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Controlled LED Lighting for Horticulture: A Review

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Abstract

As energy gradually becomes a more valuable commodity, the desire for reduced energy losses strengthens. Lighting is a critical field on this matter, as it accounts for a large percentage of the global electricity consumption and modern lighting systems are greatly more efficient than incandescent, discharge, and fluorescent lights. Previous research has proven that plants do not require the entire visible spectrum but react only to specific wavelengths, making it possible to control their growth and yield via artificial lighting. The flexibility of control of Light Emitting Diode (LED) lights allows for the combination of great energy losses reduction and controlled plant growth, achieving the improvement of two major parameters in a single action. This review paper summarizes the current research on the effect different light wavelengths have on specific plant species and discusses the applications of LED lighting for horticulture, yield storage, and disease protection.

Keywords

Horticulture Lighting, Agriculture Lighting, Controlled LED Light, Light Wavelength Effects, Light Spectrum, Vegetables, Crops, Photoreceptors

1. Introduction

Artificial lighting for horticultural use has been studied since 1860 but practical application was unfeasible at the time [1] [2]. Research progressed over the following decades using carbon arc and low-pressure discharge lamps [3] [4] [5] [6], yet no technology reached commercial use. The prospect of cultivation in controlled environments with artificial lighting came into existence in the 1980s, when the ever-rising population in conjunction with the failing crops due to the climate change pushed for the development of alternative food sources [7]. The development of more efficient forms of lighting, such as high-pressure sodium

(HPS) lamps marked the point where artificial crop lighting became both technically and economically feasible, with researchers directly or indirectly identifying the significantly lower energy requirements [8] [9].

Light-Emitting Diodes (LEDs) first appear in the early 20th century, when Henry Josef Round observed the emission of light when applying current to silicon carbide crystals [10]. Still, the first commercial LEDs were developed many decades later, with the first products appearing in the late 1960s [11]. The potential of LEDs as a lighting source for horticulture was first explored in the early 1990s [12], revealing distinct advantageous features and configurations that the use of LEDs unshackles [13]. Their efficiency and very low radiant heat offer more than just lower energy cost; they allow for the design of much denser horticultural canopies, greatly decreasing space requirements. Furthermore, the use of LEDs allows for control of the light spectrum, as they can be configured to produce light in the spectral range required by the application. Nowadays, controlling the light output of LEDs is easy and cheap [14] [15].

The rapid development of LED lighting over the past decade is a technical and economic opportunity for horticulture; LEDs can greatly outlive HPS lamps and consume significantly lower amounts of energy. LED luminaire efficacy has more than doubled over the past five years, with projections suggesting that efficacy will improve by at least another 25% by 2025 [16]. With plants using radiant energy only in the photosynthetically active region of 400 to 700 nm [17], LED technology allows for the control of the exact light wavelength and intensity output, providing the unique opportunity to design lighting systems that are both technically and energetically optimized for specific cultivations [18]. In this review, we summarize the research on LED lighting for horticultural use and classify what effect specific LED light wavelengths have on cultivations.

2. Red (610 - 700 nm) & Far-Red (700 - 800 nm) Light Effects

Red light is generally associated with the growth rate and dry weight increase of plants. Red light can delay, or even completely inhibit, a plant's transition to flowering, allowing them to significantly increase their biomass [19]. The issue here is that although red light is proven to increase the total biomass of certain plants [20] [21], it also increases elongation [22] and tends to deteriorates pigment [23], decreasing the overall value of many plants. Nevertheless, there are cases where this canon does not apply, with studies suggesting that monochromatic 660 nm light actually improves anthocyanin content and, in extend, the quality of certain plants [24].

One of the first studies exploring the effect of red/far-red wavelength LED light on plants was performed by Brown *et al.*, displaying that the addition of 700 - 740 nm light increases the height and mass of sweet pepper (Capsicum annuum) plants [25]. A later study verified these results but showcased that the increased size had virtually no effect on the fresh and dry weight of peppers [26].

A study on cucumber transplants revealed that supplemental 622 nm LED light can increase the growth rate but, ultimately, has no effect on the total mass or yield [27]. Similar results were obtained by supplemental red light on spinach, which accelerated the formation of new leaves but was not optimal for the final weight of the plant [28]. A study on tomatoes suggests that 680 nm light will significantly increase yield [29], yet a newer study indicates that red LED light will cause leaf curling on several tomato genotypes, with virtually no tangible advantage [30]. More recent research found that the combination of red and blue LED light in 3:1 ratio assists the morphologic development of tomato plants and significantly improves the fruit yield and quality [31]. Red 640 nm light is also found to be important for the growth, pigment, and nutritional quality of kale [32].

The effect of red spectrum LED light on the growth and yield of lettuce (Lactuca Sativa) has been extensively studied, with conflicting results. Early studies claim that red light alone is unacceptable for the proper growth of lettuce [12] [33] [34] but more recent studies suggest otherwise. Stutte *et al.* studied the effect of multiple light wavelengths on red leaf lettuce, concluding that the application of far-red 730 nm light on red leaf lettuce elongated the leaves and significantly increased the dry weight of the plant [22]. A parallel study from Li and Kubota concluded that supplemental red and far-red LED light has similar results on the growth of baby leaf lettuce, considerably increasing the stem and leaves length of the plants, reducing however phytochemical concentrations when no other light is present [23]. The effect of red (660 nm) and far-red (735 nm) light on lettuce was also studied by Lee *et al.*, who derived that it increased the number and size of the leaves on grown plants, whereas it also improved the shoot and root growth of red lettuce leaf seedlings [20]. These effects were more prominent as the wavelength increased. Pinho *et al.* [21] and Chen *et al.* [35] both verified that wavelengths longer than 700 nm significantly contribute to photosynthesis and considerably increase the growth rate of lettuce, warning however that the increased rate of growth decreases the fresh and dry weight of the plants, a comment that is in complete antithesis to the results of other studies [22] [23].

Lettuce also seems to react positively to red light in terms of nutritional quality. The use of 620 nm to 700 nm has several positive effects on the nutritional value of lettuce, reducing ascorbic acid concentrations [36], increasing antioxidant properties [37], and stimulating the uptake of N, K, Ca, and Mg [21]. Another study showed that 620 nm light can increase chlorophyll and carotenoids concentrations [35], yet far red 735 nm light has the exact opposite effect [23].

Studies on cabbage suggest that monochromatic red LED light is not optimal for the growth or the properties of the plants. However, a red to blue 7:1 ratio provides adequate light conditions for the growth of non-heading Chinese cabbage, with no weight or nutrients loss compared to HPS lamp light [38].

3. Green (500 - 600 nm) Light Effects

Early research suggests that green light will repress the growth of algae and some plants [39] [40]. However, more recent research suggests that several types of plants can greatly benefit from 510 nm to 585 nm wavelength light, yet mostly in conjunction with red and/or blue light. In nature, green wavebands are generally found in plant-shaded environments and, expectedly, affect organisms that populate such environments, such as fungi, algae, and bacteria [39] [41]. For higher plants, green light regulates growth, usually negatively affecting the growth of plants if no red or blue waveband light is present, as it serves as a signal of unfavorable photosynthesis conditions [42]. Green light also signals the closing of stomata in several plant species, reducing stomatal conductance [43] [44] [45].

Both the fresh and the dry weight of cucumber transplants, as well as their growth rate, were found augmented via the application of 505 nm to 530 nm green LED light [46] [47]. In contrast to research suggesting that green light increases the hypocotyl length of plants [48], the addition of green light decreases the hypocotyl elongation of cucumber transplant seedlings [46]. In the case of tomato plants and sweet peppers, supplemental 505 nm LED light significantly increased the leaf area of the plants, as well as their fresh and dry weights, but the plants did not react positively to 530 nm light, suggesting a very selective wavelength behavior [47].

Green light wavelength was found to further improve the growth rate and quality of lettuce when combined with red and blue LED arrays [45]. Later studies discovered that partial green light, up to 50%, can increase lettuce growth but higher figures would cause a reduction of it [49]. The effect of green light wavelength on red leaf lettuce has been studied by Johkan *et al.*, concluding that green light is an effective growth stimulant, with 510 nm high-intensity light displaying the most prominent growth effect [50]. A later study added that 518 nm light can also have a dramatic effect on the fresh and dry weight of lettuce, with the increase of fresh weight reaching 61%, but only in conjunction with 655 nm light [51]. Green light also appears to have a significant effect on the nutritional quality of lettuce, increasing saccharide concentrations [52] and decreasing nitrate concentrations [53].

4. Blue (380 - 500 nm) Light Effects

Blue light is frequently researched as supplementary to red or polychromatic light, with few researchers solely focusing on the effects of blue waveform light alone. Blue light wavelength generally is responsible for the opening of stomata [43] [54].

Supplementary blue light was found to be necessary for the proper growth of wheat, which was unable to fully develop with 660 nm red light alone. The addition of 10% blue light significantly increased fresh and dry weight, decreased the number of sub-tillers and spikes, and greatly increased seed yield, producing comparative results to plants grown in white light [55] [56].

456 nm light also leads to the accumulation of antioxidants in lettuce [51] [57], as well as an increase in carotenoids and chlorophyll concentration [58]. However, blue spectrum LED light on lettuce promotes leaf expansion and retards growth, leading to compact plant morphology [22] [58]. Regardless, even though lettuce seedlings initially grow much faster with red 660 nm light, prolonged exposure to blue 470 nm light greatly increases the fresh and dry weight of lettuce, ultimately resulting to significantly heavier harvestable plants [57]. According to the same study, the combination of blue and red light has no further effect on the plant's ultimate weight but significantly increases chlorogenic acid contents. This is in agreement with earlier studies that suggest the supplementation of lettuce cultivations with blue spectrum light in order to enhance yield [33]. Finally, supplemental 400 nm to 500 nm blue light increases anthocyanins on lettuce by 31%, vividly improving the plant's quality [22] [23].

In combination with red 660 nm light, 450 nm light was found to shorten the length of tomato seedling stems [59] and to increase the leaf area of the plant [47], as well as to improve the nutritional quality of their fruits [60]. Medium intensity 455 nm light also decreases the hypocotyl elongation of tomato plant stems but low and high intensities have the opposite effect [61]. Blue light was found to increase the tomato plant's biomass and quality [62] but some researchers report a negative impact on fruit yield [63]; however, the combination of blue and red LED light seems to enhance tomato plant biomass with ostensibly no effect on fruit yield, an effect that could not be achieved with red or blue light alone [30]. The introduction of blue LED light to tomato genotypes also increases chlorophyll and flavonol contents [30] and improves the disease resistance of tomato crops [62].

The addition of blue light appears to have several positive effects on cucumbers, with no adverse effects listed to this date. Hogewoning *et al.* found that a 7% - 93% blue-red light ratio is sufficient to pervert any overt dysfunctional photosynthesis and doubles the photosynthetic capacity of cucumber plants, effects that increase while blue light remains below 50% of the total irradiance [64]. The same research notes that the effect of blue light on the photosynthetic capacity of the plan also improved the weight of the plant, nitrogen and chlorophyll content, as well as stomatal conductance, improving the rate of passage of CO_2 and water vapors through the stomata of the leaves. Cao *et al.* obtained very similar results with 20% - 80% blue-red light on cucumber seedling growth [65]. More recent research claims that monochromatic blue light enhances the growth rate of cucumbers the most [66]. 455 nm light also improves cucumber photosynthetic pigment concentrations, bettering their overall quality [46].

Blue light is also beneficial for the growth and properties of cabbage. Mizuno *et al.* discovered that 470 nm light improves petiole elongation in both green and red leave cabbage varieties but affects chlorophyll content only on the green leave cabbage variety [24]. In the case of non-heading Chinese cabbage, blue light also increases their nutritional quality, benefiting Vitamin C, rising sucrose levels, improving soluble protein and soluble sugar concentration, and increasing chlorophylls accumulation [67].

Supplemental blue LED light also seems to accelerate the growth rate of certain plants, such as strawberries [68] and azalea [69], yet they still require red light wavelength in order to maintain their physical and nutritional quality. Spinach also displays a similar reaction to supplemental blue light, with researchers proving that cold white LEDs—LEDs with very high photon radiance on the 445 nm wavelength—advance the development of spinach plants by a full week, yet the research did not investigate what effect that has on the nutritional quality of the spinach plants [28] [33].

5. Discussion

It can be surmised from the previous paragraphs that there is no one-size-fits-all solution, as different plant species react differently to each light wavelength and intensity. Certain studies showcase that the light intensity can greatly change the effect that a specific wavelength has on certain plants [61]. This warrants further investigation on how intense LED lighting needs to be in order to induce certain effects, as well as if other effects can be induced by the same light wavelength at different intensity levels. There are also plants that react to very specific wavelengths, such as, for example, tomato and sweet pepper plants that react very well to 505 nm green light but not at all to 530 nm green light [47]. Several studies find that the combinations of two or more wavelengths yield significantly better results. For example, the combination of red and blue light wavelength greatly increases both the size and the weight of peppers, while it offers easy modulation of capsaicinoids and carotenoids, as well as control over the fruit's color [26]. Basil and strawberries perhaps the most prominent example, with researchers identifying that the combination of red and blue LED light increases both the leaf yield and the nutritional quality of the plant [68]. There are also studies concluding that monochromatic or duochromatic LED light have poor results on the yield of certain plants, such as radish [33], suggesting that other wavelength and/or intensity combinations need to be investigated. Conversely, research on some plants has only been performed with polychromatic LEDs that include four or more light wavelengths, making it difficult to discern which wavelength affects what parameter and if any are unnecessary for the yield and/or the quality of the plants and fruits, warranting further research [70] [71] [72].

There are also a few studies investigating the effect of LED lighting on harvested plants during the storage period, suggesting that specific LED light wavelengths have interesting effects on the nutritional quality of fruits [73], with the researchers identifying that specific light wavelength can affect anti-oxidant concentrations, phenolic content, pigment, tocopherols, firmness, and more. Reviewing what effect which light wavelength has on plants, one can easily conclude that there are no formulae applicable to every plant species; different plants react differently to various light wavelengths and intensity. For example, although red light increases the harvest weight of lettuce [22], it seems to have no effect on the weight of peppers [26], and while blue light increases the nutritional quality of cabbage [67], it decreases the nutritional quality of garlic seeds [74] and pea sprouts [75]. Researchers who examined the effects of supplementary lighting on several types of plants also found that reactions to specific wavelengths are species dependent [76]. Combining the above, we can assess that both light waveform combinations and light intensity affect how a plant develops, with different plants having a different optimal lighting configuration, suggesting that the optimization of LED lighting for horticulture is complex and needs to be a per-species approach. There are but a few detailed case studies currently published, such as the study for growing lettuce in plant factories with artificial lighting by [77], but such holistic approaches seem necessary to optimize the characteristics and determine the cost-effectiveness of managing and improving horticultural crops via controlled LED lighting.

Another seemingly viable application of LED lighting is for the protection of crops from disease. Depending on the plant species, it has been suggested that certain wavelengths can suppress disease or even prevent it altogether. Strawberry plant disease seems preventable by UV-B light [78], while blue-violet light wavelength seems to improve the resistance of tomato and other higher plants [79] [80]. A more recent study suggests that UV light can very effectively increase resistance to insect and pathogens—the study is primarily focused on ornamental crops but suggests that could apply to edible crops [81]. Although this research topic has been only superficially studied, it represents a practicable indirect approach of using artificial LED lighting to improve the final quality of crops.

It is interesting to note that there is a shortage of studies on the economic impact that supplemental LED lighting may have on crops, asserting whether the gains from installing such lighting systems will overcome the capital costs of the system, or even the energy cost from running the LEDs. Recent research suggests that the replacement of HPS lamps with LED lighting may be economically feasible only in regions where the energy cost is high or if the capital cost of the LED systems decreases significantly [82] [83]. Still, the efficacy of LEDs increases exponentially with each passing year and the economic feasibility of LED-based horticultural designs, such as dense vertical canopies, has not been adequately investigated yet. With studies suggesting that certain high-intensity configurations probably are unrealistic [69], the practical application of LED lighting for crops warrants thorough investigation. Finally, it has been proven that the placement of the LEDs can also be optimized in order to minimize energy use [84], which suggests that not only the correct light wavelength for each intended excitation must be identified for each type of plant but the placement of the lighting must also be researched for the optimization of energy use.

6. Conclusion

LED lighting has great potential either as a supplemental or the sole lighting source in horticulture. Due to the technical characteristics of LEDs, such as their small size and excellent efficacy, the design of very dense farming canopies is possible, greatly improving the feasibility and yield of cultivation in artificial constructs. This is exceptionally important for locations or constructs where space for food production is very limited and energy is a costly commodity. What is equally important, however, is to gain a better understanding of how different plants react to different wavelengths and intensities of the light spectrum. Only a handful of plants and lighting configurations have been explored to this date, leaving colossal research headroom toward the lighting optimization for every horticultural plant species. The optimization of controlled cultivation environments can have a very significant impact on the yield, quality, and cost of horticultural products.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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