Light Intensity, Photosynthetic Photon Flux Density, and Daily Light Integral in Hydroponic Controlled-Environment Agriculture

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***Abstract*—Controlled-environment agriculture (CEA) and hydroponic production have expanded the capacity to cultivate crops without soil by replacing natural field processes with precise management of light, nutrient solution chemistry, and root zone conditions. Light intensity, expressed as photosynthetic photon flux density (PPFD) in micromoles of photons per square metre per second, and the derived daily light integral (DLI) in moles per square metre per day, are the primary quantitative descriptors of the light environment experienced by crops in indoor and greenhouse hydroponic systems. This paper synthesises current evidence on how PPFD and DLI determine photosynthetic performance, biomass accumulation, and light use efficiency in hydroponic crops, with particular attention to the plant physiology mechanisms that mediate these responses. Evidence from controlled-environment studies of leafy crops and fruiting vegetables demonstrates that photoresponses are cultivar-specific, that spatial uniformity of PPFD across the canopy materially affects yield outcomes, and that optical simulation methods offer a pathway to improved lighting design. The paper also identifies the physiological coupling between light intensity, stomatal conductance, and root zone conditions, and notes that direct experimental characterisation of nutrient solution chemistry and water quality responses to varying PPFD remains a substantive evidence gap warranting future investigation. Practical implications for hydroponic system design and operation are discussed alongside limitations of the current knowledge base.**

I. Introduction

Light is the essential energy currency of photosynthetic plant growth, and in controlled-environment agriculture its management through artificial sources is both a technical challenge and a commercial imperative. Research examining PPFD and DLI effects on Portulaca oleracea cultivars in CEA chambers demonstrates that photoresponses to varying light intensities are cultivar-specific, with green and golden purslane cultivars accumulating biomass at markedly different rates across experimental PPFD treatments spanning 150 to 300 µmol m-2 s-1, corresponding to DLIs of 8.64 to 17.28 mol m-2 d-1 across a 16-hour photoperiod [1]. The green cultivar accumulated approximately 174 per cent more dry weight at 300 µmol m-2 s-1 compared with the golden cultivar under identical conditions, a divergence that illustrates why PPFD and DLI optima derived from one cultivar cannot be assumed to generalise to another [1]. For hydroponic system operators in controlled-environment agriculture, this cultivar specificity of plant physiology implies that lighting programmes must be validated against each crop grown rather than inferred from generic intensity tables, a requirement that has significant consequences for the design and commissioning of artificial lighting infrastructure.

Hydroponic lettuce provides a well-documented model for understanding how plant physiology adapts its canopy architecture to the PPFD supplied by artificial sources. At lower PPFD levels of 201 to 292 µmol m-2 s-1, lettuce plants increase projected canopy size and specific leaf area to enhance light capture by approximately 36.2 per cent relative to performance at higher PPFD levels of 333 to 413 µmol m-2 s-1, while simultaneously exhibiting a lower canopy overlap ratio [2]. These morphological adjustments reflect the plant's capacity to regulate its own photon capture strategies in response to the light environment, and they have downstream consequences for root zone conditions: canopy expansion at low PPFD alters the pattern of shading and air movement at the root zone, affecting the humidity and thermal environment of the root system. The relationship between light management and root zone conditions is therefore mediated by plant physiology as well as by engineering factors, establishing a central theme that this paper develops across subsequent sections.

Artificial lighting in controlled-environment agriculture introduces engineering complexity that extends well beyond selecting a target PPFD value. Modelling of intra-canopy and top LED lighting configurations in tomato production demonstrates that the spatial distribution of PPFD across and within the crop canopy varies substantially depending on lamp placement strategy, with combined intra-canopy and top lighting reducing the coefficient of variation in absorbed PPFD to approximately 37 per cent compared with 43 per cent for top lighting alone and 48 per cent for intra-canopy lighting alone [3]. Intra-canopy lighting also achieved 8 per cent higher total light absorption than top lighting, indicating that the choice of lighting architecture affects both the intensity and the distribution of photons reaching productive leaf area [3]. These findings establish that achieving PPFD and DLI targets at the crop level requires spatial optimisation of the lamp array as well as intensity specification, a principle that motivates the lighting design and plant physiology analysis developed throughout this paper.

II. Background and Scope

The optimisation of PPFD uniformity in plant factories has developed into a formal engineering problem, with optical simulation and meta-heuristic algorithms applied to lamp placement and configuration. Research using differential evolution combined with optical modelling to determine lamp height and horizontal arrangement demonstrates that increasing lamp height above the crop surface reduces point-source variability in emitted flux, thereby improving the uniformity factor of PPFD on the illuminated surface, while simultaneously reducing the absolute intensity delivered to the plant [4]. This trade-off between uniformity and intensity creates a multi-objective design problem: a configuration achieving high uniformity may require greater total lamp power to sustain the target PPFD at canopy level, increasing energy costs. For hydroponic operators, the practical implication is that lighting system selection cannot be reduced to a single intensity metric but involves a considered balance of distribution quality, intensity delivery, energy efficiency, and infrastructure investment.

Understanding the plant physiology mechanisms governing photosynthetic response to PPFD provides the biological foundation for interpreting lighting requirements in hydroponic systems. The photosynthetic rate increases approximately linearly with PPFD within the sub-saturation range, with light use efficiency and electron transport rate tracking the photon supply across this productive linear region [5]. Stomatal conductance, which regulates CO2 entry for carbon fixation, is also sensitive to PPFD and rises with increasing light intensity, coupling light-driven carbon assimilation with transpirational water loss from the leaf surface. This physiological coupling between PPFD, stomatal conductance, and transpiration has direct relevance to root zone conditions experienced by hydroponic plants: elevated light intensity increases the rate of water uptake from the nutrient solution, and if replenishment of the nutrient solution is not adjusted to match this increased demand, the ionic concentration and water quality of the root zone environment will shift. The evidence reviewed here addresses these relationships primarily through canopy-level measurements, with direct root zone characterisation representing a notable gap in the current literature [5].

Spectral composition adds a further dimension to the analysis of light intensity in controlled-environment agriculture and modulates the biological significance of any stated PPFD value. Research on photon irradiance uniformity and spectral composition in CEA confirms that different wavebands within the photosynthetically active radiation range of 400 to 700 nm interact differently with plant pigments: red wavelengths at approximately 660 nm and blue wavelengths at approximately 450 nm are preferentially absorbed by chlorophyll and carotenoid pigments, while green wavelengths penetrate deeper into the canopy and contribute to photosynthesis in lower leaves [6]. A PPFD value stated in micromoles per square metre per second therefore carries different biological significance depending on the spectral distribution of the light source, which means that LED arrays must specify spectral composition alongside intensity to predict plant physiological responses reliably. The scope of this paper concentrates on PPFD and DLI as the primary quantitative metrics used in hydroponic system design, while treating spectral composition as a co-determining factor whose interactions with intensity are noted where supported by the available evidence [6].

III. Core Concepts and Mechanisms

Biomass production in hydroponic plants is fundamentally determined by the quantity of photosynthetically useful photons absorbed by the leaf canopy and the efficiency with which those photons drive carbon fixation. When PAR photons strike chlorophyll molecules, their energy is converted through the light-dependent reactions of photosynthesis into ATP and NADPH, which subsequently power the Calvin cycle and fix atmospheric CO2 into carbohydrate [5]. Electron transport rate, which describes the throughput of the photosynthetic electron transport chain, scales with increasing PPFD across the linear portion of the light response curve but saturates at the species-specific light saturation point, beyond which additional photons generate no further increase in photosynthetic output and may instead cause photoinhibition through reactive oxygen species accumulation [3]. The significance of this saturation behaviour for controlled-environment agriculture is that economic returns on additional lighting investment diminish sharply once PPFD approaches the light saturation threshold of the crop, making accurate knowledge of that threshold essential for cost-effective hydroponic production [4].

Daily light integral serves as an integrated management metric that captures the cumulative photon dose delivered to the crop across the full photoperiod, accommodating variation in instantaneous PPFD that may arise from lamp dimming schedules, supplemental lighting in greenhouse settings, or temporal variation in lamp output. A 16-hour photoperiod maintained at a constant PPFD of 250 μmol m-2 s-1 delivers a DLI of 14.4 mol m-2 d-1, which is broadly consistent with reported optima for leafy crop hydroponic production [5]. Spatial modelling of tomato canopies demonstrates that individual leaves within the canopy receive substantially different cumulative DLI depending on their position relative to the lamp array and their depth within the canopy, with intra-canopy lighting modules improving the DLI received by lower-canopy leaves compared with top lighting alone [3]. The implication is that canopy-averaged DLI measurements may overstate the effective photon dose received by a significant proportion of leaf area, particularly in dense or multi-tier hydroponic systems where spatial heterogeneity in absorbed PPFD is difficult to avoid without explicit lighting design intervention [4].

A critical constraint on the application of published PPFD and DLI optima is the cultivar specificity of photoresponse documented across multiple crop types and growing conditions. Beyond the numerical targets themselves, the relationship between PPFD, canopy morphology, and light use

efficiency is mediated by the genetic and developmental characteristics of individual cultivars, which determine both the light saturation point and the magnitude of the morphological response to sub-optimal illumination. Research on lettuce shows that canopy architecture responds dynamically to PPFD: at lower intensities, plants expand their canopy and increase specific leaf area to maximise photon capture, while at higher intensities they develop more compact canopies with increased leaf overlap and higher shoot and root fresh and dry weights [3]. Optical simulation can model these interactions to a useful degree, but the parametric demands of such models, including detailed representation of leaf angle, canopy geometry, and optical properties, have constrained their adoption in commercial hydroponic facilities, where empirical adjustment of lamp configurations guided by crop monitoring remains the prevailing practice [4].

IV. Evidence Synthesis

Synthesising the quantitative evidence across CEA lighting studies reveals a broadly consistent productive operating envelope for leafy crop hydroponic systems, centred on PPFD values of approximately 200 to 300 μmol m-2 s-1 and DLIs of approximately 11.5 to 17 mol m-2 d-1 for standard 16-hour photoperiods [4]. Within this envelope, plant physiology responses including biomass accumulation, light use efficiency, and stomatal conductance are generally proportional to PPFD, whereas evidence from cultivar-specific studies indicates that efficiency gains diminish and may reverse at intensities above the species-specific light saturation point [5]. Spectral composition modulates the biological effectiveness of delivered PPFD: the relative proportions of red and blue wavebands influence pigment synthesis, photomorphogenesis, and canopy development in ways not captured by PPFD or DLI metrics alone, meaning that two light sources delivering identical PPFD values may produce different physiological outcomes [6]. These converging findings support a view of light management in hydroponic controlled-environment agriculture as a multi-parameter optimisation problem in which intensity, spectral quality, spatial uniformity, and photoperiod duration must be managed as an integrated system rather than as independent variables.

The evidence also illuminates assumptions embedded in standard PPFD and DLI recommendations that constrain their generalisability to operational hydroponic systems. Most quantitative studies evaluate crop performance under static, uniform PPFD conditions maintained throughout the photoperiod, whereas operational facilities commonly employ dynamic lighting schedules that modulate intensity and spectrum in response to energy tariff variation, ambient daylight availability, or crop growth stage [6]. The physiological response of stomatal conductance to light is not instantaneous: stomata adjust aperture over time scales of minutes, and abscisic acid-mediated feedback regulation means that recent light history influences current transpiration rate and therefore the volume of water drawn from the nutrient solution [5]. Dynamic lighting schedules that cycle between high and low PPFD phases could therefore produce different root zone conditions and different demands on the nutrient solution than a constant PPFD delivering the same total DLI, and this interaction between lighting dynamics and nutrient solution chemistry remains poorly characterised in the evidence reviewed here [4].

From the perspective of nutrient solution chemistry, water quality, and root zone conditions, the reviewed evidence is largely inferential rather than directly experimental. The physiological coupling between PPFD and stomatal conductance implies that elevated light intensity increases transpiration and water uptake from the root zone, potentially concentrating dissolved ions in the nutrient solution if replenishment is not adjusted accordingly, while prolonged low-PPFD periods reduce transpiration and may allow progressive nutrient enrichment in root zone conditions that imposes osmotic stress on roots [5]. None of the primary studies in this review directly measured nutrient solution chemistry, electrical conductivity, pH, or individual ion concentrations as dependent variables in controlled PPFD experiments, representing a substantive evidence gap that limits the derivation of specific water quality management targets from the reviewed PPFD and DLI findings [6]. Integrating root zone monitoring and nutrient solution chemistry measurements with canopy-level light management in future research would substantially improve the scientific basis for co-managing light intensity and solution quality in hydroponic systems.

V. Practical Implications and Limitations

For practitioners designing or operating hydroponic systems in a controlled-environment agriculture context, the reviewed evidence supports several actionable principles. Targeting a PPFD in the range of 200 to 250 μmol m-2 s-1 and a DLI of approximately 11.5 to 14.4 mol m-2 d-1 represents a defensible starting point for leafy crops such as lettuce, consistent with the operating range in which light use efficiency, canopy development, and biomass gain are generally optimised [5]. LED lighting configurations that deliver spatially uniform PPFD across the growing surface are preferable to systems that meet mean PPFD targets but leave interior regions of the canopy underlit, because spatial heterogeneity in photon distribution produces uneven transpiration rates, variable root zone conditions, and yield variability across the growing area that complicates nutrient solution management [6]. These connections between light intensity uniformity, plant physiology, and root zone conditions reinforce the principle that light management in hydroponics is not separable from nutrient solution chemistry and water quality management.

The water quality implications of artificial lighting deserve particular attention in hydroponic system design, even though the direct experimental evidence linking PPFD manipulation to nutrient solution parameters remains limited. High PPFD drives elevated stomatal conductance and transpiration, increasing the volume of water drawn from the circulating nutrient solution and potentially concentrating dissolved ions if replenishment rates are not continuously calibrated to match

evapotranspirational demand [5]. Conversely, extended low-PPFD periods reduce transpiration and may allow progressive enrichment of the nutrient solution in root zone conditions that suppress root function through ionic imbalance. The accepted evidence is insufficient to define precise water quality targets at each PPFD level; empirical studies directly linking PPFD manipulation to parameters such as electrical conductivity, pH, and individual ion concentrations in recirculating nutrient solutions represent a priority gap for future experimental programmes. Practitioners must therefore treat current guidance as a framework requiring empirical calibration rather than as prescriptive standards directly applicable across all species and system configurations [6].

Several limitations constrain the generalisability of current PPFD and DLI knowledge to real-world hydroponic production. The majority of quantitative studies informing current guidelines are conducted under controlled chamber conditions with uniform temperature, humidity, CO2 concentration, and root zone temperature, whereas commercial hydroponic facilities expose crops to greater environmental heterogeneity that may alter the photosynthetic response curves measured under idealised conditions [5]. The evidence for direct interactions between light intensity and nutrient solution chemistry, water quality, and root zone conditions is grounded in plant physiology inference rather than demonstrated through dedicated experimental manipulation in the reviewed sources. Scale effects are also poorly characterised: results from small experimental units may not translate directly to multi-tier vertical farms or large-format controlled greenhouses, where light gradients, thermal stratification, and air movement patterns interact with the crop canopy in ways not represented in single-level chamber experiments [6]. These limitations collectively point to the need for large-scale, multi-variable hydroponic studies integrating real-time light management with concurrent monitoring of nutrient solution chemistry and root zone conditions across commercially relevant crop species and production system types.

VI. Conclusion

This paper has reviewed the scientific principles governing light intensity, PPFD, and DLI in hydroponic production within the broader context of controlled-environment agriculture. The evidence supports a coherent account in which moderate, spatially uniform PPFD drives effective photosynthesis, light use efficiency, and biomass accumulation within physiologically defined limits, provided that artificial lighting design accounts for both intensity targets and spatial distribution quality across the crop canopy. Plant physiology mechanisms including light saturation kinetics, electron transport rate, and stomatal conductance define the productive envelope of light response, while cultivar-specific differences and canopy architecture impose important constraints on the transferability of published PPFD and DLI optima from one crop or production context to another. The reviewed evidence also establishes that light management is physiologically coupled to nutrient solution chemistry, water quality, and root zone conditions through the mediation of stomatal conductance and transpiration, though direct experimental characterisation of these interactions under controlled PPFD manipulation remains an identified gap in the current literature that represents a substantive limitation on the precision of current guidance.

The highest-value future work in this domain involves integrating root zone and nutrient solution monitoring with systematic PPFD manipulation to characterise the dynamic relationships between light intensity, water quality, nutrient solution chemistry, and root zone conditions across representative hydroponic crop species under commercially relevant production conditions. Concurrently, the development and validation of computationally accessible optical simulation tools capable of predicting canopy-level DLI distributions in complex multi-tier growing environments would support more informed lighting infrastructure decisions for CEA operators. As the energy cost of LED photon delivery continues to fall and spectral control becomes increasingly fine-grained, the scientific foundations reviewed here provide the biological and physical basis for a more precise and resource-efficient practice of artificial-light hydroponic production.

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