Light Spectrum and Plant Form in Hydroponic Crops: Morphological Responses to Spectral Distribution Under Similar Photon Supply

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***Abstract*—Light spectrum influences plant form through signalling pathways that operate alongside photosynthesis, so crops exposed to broadly similar photon quantities can still develop markedly different morphologies. This paper examines how spectral distribution is described in horticulture and synthesises current evidence on wavelength dependent effects of red, blue, far red, and, where evidence is more limited, green light on stem elongation, compactness, leaf expansion, and related developmental traits in controlled hydroponic production. The review focuses on photomorphogenic interpretation rather than detailed molecular photobiology, with particular attention to phytochrome photoequilibrium or photostationary state as a useful, but imperfect, framework for understanding spectral responses. Across the literature, far red commonly promotes extension growth and modifies leaf expansion, blue light often suppresses excessive elongation and increases compactness, and the response to red or green light depends strongly on spectral context rather than any universal wavelength recipe. The evidence also shows that species, cultivar, developmental stage, photon quantity, and temperature context can shift outcomes substantially. Practical implications for controlled environment hydroponics therefore depend on crop specific validation rather than simplified marketing claims. Current studies support spectrum as a meaningful developmental control, but they also show important uncertainty and limited transferability of controlled studies across crops and production environments.**

I. Introduction

In controlled hydroponic production, light is not only a source of photosynthetic energy but also a developmental signal that shapes plant architecture. This distinction matters because two lighting treatments can deliver broadly similar photon quantities while producing different stem length, leaf area, and biomass partitioning. Recent controlled environment evidence in arugula and romaine lettuce shows that far red light and day to night temperature difference can jointly promote stem elongation and alter leaf expansion, but that these responses are substantially modified when blue light is increased [1]. The implication is that plant form cannot be inferred from photon quantity alone. For growers, this means spectral distribution is relevant when crop compactness, canopy fill, and harvestable morphology are important production targets, although the observed responses already indicate a limitation: spectrum acts through interaction with other environmental variables rather than as an isolated universal control [1].

Evidence from lettuce further shows that spectral composition has effects that are not reducible to total photosynthetic photon flux density. In experiments that varied far red supplementation and red to blue ratio independently, treatments with equal photosynthetically active radiation still differed in spectral balance, phytochrome related metrics, and crop outcomes [2]. This is central to the present topic because it demonstrates how spectral distribution can alter development even when total photon quantity remains similar. It also cautions against simplistic claims that one colour alone determines morphology. Red, blue, and far red act within a composite spectral environment, and their practical effects depend on how the spectrum shifts the signalling state perceived by the crop [2].

A useful framework for interpreting these effects is phytochrome photoequilibrium, also called photostationary state, which estimates the balance between active and inactive phytochrome forms under a given spectral photon distribution. However, this framework is informative rather than fully deterministic. Work on spectral distortion within leaves shows that estimates based only on the spectrum above the canopy can be inadequate predictors of morphology, especially when wavelengths beyond a simple red to far red contrast are varied [3]. Accordingly, this paper argues that light spectrum and plant form should be understood through a synthesis of spectral description, photoreceptor signalling, and crop specific experimental evidence. The discussion first establishes how horticultural spectra are described, then examines red, blue, far red, and limited green light effects, before considering practical implications, uncertainty, and the transferability of controlled studies [3].

II. Background and Scope

Current horticultural literature treats blue light as a major regulator of plant morphogenesis, but it also emphasises that responses are inconsistent across species, cultivars, growth stages, and cultivation conditions [4]. This inconsistency is not a weakness of the topic so much as a warning about scope. A spectrum is usually described through its spectral photon distribution, through waveband integrated photon fluxes such as blue, green, red, and far red fractions, and through derived ratios such as red to blue or red to far red [4]. These descriptors help compare treatments, yet they do not automatically predict morphology because plant responses arise from integrated photoreceptor signalling. For that reason, the present paper

focuses specifically on plant form, including stem elongation, compactness, and leaf expansion, rather than on fixture efficacy, photoperiod management, or general energy trade offs, which require separate analytical treatment [4].

A second background issue is how to interpret spectra that contain appreciable blue or green radiation. Under those conditions, red to far red ratio alone can become an incomplete indicator because phytochrome is affected by a broader spectral field. Modelling work on photostationary state under artificial light argues that when blue or green light is prominent, phytochrome interpretation should move beyond a simple red to far red ratio and use a fuller spectral measure such as PSS [5]. Even then, the relationship between PSS and plant response may be nonlinear, threshold dependent, and modified by other photoreceptors [5]. This paper therefore uses spectral descriptors as explanatory tools rather than as universal predictive laws. The gap addressed here is not a lack of studies on spectral manipulation, but a need for a careful synthesis that connects spectral description to observed morphology without overstating mechanistic certainty [5].

The scope is consequently that of an evidence based overview rather than a new experiment or a detailed molecular review. Blue light is examined closely because recent synthesis identifies it as a strong but context dependent regulator of elongation, compactness, pigment accumulation, and developmental timing, while also noting that parameter optimisation remains insufficiently resolved for many crops [4]. Far red and red are considered mainly through their role in phytochrome mediated signalling and extension growth, and green light is discussed more cautiously because the accepted evidence here supports its relevance to spectral modelling more clearly than it supports a standalone morphological recipe [4], [5]. This framing is intended to separate robust relationships from marketing narratives that imply simple wavelength prescriptions for all hydroponic crops.

III. Core Concepts and Mechanisms

The central mechanism linking light spectrum to plant form is photomorphogenic signalling, especially through phytochrome in the red and far red region, together with blue light sensing pathways that influence elongation and leaf development [3], [4], [5]. In horticultural practice, a spectrum can deliver the same broad photon quantity while shifting the proportion of photons in blue, red, or far red bands. That shift changes the signalling environment perceived by the plant, which can alter allocation to stems and leaves without requiring a large change in total light input. This is why morphological outcomes such as compactness or extension growth may diverge under similar PPFD or DLI. The mechanism is conceptually straightforward, but its application is constrained by the fact that signalling metrics are approximations and not direct measurements of whole plant developmental response [3], [5].

Far red is especially important because it modifies the phytochrome state associated with shade related developmental responses. When the effective red to far red balance declines, extension growth commonly increases, and traits such as stem elongation or altered leaf expansion can follow [3], [5]. Yet the signalling picture becomes more complex when blue light is varied at the same time. Blue light can suppress excessive elongation even when far red is present, indicating that the final morphology reflects photoreceptor interaction rather than a single spectral channel acting alone [4], [5]. This interaction matters for hydroponics because growers often work with mixed spectra, not monochromatic treatments. It also explains why the same far red addition may improve canopy expansion in one context but drive unwanted stretching in another.

Blue light contributes to morphology through more than one route. The reviewed evidence indicates that increased blue photon fraction often produces shorter, more compact plants, while lower blue fractions can permit greater extension growth [4]. However, pure or dominant blue conditions should not be interpreted simplistically because phytochrome related metrics may also shift under such spectra, and observed morphology may partly reflect reduced phytochrome activation rather than a blue specific effect in isolation [4], [5]. This is an important limitation for interpretation. It means that statements such as blue light always suppresses elongation are too coarse unless the surrounding spectrum is specified. Green light enters this mechanistic discussion mainly because it contributes to the total spectral field that shapes PSS estimation, so its developmental significance in this evidence base is better treated as contextual modulation than as a standalone universal driver of form [5].

IV. Evidence Synthesis

The strongest direct evidence for spectrum driven changes in plant form under similar photon supply comes from controlled studies in leafy crops. In lettuce and arugula, far red and positive day to night temperature difference acted synergistically to increase stem elongation under low blue light, whereas higher blue light suppressed this excessive elongation and preserved beneficial effects on total leaf area and biomass [1]. This is highly relevant to hydroponic production because it shows that morphological control depends on spectral composition and environmental context together. The practical message is not that blue is good and far red is bad, but that the same far red input can shift from undesirable stretching to productive leaf expansion depending on the blue background and thermal regime [1].

Independent lettuce evidence also shows that far red effects and red to blue ratio effects should be distinguished analytically rather than collapsed into a single recipe [2]. In those experiments, treatments varied in waveband composition, red to blue ratio, red to far red ratio, and PSS while maintaining a common PAR level. Such designs demonstrate that a crop can respond to the spectral arrangement of photons, not merely their total amount [2]. This supports the paper's central argument that spectral composition must be separated conceptually from PPFD or DLI. At the same time, the evidence indicates uncertainty about generalisation because these responses were measured in lettuce under controlled conditions, and they do

not justify universal wavelength prescriptions for unrelated species, cultivars, or production goals [2].

A broader synthesis of blue light literature reinforces this caution. Reviews of controlled environment studies report that blue light mediated elongation responses can be inconsistent across taxa and developmental stages, and that outcomes depend on genotype, spectral interactions, and cultivation conditions [4]. That wider context helps explain why direct experiments and photoreceptor models do not always align neatly. PSS based interpretation clarifies part of the signalling basis, particularly when blue and green photons alter the effective phytochrome environment, but modelling work also indicates nonlinear and threshold like behaviour [5]. Therefore, current evidence supports a mechanistic and practical role for spectral distribution in shaping morphology, while also requiring careful interpretation of uncertainty and the transferability of controlled studies beyond the experimental setting [4], [5].

V. Practical Implications and Limitations

For hydroponic growers, the most defensible practical implication is that spectrum can be used to steer morphology, but only within a crop specific management framework. If the objective is a more compact canopy, a higher blue fraction may help suppress extension growth in some leafy crops, whereas adding far red may increase expansion or elongation depending on background spectrum and temperature conditions [1], [4]. However, spectrum should not be treated as a substitute term for photon quantity. Similar PPFD does not guarantee similar morphology, yet altered morphology under different spectra also does not mean photon quantity has become irrelevant. A useful operational distinction is that PPFD and DLI describe how many photons are delivered, while spectral distribution helps explain what developmental signals those photons carry [5].

The evidence base also exposes important limitations. First, some common descriptors are easier to communicate than they are to interpret biologically. Red to far red ratio is intuitive, but when blue or green photons change materially, PSS may be more informative, and even PSS may not linearly predict form across all crops or conditions [5]. Second, controlled studies often focus on a small number of species, cultivars, and developmental windows. That restricts transferability of controlled studies, especially when moving from chamber experiments to commercial hydroponic systems with different canopies, temperatures, and management aims [1], [4]. As a result, practical recommendations should be validated locally rather than adopted as universal wavelength recipes.

There is also persistent uncertainty around how far current evidence can be generalised for green light and for interactions among spectrum, cultivar, and developmental stage. Within the accepted evidence, green light is clearly relevant to whole spectrum description and to PSS interpretation, but support for strong independent morphological claims about green light is comparatively limited [5]. Likewise, broader reviews indicate that species specific and stage specific responses remain insufficiently resolved for many horticultural crops [4]. The most responsible reading is therefore that spectral control of morphology is real and usable, but bounded by uncertainty, context dependence, and incomplete transferability of controlled studies. This conclusion is more valuable to hydroponic practice than oversimplified marketing claims, because it encourages calibration, observation, and crop specific spectral testing instead of one size fits all lighting formulas.

VI. Conclusion

Current evidence supports the conclusion that light spectrum can alter plant form in hydroponic crops even when total photon quantity is broadly similar. The effect arises because spectral distribution changes the developmental signals perceived by the plant, particularly through phytochrome related responses to red and far red and through blue light interactions that modify elongation, compactness, and leaf expansion [1], [2], [3]. Across the literature considered here, far red often promotes extension growth, blue often restrains it, and the final morphology depends on spectral context rather than on any universal recipe. This makes spectrum a meaningful production variable, but not an autonomous control that can be interpreted apart from crop identity and environmental conditions.

The most important limitation is that mechanistic understanding and practical recommendation do not yet align perfectly. Metrics such as PSS improve interpretation, especially when blue and green wavelengths are involved, but they remain approximations rather than complete predictors of morphology [3], [5]. Future work should therefore focus on better validation across species, cultivars, and developmental stages, with explicit attention to uncertainty and the transferability of controlled studies into commercial hydroponic environments [4]. Until that evidence base broadens, the strongest conclusion is a cautious one: spectral composition is a powerful developmental lever, but its value depends on crop specific testing and disciplined separation of supported relationships from universal marketing claims.

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