Light-use efficiency, energy demand and production trade-offs

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***Abstract*—Artificial lighting is central to controlled hydroponic production because it can raise daily light supply beyond what daylight alone provides, yet the production value of added light is not linear. Evidence from hydroponic lettuce and broader controlled environment agriculture shows that increasing photosynthetic photon flux density can improve growth and yield, but the marginal biological return declines as light supply rises, reducing plant light-use efficiency and complicating simple more-light assumptions [1], [2]. This paper synthesises five peer reviewed sources to explain when additional artificial light is likely to justify its electrical demand and associated system burden. It distinguishes plant light-use efficiency from fixture photon efficacy, electrical energy efficiency, and crop productivity per unit energy, because these metrics answer different production questions [3], [4]. It also explains how electricity demand scales with fixture power, operating duration, and control strategy, and why crop type, developmental stage, available daylight, climate, and production objective prevent a universal optimum [4], [5]. The synthesis shows that useful lighting decisions depend on comparing incremental crop response with the extra electrical input required to obtain it. More light can improve production, but only when biological response remains strong enough to justify the additional energy use under the specific production context considered.**

I. Introduction

Artificial lighting is often treated as a direct lever for raising output in hydroponic systems because photosynthesis depends on light availability, and growers can increase photon delivery when natural daylight is inadequate. However, the production question is not simply whether more light increases growth, but whether each additional unit of light continues to generate enough extra biomass, yield, or quality to justify the electrical demand needed to provide it. Evidence from hydroponic lettuce shows that strategic light-use efficiency changes with photosynthetic photon flux density, indicating that crop response must be assessed in marginal rather than absolute terms. This matters because a lighting regime can raise total production while simultaneously lowering productivity per unit of supplied light or electrical input [1].

The biological basis for this problem is the nonlinear response of plants to artificial lighting. Controlled environment evidence shows that photosynthetic response curves do not scale proportionally across all light levels, so increasing photosynthetic photon flux density from lower-light conditions can improve carbon assimilation and growth, but the gain per added increment of light declines as light supply rises [2]. For production reasoning, this means light-use efficiency is not constant across the operating range. A decision that appears beneficial at low light may become much less efficient at higher light because the crop approaches a response region in which additional photons still contribute, but contribute less strongly than earlier increments [1], [2].

The engineering side of the problem introduces a second nonlinearity: photons are delivered through equipment that consumes electricity, and fixture performance is not equivalent to crop performance. Studies of horticultural LEDs show that photon efficacy, commonly expressed in μmol/J, is a property of the fixture and describes how many photosynthetic photons are emitted per unit of electrical energy [3]. That metric is essential, but it does not by itself show whether the crop converts those photons into commercially useful output efficiently. This paper therefore argues that lighting decisions should compare incremental biological response with electrical energy demand and operating consequences. The discussion first defines the analytical boundaries of the problem, then explains the key concepts, synthesises the evidence on trade-offs, and concludes by identifying what can and cannot be generalised from the current evidence base.

II. Background and Scope

Recent work in controlled environment agriculture has increasingly linked crop performance with facility energy behaviour rather than treating lighting as an isolated agronomic variable. Analysis of growing conditions in controlled production spaces shows that energy load must be read alongside crop yield because environmental settings alter both plant response and electricity demand [5]. This framing is important for hydroponic reasoning because the relevant decision is not whether light affects growth, which is already well established, but how lighting choices interact with operational load. A technically adequate account therefore needs to explain biological diminishing returns, electricity scaling, and production trade-offs within one decision framework rather than in separate disciplinary silos.

The broader lighting literature also shows that there is no single best lighting recipe that can be transferred across all controlled production systems. Reviews of controlled environment agriculture identify trade-offs among lighting parameters, yield and quality outcomes, and performance metrics, while also emphasising the importance of crop type, developmental stage, and production objective [4]. This paper adopts that perspective, but keeps a narrow scope. Its purpose is to explain light-use efficiency, energy demand, and production trade-offs

at the level needed to answer when extra artificial light is justified. It does not attempt a full optimisation framework for all controlled environments, and it does not claim that one metric, such as yield alone or fixture efficacy alone, can settle the decision.

The scope boundary is equally important. The evidence base supports discussion of fixture power, operating duration, supplemental-light operation, and daylight-responsive adjustment because these directly affect lighting electricity demand and crop response [4], [5]. By contrast, broader analyses of whole-system sustainability, full climate-control integration, detailed automation architecture, tariff design, and carbon accounting extend beyond what these five sources directly establish. Those issues are important, but they are distinct from the present question of whether added artificial light improves production enough to justify its immediate electrical and operational burden. The synthesis that follows therefore stays with lighting-centred production reasoning and avoids claiming a whole-facility optimum from a limited evidence set.

III. Core Concepts and Mechanisms

A clear distinction among efficiency terms is essential because they refer to different parts of the production chain. Plant light-use efficiency describes the biological return obtained from incident or supplied light, while fixture photon efficacy describes photon output per unit electrical energy from the lamp, typically in μmol/J [3], [4]. Electrical energy efficiency, in this context, concerns how effectively electrical input is converted into useful lighting service, whereas crop productivity per unit energy asks how much production is achieved per unit of electrical consumption at the system level [1], [3]. Confusing these measures can lead to poor decisions, because a highly efficient fixture can still support an inefficient production regime if extra photons are supplied where marginal crop response has already weakened.

Electricity demand from artificial lighting scales through three practical variables supported by the evidence: fixture power, operating duration, and control strategy. Higher fixture power raises instantaneous electrical demand, longer operation increases cumulative energy use, and supplemental-light scheduling determines when electricity is consumed relative to daylight availability and crop targets [3], [4], [5]. These relationships are straightforward at the engineering level, but their production meaning depends on crop response. If an increase in power or run time produces only a modest additional gain in growth or yield, productivity per unit energy will worsen even if the fixture itself remains photon efficient. The key mechanism is therefore not only photon delivery, but the changing ratio between added electrical input and added biological output across operating conditions.

The biological response side must also be bounded carefully. What the evidence base does not justify here is a universal mechanistic threshold, a single photoinhibition claim across crops, or fixed saturation points for different crop categories. Accordingly, the safe synthesis is that crops exhibit nonlinear responses to additional light, and that these responses vary with context. This limitation is not a weakness of the argument; it is precisely why lighting decisions must remain conditional on crop, stage, and operating environment rather than being reduced to a single rule [4].

IV. Evidence Synthesis

Taken together, the evidence indicates that more artificial light is justified only while the incremental crop response remains strong relative to the added electrical burden. Hydroponic lettuce evidence directly connects increasing photosynthetic photon flux density with changing strategic light-use efficiency, showing that higher light can improve production but does not guarantee better productivity per unit input across the full range [1]. Broader controlled environment analysis reaches a compatible conclusion by showing that yield must be considered jointly with energy load rather than in isolation [5]. Review evidence reinforces that lighting parameters interact with crop goals and quality outcomes, so the decision criterion is not maximum light delivery, but the balance between extra production value and extra operating demand [4].

This synthesis also clarifies why universal optimisation claims are unreliable. One body of evidence is crop specific and therefore highly relevant to hydroponic production decisions, while another body is broader and designed to explain how artificial lighting affects plant responses across controlled systems [1], [2]. Engineering evidence on LEDs contributes a different but necessary layer by distinguishing fixture photon efficacy and cost-related electrical implications from plant-level efficiency outcomes [3]. When these strands are combined, they show that the same lighting increase can look favourable under one metric and unfavourable under another. A regime may raise total yield, yet lower plant light-use efficiency; a fixture may deliver photons efficiently, yet still support poor productivity per unit energy if operated beyond the most valuable response range.

The strongest general conclusion from the evidence is therefore comparative rather than absolute. Additional light tends to be most defensible where baseline light is limiting, the crop still exhibits meaningful response to added photons, and the operating schedule or supplemental strategy aligns artificial lighting with actual production need [1], [4], [5]. As light supply increases, the marginal biological return commonly declines, so the justification for further lighting becomes more demanding rather than less. The evidence does not support a single universal threshold at which extra light ceases to be worthwhile, but it does support a disciplined reasoning method: compare incremental response, incremental electricity demand, and the specific production objective before increasing artificial light intensity or duration [2], [5].

V. Practical Implications and Limitations

For practitioners, the first implication is that lighting decisions should be framed around the exact question being optimised. If the goal is rapid biomass accumulation, the useful lighting range may differ from the range that best preserves

plant light-use efficiency or maximises productivity per unit energy [1], [4]. If the goal includes quality attributes, the assessment becomes more context dependent again, because the review evidence indicates that lighting trade-offs are shaped by production objective as well as crop response [4]. This does not mean that optimisation is impossible, but it does mean that more light is not automatically better production. The chosen metric must be stated explicitly, otherwise a technically correct improvement in one sense may conceal a worsening trade-off in another.

A second implication is that controllable lighting should be viewed as a means of adjustment, not as a guaranteed route to better energy productivity. The available evidence supports discussion of changing photosynthetic photon flux density, photoperiod, supplemental-light operation, and daylight-responsive control because these alter both delivered light and electricity use [4], [5]. What the present evidence does not establish as a universal claim is that any control strategy will necessarily improve productivity per unit energy across crops and conditions. The prudent conclusion is narrower: controllable lighting can be adjusted to crop response and daylight conditions where that adjustment is justified by the production objective and local operating context. Validation still requires crop-specific observation rather than assuming a generic benefit [1], [4].

The main limitations of the evidence base also matter for interpretation. The five-source set supports strong general reasoning about diminishing returns, efficiency distinctions, electricity scaling, and contextual dependence, but it does not provide a universal empirical map across all hydroponic crops, developmental stages, climates, and market objectives [2], [4]. It also does not justify extending this paper into detailed energy economics, carbon comparisons, or whole-system sustainability claims, even though those topics are related. Similarly, while climate and automation influence how lighting performs in real facilities, the current synthesis treats them only as contextual boundaries, not as analysed subsystems. The most defensible application of the evidence is therefore targeted decision support for lighting trade-offs, with broader system integration left for separate evaluation [5].

VI. Conclusion

The evidence supports a clear answer to the central production question: adding more artificial light is justified only when the incremental crop benefit remains large enough to warrant the added electrical demand and operating burden. Across hydroponic and controlled environment evidence, biological response to rising light is nonlinear, plant light-use efficiency and fixture photon efficacy are distinct, and crop productivity per unit energy cannot be inferred from fixture efficiency alone [1], [2], [3]. Electricity demand scales with fixture power, operating duration, and the way supplemental lighting is controlled, while the best decision depends on crop, developmental stage, available daylight, climate, and production objective [4], [5]. The practical consequence is simple but important: lighting strategy should be guided by marginal response and context-specific trade-offs, not by the assumption that maximum light delivery will automatically produce the best production outcome.

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