectory documented in that period established the performance parameters against which subsequent LED generations have been assessed.

Research has moved beyond lamp-versus-lamp comparisons to examine how lighting geometry interacts with crop architecture and the available solar resource. In greenhouse settings where natural light dominates during portions of the year, supplemental fixtures must be sized and positioned to compensate for irradiance shortfalls without creating redundant energy expenditure under clear-sky conditions. Studies of interlighting geometry in tall-vine crops showed that positioning LED fixtures within the canopy rather than solely overhead improves PAR distribution uniformity and increases yield per unit of electrical energy consumed when solar radiation is limited [3]. This finding reframes the design problem from one of maximising photon output to one of optimising the spatial and temporal match between delivered light and crop demand across varying natural irradiance conditions.

The scope of CEA lighting research now encompasses controllability, spectral tuning, and integration of lighting control with environmental management systems. A review of lighting conditions in controlled environment agriculture identifies technology families and their operating characteristics as the primary determinants of how flexibly a grower can respond to changing crop requirements, and notes that the physical mechanisms underlying each technology constrain the adjustments that are practically feasible [1]. This paper synthesises that evidence to compare major horticultural lighting technology families, explain the physical and optical mechanisms that govern light delivery, and identify the practical consequences of technology choice, fixture geometry, and controllability for hydroponic and broader CEA production. The analysis does not revisit plant spectral biology in detail, and full climate energy trade-off analysis is deferred, in line with the scoping boundaries for this section of the research programme.

III. Core Concepts and Mechanisms

The fundamental performance metric for any horticultural light source is photon efficacy, expressed as micromoles of photosynthetically active photons delivered per joule of electrical energy consumed (umol/J). This metric is distinct from luminous efficacy, which is weighted to human visual response, and the distinction is practically important because luminous metrics do not map reliably onto photosynthetic utility across the different spectral distributions produced by HPS and LED sources. LED technology, when optimised for the PAR waveband (400 to 700 nm), achieves photon efficacies that can substantially exceed those of HPS lamps operating at comparable wattage, as confirmed in comparative greenhouse lighting evaluations [2]. The semiconductor architecture of LEDs also permits narrow-band spectral engineering, which allows specific ratios of red and blue photons to be delivered without the broad spectral tails that characterise gas discharge sources, though the agronomic value of such tuning is a separate question from the efficacy of photon delivery itself.

Fixture optics and mounting geometry determine how photons generated by a lamp are spatially distributed across the canopy. Reflector design in HPS and metal halide fixtures redirects the omnidirectional output of a discharge arc into a more defined beam, but the distribution achieved is constrained by the geometry of the arc tube and the reflector bowl, limiting the flexibility of optical design. LED fixtures permit substantially greater freedom in optical design because individual emitter elements can be arranged in arbitrary spatial patterns and secondary lenses or diffusers can be applied per emitter. Reviews of lighting technology for CEA note that the angular distribution of emitted light, combined with fixture mounting height and inter-fixture spacing, governs the uniformity coefficient of PAR across the canopy plane [1]. Non-uniform distribution produces areas of both excess and deficient PAR simultaneously, reducing overall crop efficiency regardless of the average delivered intensity.

The thermal characteristics of each technology family constitute a third mechanistic dimension that directly constrains light delivery options. HPS lamps dissipate a substantial proportion of their electrical input as radiant heat in the near-infrared region, as well as conducted and convected heat from the lamp envelope, creating an elevated thermal environment in the canopy volume immediately beneath the fixture. LEDs produce less infrared radiation and concentrate their waste heat at the semiconductor junction rather than radiating it into the crop space, which allows fixtures to be positioned closer to the canopy or within it without inducing heat stress in adjacent tissue [3]. This thermal difference directly constrains the minimum mounting height of discharge-based fixtures and therefore limits the minimum uniformity footprint achievable at a given wattage, making the thermal and optical characteristics of a technology family interdependent from a placement design perspective.

IV. Evidence Synthesis

Synthesising the available comparative evidence, LED technology consistently demonstrates higher photon efficacy than HPS technology under controlled measurement conditions, although the magnitude of the advantage varies with the specific product generation and measurement protocol used. Early commercial LED horticultural fixtures did not uniformly outperform HPS on a photon-per-joule basis, and economic analyses identified conditions under which the capital cost premium of LED systems was not recovered through electricity savings within a commercially relevant payback period [2]. This historical context is important because it explains the cautious pace of LED adoption in high-production greenhouse operations during the early commercialisation phase and underscores that photon efficacy comparisons must account for fixture-level output across the full PAR waveband rather than point-source measurements of individual emitter components at peak efficiency.

The evidence on inter-lighting geometry reinforces the principle that physical placement is an independent and consequential variable in light delivery. Research demonstrated that LED inter-lighting positioned within a tomato canopy compensated for solar radiation deficits more effectively than overhead supplemental fixtures alone in terms of yield per unit of electricity consumed, because inter-lighting delivers photons directly to mid-canopy leaves that are most constrained by shading from upper layers [3]. This finding does not generalise without qualification to short-stature crops in vertical farming systems, where canopy depth is limited and overhead sole-source arrays can achieve sufficient uniformity, but for tall-vine crops in greenhouse settings it establishes that geometry is a design variable with measurable agronomic and energy-efficiency consequences that are distinct from the lamp technology choice itself.

At the technology-family level, the review by Neo and colleagues frames the lighting technology selection problem in CEA as one of matching operating characteristics to production requirements across multiple dimensions simultaneously: photon efficacy, spectral composition, thermal load, optical distribution, and controllability [1]. No single technology family optimises all dimensions at once. HPS fixtures offer mature supply chains, proven long-run reliability in large-scale greenhouse operations, and a body of crop response data accumulated over decades of commercial use, but their spectral breadth, thermal output, and limited dimming range constrain their flexibility in systems requiring dynamic light management. LED fixtures offer spectral programmability and continuous dimming capability but introduce greater design complexity and higher upfront capital requirements. The comparative evidence therefore supports a nuanced technology selection framework rather than a simple preference for one technology family across all production contexts.

V. Practical Implications and Limitations

The practical implications of technology and geometry choices differ substantially between supplemental lighting and sole-source artificial lighting systems. In supplemental lighting, where natural solar radiation provides the baseline photon environment, the artificial fixture contributes a fraction of the daily light integral and its role changes continuously with season, weather, and latitude. Supplemental fixtures must therefore be controllable across a meaningful output range to avoid delivering excess PAR on bright days or during periods when crop demand is below the threshold for beneficial light response [1]. The controllability of HPS lamps is limited: most commercial HPS systems operate at full output or at a small number of stepped power levels, whereas LED drivers accept 0 to 100 per cent dimming signals from environmental control systems, enabling continuous adjustment in response to real-time solar irradiance measurements. In hydroponic greenhouse settings, this distinction in controllability becomes agronomically and economically significant over a growing season.

Sole-source artificial lighting, as used in fully enclosed vertical farms and controlled growth chambers, removes solar variability but introduces different constraints. The entire photon environment must be engineered, making fixture efficacy the dominant determinant of electricity consumption per unit of crop output. Under sole-source conditions the economic case for high-efficacy LED technology is stronger than in supplemental greenhouse applications, because electricity savings are proportional to total run-hours at full output and there is no period during which supplemental output is redundant due to competing solar input [2]. The thermal implications also differ: in a sealed growing environment, the reduced radiant heat output of LED fixtures lessens the cooling load that must be offset by the climate management system, a consequence that links technology choice to facility energy balance even though the full thermal integration analysis is beyond the scope of this section.

The available evidence base carries important limitations for practitioners seeking to generalise from published studies to specific production contexts. The Nelson and Bugbee economic comparison was conducted at a time when commercial LED horticultural fixture efficacies were considerably lower than those available in subsequent product generations, meaning that the economic thresholds identified in that study may no longer apply at current product specifications [2]. The Tewolde inter-lighting study was conducted in a specific greenhouse configuration with a tall-vine crop, and the geometry and spacing parameters demonstrated may not transfer directly to different crop architectures or structural configurations [3]. Practitioners should treat the published evidence as establishing principles and order-of-magnitude benchmarks rather than directly portable performance specifications, and should seek updated fixture-level efficacy data from current product generations when conducting site-specific evaluations.

VI. Conclusion

Major horticultural lighting technologies differ in the way they generate and distribute useful light to a crop across several interacting dimensions: the physical mechanism of photon production, the spectral composition and angular distribution of the output, the thermal load imposed on the growing environment, and the degree of controllability available to the operator. The evidence reviewed here demonstrates that LED technology offers advantages in photon efficacy, spectral flexibility, thermal profile, and dimming range that are particularly significant in sole-source applications and in supplemental systems that must respond dynamically to solar variability [1], [2]. HPS technology retains practical advantages in established greenhouse operations where capital replacement is constrained and where the existing body of crop response knowledge has direct operational value. The geometry of fixture placement constitutes an additional variable that interacts with technology choice to determine the actual light environment delivered to the canopy, particularly in tall-vine crops where inter-lighting has demonstrated measurable agronomic and efficiency benefits [3].

The evidence reviewed here establishes that a lighting fixture is not useful merely because it emits photons: its technology family, optical distribution characteristics, mounting geometry, controllability, and thermal behaviour collectively determine how effectively it delivers the intended light environment to a crop. Future work of highest value would include direct comparison of current-generation LED fixtures against HPS baselines under equivalent production conditions using standardised photon efficacy measurement protocols, and more extensive characterisation of inter-lighting geometry across a broader range of crop architectures and canopy structures. The distinction between supplemental and sole-source lighting modes must be maintained throughout any such comparative evaluation, as the criteria for technology selection, the weight given to controllability, and the economic significance of efficacy differences all change substantially between these two production paradigms.

ACKNOWLEDGMENT

The author used artificial intelligence tools to assist with manuscript drafting and revision, and with LaTeX and bibliography preparation. The author reviewed all AI-assisted output and remains responsible for the final content.

REFERENCES

[1] D. C. J. Neo, M. M. X. Ong, Y. Y. Lee, E. J. Teo, Q. Ong, H. Tanoto, J. Xu, K. S. Ong, and V. Suresh, "Shaping and tuning lighting conditions in controlled environment agriculture: A review," *ACS Agricultural Science & Technology*, 2022. [Online]. Available: https://pubs.acs.org/doi/10.1021/acsagscitech.1c00241

[2] J. A. Nelson and B. Bugbee, "Economic analysis of greenhouse lighting: Light emitting diodes vs." *PLoS ONE*, 2014. [Online]. Available: https://journals.plos.org/plosone/article?id=10.1371%2Fjournal.pone.0099010

[3] F. T. Tewolde, K. Shiina, T. Maruo, M. Takagaki, T. Kozai, and W. Yamori, "Supplemental led inter-lighting compensates for a shortage of light for plant growth and yield under the lack of sunshine," *PLOS ONE*, 2018. [Online]. Available: https://journals.plos.org/plosone/article?id=10.1371%2Fjournal.pone.0206592