Photosynthesis and respiration in hydroponic crops

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***Abstract*—Hydroponic crop production changes how water and mineral nutrients are supplied, but it does not alter the central biological processes that power plant growth. This paper examines how photosynthesis and respiration work together in hydroponic crops, with a specific focus on their distinct roles in carbon capture and energy release. The evidence base shows that photosynthesis contributes carbon compounds and supports ATP generation under illumination, while mitochondrial respiration remains essential for maintaining cytosolic ATP supply and growth, including across changes in light availability [1]. Recent reviews of controlled environment agriculture also show that light spectrum and lighting conditions shape photosynthesis, morphology, and biomass accumulation, yet these studies do not by themselves explain respiration as a separate growth requirement [2], [3], [4]. A second contribution of this paper is to define the boundary between basic plant biology and quantitative light science. Questions such as ePAR definitions, sensor calibration, fixture efficacy, and spatial light uniformity are important for controlled production, but they belong to measurement and lighting evaluation rather than the core biological explanation developed here [5], [6], [7]. The paper concludes that plant growth in hydroponics depends on the continuous interaction of photosynthesis and respiration, and that sound crop interpretation requires both biological understanding and careful separation from later measurement-focused analysis.**

I. Introduction

Hydroponic crops are often discussed in terms of nutrient recipes, water delivery, and lighting systems, yet their growth still depends on the same biological foundations as soil-grown plants. Photosynthesis remains the process through which plants capture carbon and convert light energy into chemical forms that support biomass production, while respiration is required to release usable energy from those compounds for maintenance and growth. Reviews of controlled environment agriculture show that artificial lighting affects photosynthesis, plant form, and biomass accumulation, which makes photosynthesis central to any explanation of crop productivity under hydroponic management [2]. The limitation is that light-focused reviews do not, on their own, explain why growth also depends on ongoing respiratory metabolism, even when carbon gain has already occurred.

A clear explanation of hydroponic growth also requires separation between biological mechanism and quantitative light engineering. Some published work addresses whether far-red photons should be counted within definitions of photosynthetic photons and how fixture efficacy should be assessed, which are important questions for lighting design and performance comparison [5]. These issues matter because growers and researchers may otherwise confuse measurement standards with the underlying biology of carbon capture and energy use. In this paper, the scope is therefore restricted to explaining how photosynthesis and respiration work together to power plant growth, while recognising that photon accounting and fixture evaluation are related but distinct topics that should not replace a mechanistic biological account.

Recent reviews of blue light in controlled environment agriculture reinforce this distinction. They show that spectral composition regulates photosynthetic efficiency, morphogenesis, flowering, and other physiological responses, demonstrating that light quality strongly shapes plant growth outcomes [3]. However, such evidence is more informative about how light modulates photosynthetic performance than about respiration as a distinct and continuous biological requirement. The central argument of this paper is that hydroponic crop growth can only be understood properly when photosynthesis is treated as the source of carbon assimilation and respiration is treated as the continuing pathway that supplies usable energy from assimilated substrates. The following sections define that relationship, establish the evidence base, and clarify where biological interpretation ends and quantitative lighting analysis begins.

II. Background and Scope

The strongest direct evidence for distinct biological roles comes from experimental work showing that photosynthetic electron transport can increase ATP availability in the plant cytosol under illumination, but that mitochondrial respiration remains essential for sustaining cytosolic ATP supply and supporting growth [1]. This is important because it prevents a simplistic reading in which light alone appears to explain energy status in illuminated tissues. Photosynthesis contributes reducing power and carbon fixation, and it can support ATP-linked processes during the light period, yet the cell still depends on mitochondria to maintain the broader energetic balance needed for active metabolism [1]. For hydroponic crops, the implication is that productive growth is not explained solely by maximising light-driven carbon gain; energy metabolism after carbon capture remains fundamental to tissue function and biomass formation.

The same study also helps answer whether respiration continues independently of whether photosynthetic light is currently available. After light-off, cytosolic ATP remained elevated only briefly before declining, and mitochondrial activity materially contributed to ATP supply during and after transitions between dark and light conditions [1]. This finding supports a biologically important distinction: photosynthesis is contingent on illumination, whereas respiration continues

as a necessary process for maintaining cellular energy supply beyond the immediate presence of light. For hydroponic crops, this matters because roots, developing tissues, and shaded tissues still require energy for transport, maintenance, and growth even when net photosynthetic carbon fixation is reduced or absent. The limitation is that the evidence comes from cellular and physiological analysis rather than crop-scale hydroponic trials, so the interpretation should remain mechanistic rather than overstated at the production level.

The scope of this paper must also be bounded carefully. Reviews of photosynthetically active radiation measurement focus on PAR definitions, sensing technologies, calibration, unit conversion, remote sensing, and related measurement practice [6]. These topics are necessary for quantifying the light environment supplied to hydroponic crops, but they do not themselves explain the biological cooperation between photosynthesis and respiration. The gap addressed here is therefore not a lack of measurement frameworks, but a need for a clear synthesis of how carbon capture and energy release jointly power plant growth in hydroponic systems. This paper treats hydroponics as a production context in which resources are delivered differently, while the governing biology of photosynthesis and respiration remains unchanged.

III. Core Concepts and Mechanisms

At the mechanistic level, photosynthesis and respiration should be understood as complementary rather than competing processes. Photosynthesis captures carbon into organic compounds under light, whereas respiration oxidises carbon substrates to provide energy that cells can use continuously for maintenance and development. Evidence on plant responses to photoperiod and phytochrome-linked signalling shows that plants interpret light not only as an energy source but also as a biological signal that regulates development across time [8]. This is useful for hydroponic interpretation because it reminds us that light responses involve both metabolism and signalling.

A second mechanism concerns the difference between biological process and lighting assessment. Research on the spatial uniformity of light intensity and spectrum in indoor crop production shows that measurement grids, spectral uniformity, and benchmarking methods are needed to compare lighting installations reliably [7]. These approaches matter because uneven photon distribution can create uneven crop development, which affects the realised expression of photosynthesis across a canopy [7]. Even so, the biological explanation remains separate: measurement tells us how light is delivered, while plant physiology determines how captured photons contribute to carbon fixation and how assimilated products are later used through respiration. For that reason, uniformity metrics and lighting benchmarks should be treated as enabling descriptors of the crop environment, not as substitutes for an explanation of growth metabolism.

Evidence from leafy crop studies under differing spectral treatments further supports the photosynthetic side of the relationship. Blue light has been shown to modulate interactions among far-red light, temperature difference, growth, morphology, and leaf-level carbon gain in crops such as arugula and lettuce [4]. This indicates that light quality can alter the extent to which photosynthetic processes contribute to observed growth and plant form. However, the same evidence does not establish respiration as a distinct biological role beyond limited leaf-level physiological measurements [4]. The implication is that light spectrum can change the inputs to growth, especially through effects on carbon gain and morphology, but growth still depends on the downstream respiratory use of assimilated carbon, which requires evidence from other sources to explain adequately.

IV. Evidence Synthesis

Taken together, the evidence supports a two-part account of plant growth in hydroponic crops. First, photosynthesis supplies carbon compounds and contributes to energy-linked metabolism when light is available. Second, respiration remains essential for sustaining usable ATP in the cytosol and therefore for maintaining active growth processes across changing light conditions [1]. Reviews on photoperiod responses show that the plant light environment has both metabolic and signalling dimensions, while measurement-focused literature shows that the supplied light field must be described with appropriate technical methods if crop responses are to be interpreted correctly [6], [8]. The synthesis is that biological explanation and environmental quantification are mutually necessary, but they answer different questions.

This distinction becomes especially important in hydroponic systems because controlled environments can create a false impression that growth is fully determined by external settings such as spectrum, intensity, or fixture performance. The accepted evidence suggests a more careful interpretation. Lighting reviews demonstrate that artificial light influences photosynthesis, morphology, and biomass, and spectral studies show that different wavebands can shift leaf-level carbon gain and growth responses [2], [3], [4]. Yet the direct evidence for respiration shows that mitochondrial function remains essential even in illuminated cells and across light transitions [1]. In other words, better light delivery can improve the conditions for carbon capture, but it does not remove the requirement for continuous respiratory energy release from the carbon compounds that photosynthesis has produced.

The boundary between basic photosynthetic biology and quantitative light science can therefore be stated precisely. Biological explanation should cover how plants use light to fix carbon, how that carbon contributes to metabolism, and why respiration remains necessary for usable energy supply and growth [1]. Quantitative light science, by contrast, should address how photons are defined, measured, calibrated, spatially distributed, and compared across lighting systems [5], [6], [7]. This boundary is not merely academic. If these domains are blurred, growers and students may mistake improvements in measurement practice or fixture benchmarking for direct explanations of plant growth. The evidence instead supports a layered view in which hydroponic productivity emerges from

both sound environmental control and unchanged core plant physiology.

V. Practical Implications and Limitations

For hydroponic practice, the main implication is that management decisions should respect the complementarity of photosynthesis and respiration rather than prioritising only one process. Accurate assessment of supplied light remains important, because PAR measurement, calibration, and related methods shape how the production environment is characterised [6]. Photoperiod research further indicates that timing and duration of light exposure affect biological responses beyond simple photon delivery [8]. In parallel, studies of light uniformity show that uneven distribution can create within-canopy variation in crop development [7]. Together, these findings suggest that hydroponic management should interpret light as a driver of carbon capture and developmental signalling, while recognising that respiratory demand persists across tissues and across the daily cycle.

A second implication is interpretive restraint. Because the evidence base here is strongest for mechanistic distinction and scope setting, it supports careful explanation rather than broad production claims. The studies on PAR measurement and lighting uniformity describe how to quantify and compare the light environment, but they do not prove that any single measurement framework automatically optimises whole-crop growth [6], [7]. Likewise, photoperiod literature clarifies that plants respond to the temporal structure of light as a biological signal, but it is not a direct substitute for evidence on respiratory metabolism in hydroponic production [8]. Practically, this means that growers should avoid assuming that a well-measured lighting system alone explains performance differences when respiratory constraints and tissue-level metabolic needs are also involved.

The main limitation of the present evidence base is that it combines strong physiological evidence for respiration with broader review and environmental measurement literature, rather than providing a fully integrated hydroponic crop experiment that tracks carbon capture, ATP dynamics, and crop growth simultaneously. The respiratory evidence is persuasive for establishing distinct roles and the persistence of respiration beyond immediate light availability [1], but additional crop-scale validation would be needed to connect these mechanisms more directly to species-specific hydroponic outcomes. Similarly, the measurement literature clearly defines how light can be quantified and benchmarked [6], [7], yet that does not remove the need for biologically grounded interpretation. Future validation should therefore link environmental measurements, light response biology, and respiratory function within the same hydroponic cropping context.

VI. Conclusion

Photosynthesis and respiration work together to power plant growth in hydroponic crops, but they do so through distinct biological roles. Photosynthesis captures carbon and contributes to energy-linked metabolism under illumination, whereas respiration continuously releases usable energy needed for growth, including across changes in light availability [1]. Evidence from controlled environment agriculture shows that light quality and artificial lighting strongly influence photosynthesis, morphology, and biomass [2], [3], [4], but the same evidence does not remove the central importance of respiration. Hydroponics therefore changes the mode of resource supply, not the underlying requirement that carbon assimilation and respiratory energy release must operate together.

The most important next step is stronger integration of biological and environmental analysis. Measurement frameworks for photon definition, sensor calibration, and spatial light distribution are valuable for describing the hydroponic environment [5], [6], [7], yet they should remain analytically separate from the core explanation of how growth is powered. A robust understanding of hydroponic crop performance requires both: precise characterisation of the light environment and a clear account of the complementary roles of photosynthesis and respiration.

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