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Review Article

LEDs lead the way: maximizing vegetable potential through photonics

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Vegetables are considered protective foods as they are rich in vitamins, minerals and supply essential amino acids that our body cannot synthesize alone. Lighting can be used to alter the nutritional properties of vegetables. It also affects various stages of development in plants, which can be termed photomorphogenesis. Spectral quality, duration of exposure and amount of photon flux density significantly affect plants' physical, physiological and genetic parameters. Compared to other light sources, light-emitting diodes (LEDs) are highly preferred for growing plants in a controlled environment due to their high energy use efficiency and supply of narrow light spectra. This review focuses on various studies that have been carried out to understand the effect of LED light with different spectra on various properties of vegetable crops, from their development to post-harvest quality. In addition, we have discussed the effect of LEDs on gene expression profiles.

Keywords: *LED, far red, photon flux density, high intensity LED*

Introduction

The production of vegetables in India is about 204.61 million metric tonnes (2021 – 2022). Some of the important vegetable crops grown in India are beans, tomato, bottle gourd, brinjal, cabbage, carrot, cauliflower, chilli, cucumber, muskmelon, okra, onion, pea, pumpkin, radish and watermelon. They are considered low-volume, high-value commodities and rich in vitamins and minerals. They also act as curatives for different ailments. Pigments like lycopene and anthocyanin have antioxidant properties. Vegetables like pumpkin, zucchini, celery, asparagus, onion, garlic, leek, greens etc., are rich in essential amino acids (threonine, tryptophan, leucine, valine, and methionine). These nutritional properties of vegetables are affected by different spectra of light of light. Light has a characteristic effect on the growth and development of plants. Artificial light sources like fluorescent tubes, light-emitting diodes (LEDs), and high-intensity discharge lamps are commonly used to grow plants in greenhouses. However, fluorescent tubes lack the sustained photosynthetic photon flux capability for high crop productivity (Massa et al., 2006). LEDs have various advantages over other light sources. Preliminary works on LEDs started in the early 20th century with the discovery of the phenomenon of electroluminescence by H.J.Round. In the mid-1920s, Oleg V Losev elucidated the emission of different light spectra with variation in applied voltage to silicon carbide diode. In 1961, James R Biard and Gary Pittman developed infrared LEDs using gallium arsenide semiconductors. Then, the first red LED was discovered by Holonyak in 1962 using gallium arsenide phosphide semiconductor. Following this, orange, green and yellow LEDs were developed by George Craford in 1967. During the early period, studies were carried out using red LEDs, and there were fewer advancements in blue LED technology (Barta et al., 1992; Emmerich et al., 2004; Morrow, 2008). The breakthrough in lighting technology was made with the discovery of high-quality gallium nitride-based blue LED by Shuji Nakamura, Isamu Akasaki and Hiroshi Amano in 1979. With this discovery, white LEDs were developed, replacing incandescent bulbs. Later on, LED-based lighting systems were developed for use in physiology-based experiments. LEDs are used in various fields of horticulture, and the development of LEDs is one of the recent advances in horticulture. They provide a way to control light intensity and select a particular wavelength spectrum. Thus, they are used as a source of lighting in controlled environmental structures like greenhouses and tissue culture (Morrow, 2008; Ying et al., 2020). They are cheap, durable, have long lifetimes, high radiant efficiency, and relatively narrow emission spectra (Massa et al., 2006; Morrow, 2008). LEDs of different spectrums, like red, blue, green, white and their combinations (Figure 1) affect plant morphology and development. Various studies have been carried out to understand this effect. Recent studies have reported changes in antioxidant activity, gene expression pattern and metabolism (Ma et al., 2012) of different vegetable crops on exposure to LED wavelengths. Moreover, they also affect leaf thickness, area, stem elongation and pigment synthesis. Hence, these properties can be manipulated to increase the market value of vegetables.

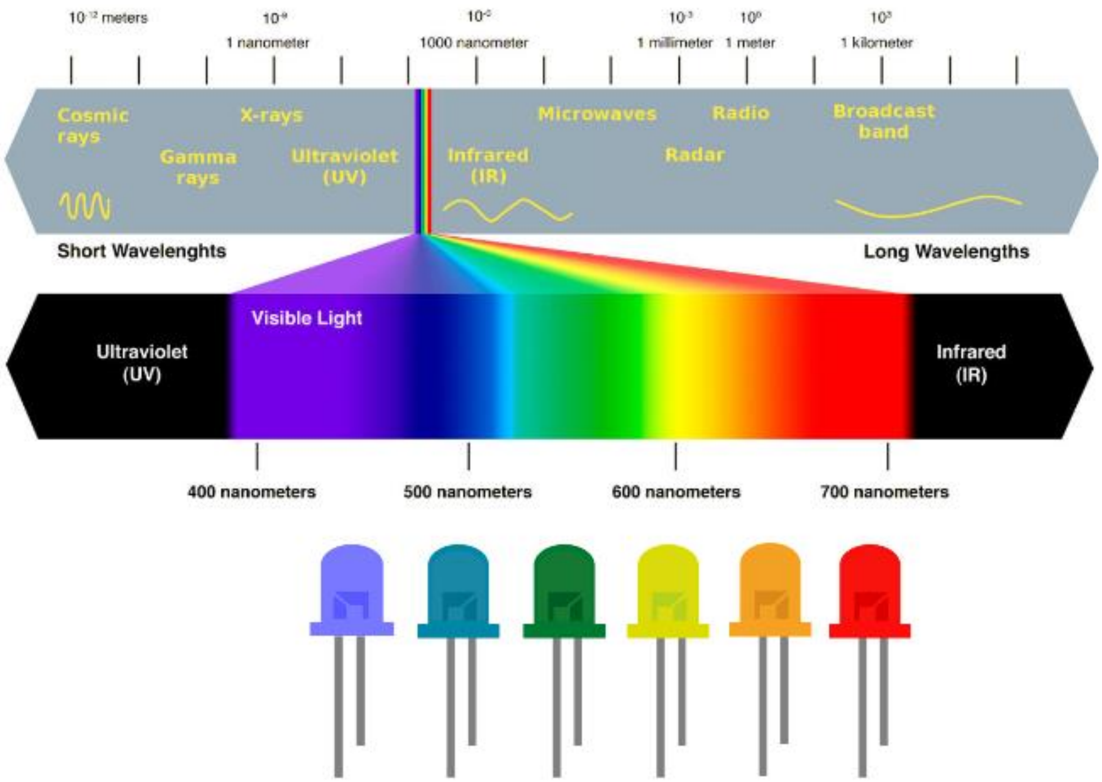

Figure 1. Light-emitting diodes with different spectrums of light.

1. Effect of LED light on growth parameters of different vegetables

LEDs have a characteristic effect on the photo morphogenetic development of a plant. They affect the germination of seeds; shoot length, root length, leaf area, thickness, leaf fresh weight, dry weight etc. Red light induces stem elongation, whereas blue light increases stem diameter. In this way, light with different spectral quality affects various growth parameters.

1.1 Shoot and root length

Light affects both the morphological and physiological development of a plant. When plants are grown under monochromatic light, abnormal differences in growth are produced. Combining different light spectra in different ratios significantly affects its development. Increased blue light percentage produced plants with reduced height, whereas less blue light percentage comparatively produced taller plants (Chiang et al., 2020). A contrast was recorded when artichoke seedlings were treated with red light. Taller seedlings with increased root length were obtained (Rabara et al., 2017). The addition of far red to red light affected the development of the plant. Appolloni et al. (2022) studied the effect of far red on hydroponically grown tomato plants under an integrated rooftop greenhouse. They were subjected to supplemental LED light of various spectrum like red (660nm), blue (465nm), Red and Blue (RB) combination of 3:1 ratio with total Photosynthetic Photon Flux Density (PPFD) of 170µmol/m2/s, RB treatment along with 40 µmol/m2/s of Far Red (FR) (730nm) for whole period and RB treatment along with an addition of 40 µmol/m2/s of FR for half an hour at end of the day. They also used buffer plants to screen the radiation from parallel rows. As a result of being treated with far-red, plants exhibited more excellent internodal elongation and apical growth. Phytochrome's diminished R: FR perception led to stem elongation as a symptom of shade avoidance syndrome (Appolloni et al., 2022).

Beyond these, research on white light demonstrated that it elicited an impact comparable to blue light. In contrast to other LED light treatments, pea seedlings radiated with white light were shorter, according to Wu et al. (2007). An analogous consequence was noted in artichoke seedlings, wherein exposure to blue and white light reduced shoot and root lengths. Despite being subterranean, the growth of the root is influenced by various light spectra. This could be attributed to the effective conveyance of diverse light spectrums across the tissues of plants. According to a study on photometric measurement of transmitted light, grey-white soil transmits light to a depth of 8 mm (Kasperbauer & Hunt, 1988). Further, the vascular tissues of stems and roots can conduct light axially. In addition to light quality, the duration of exposure and light intensity also alter plant growth. Increased shoot-to-root ratio was observed in rocket plants grown under the W-CL condition compared to the W-12 hrs condition (Proietti et al., 2021). Moreover, different growth characteristic was observed between cultivars of lettuce, namely Crunchy and Deangelia, under light intensity 120µmol/m^2/s, 240µmol/m^2/s and 300µmol/m^2/s. Crunchy cultivar exhibited increased height under a light intensity of 120µmol/m^2/s, whereas the maximum height for the Deangelia cultivar was recorded under a light intensity of 300µmol/m^2/s (Miao et al., 2023).

1.2 Leaf fresh weight and dry weight

Different spectrums of light-influences leaf fresh and dry weights. Moreover, photoperiod and Photosynthetic Photon Flux Density (PPFD) have also been shown to modify plants' fresh and dry weights. Some treatments showed significant differences, whereas some treatments did not show much significant difference. Hence, the change in fresh and dry weights varies based on the type of plant, the type of LED spectrum used and the duration of exposure. The leaf fresh and dried weights of sweet potatoes exhibited a notable increase when subjected to SL (natural sunlight) in combination with L-LED (150 µmol/m^2/s) and SL + H-LED (300 µmol/m^2/s). Elevated leaf thickness could account for this (He & Qin, 2020). *Eruca vesicaria* plants cultivated under the White continuous light (W-CL) condition exhibited greater leaf fresh and dried weights than those cultivated under the W-12 hours and Red and Blue continuous light (RB-CL) conditions. This phenomenon could be attributed to the increased accumulation of fresh and dry matter in W-CL conditions (Proietti et al., 2021).

1.3 Leaf thickness, leaf area and specific leaf area

Leaf thickness and leaf area are significant factors affecting plants' photosynthetic efficiency. Both are inversely related in most of the plants. Different light spectrums have distinct effects on different plants. The leaf area of sweet potato leaves grown hydroponically in a tropical greenhouse was measured using a leaf area meter. Leaves of sweet potato plants exposed to SL + H- LED (330 µmol/m^2/s) recorded more leaf area, whereas specific leaf area was recorded more under SL. This experiment showed that low specific leaf area is associated with greater leaf thickness (He & Qin, 2020). Lower specific leaf areas can help plants increase the efficiency of capturing light (Evans & Poorter, 2001; Liu et al., 2016). In cucumber seedlings, leaf thickness was determined by slicing a cross-section of the leaves. When subjected to red light, the foliage formed a thinner appearance. Red light treatment may cause a reduction in palisade thickness and the formation of spongy tissues in the leaves. An increase in leaf thickness was noted in the presence of blue light (Miao et al., 2019). The leaf area was larger in the red-light treatment compared to the red and blue (RB) and blue light-alone conditions. This indicates that the accumulation of particulate matter was increased under blue light conditions. Moreover, in RB treatment, blue light alleviated the effect of red light. Among artichoke seedlings that were grown under red, blue and white light, the seedlings under red light produced thicker leaves (Rabara et al., 2017). This finding was in contrast with the effect of red light on the leaf thickness of cucumber seedlings. In an integrated greenhouse, tomato plants were grown under different RB and Far Red (FR) combinations. Using a hand-held leaf area instrument, the leaf area of the first leaf above the third fruit truss was measured in each plant. According to this study, adding FR increased leaf area to some extent. The leaf area and dry matter ratio give a specific leaf area. Different light regimes did not significantly affect this (Appolloni et al., 2022).

2. Effect of LED light on photosynthesis and chlorophyll content

Photosynthesis is the process of carbon fixation. It is governed by photosynthetically active solar radiation of spectral range from 400 to 700nm. Chlorophyll pigments absorb this light in the chloroplast. 80 – 95 percent of absorbed radiations fall under red and blue light regions. These regions have contradictory effects on photosynthesis. Artichoke seedlings grown under red light conditions had higher total chlorophyll than natural sunlight (Rabara et al., 2017). The experiment on different LED spectra on cucumber seedlings showed that chlorophyll a and b were highly reduced under red light. Red and blue light alters the chloroplast structure. Both exhibited opposing consequences. When exposed to red light, chloroplasts and starch molecules exhibited a size reduction. The result indicated that the quantity of soluble carbohydrates decreased due to red light's decrease in the net photosynthesis rate.

Moreover, chloroplasts and starch granules were highly developed when exposed to blue light. According to this finding, dried matter accumulation increased and photosynthesis was positively impacted by blue light (Miao et al., 2019). Blue light stimulates cryptochrome and interacts with positive regulators of photomorphogenesis (Zhao et al., 2007). Under continuous lighting, the chlorophyll content of *Eruca vesicaria* showed a significant difference. Total chlorophyll under RB-CL was less than the W- CL treatment. The data shows that extended photoperiod combined with RB wave bands negatively affects chlorophyll pigment synthesis (Proietti et al., 2021). Apart from red and blue light, yellow light was found to alter photosynthesis and chlorophyll content in the leaves of purple cabbage. Under RBY treatment, electron transport per active center and density of the PS II reaction center were higher, enhancing the photosynthetic performance of the plant. The no. of light energy conversion center and PS II, reaction center stability, was more under red: blue: yellow (RBY) treatment (Yang et al., 2016).Similar to the study in artichoke seedlings (Rabara et al., 2017), the study in purple cabbage (Yang et al., 2016) also indicated that the amount of chlorophyll a, chlorophyll b and total chlorophyll were highest under red light conditions. Hence, the photosynthate accumulation was more significant under red than blue light. This finding contrasted photosynthate accumulation in cucumber seedlings under red and blue light treatment (Miao et al., 2019). Tomato plants were grown under an integrated rooftop greenhouse, and non-destructive estimation of chlorophyll was performed using the first leaf under the third fruit truss of each plant. However, in this study, no significant difference was found in chlorophyll content under different light treatments (Appolloni et al., 2022). In sweet potato leaves, chlorophyll a, b, and total chlorophyll were more under SL-H-LED treated plants. The data indicates that chlorophyll synthesis increases with increasing light intensity, increasing the ETR (electron transport rate). Increased ETR may be due to increased active centers in PS II. However, this condition varies within species (He & Qin, 2020).

3. Effect of LED light on the nutrient content of vegetables

Vegetables' nutritional value can also be changed by utilizing LEDs with various light spectra and varying the exposure time. Variations in the C: N ratio, antioxidant content, micro and macro element composition, and polyphenol levels result from this. It is possible to increase the market value of vegetables by modifying these values.

3.1 Antioxidants and other pigments

Pigments like anthocyanin, lycopene and carotenoids have antioxidant properties. They scavenge free radicals and protect us from various cardiovascular ailments. Hydroponically grown sweet potato plants accumulated more carotenoids when exposed to SL-H-LED than SL. The amount of carotenoid increased by 27 percent under SL-H-LED (He & Qin, 2020). Lycopene and beta-carotene content vary at different stages of tomato fruit development when exposed to light conditions. This condition is also affected by the season of development. In the summer, lycopene content was recorded as being under control in mature fruits and under RB treatment in immature fruits. In spring, more lycopene and beta carotene content were recorded under RB treatment in mature fruit (Appolloni et al., 2022). In cucumber seedlings, the negative effect of red light is alleviated by blue light. Red light decreased the effect of carotenoids, but this effect was alleviated by blue light (Miao et al., 2019). Similar to the study in cucumber seedlings, the study on purple cabbage also showed an increase in carotenoid content by 29 percent under blue light conditions compared to the control. From the above study, it may be concluded that blue light is beneficial to increase carotenoid content. When different monochromatic lights are combined and used, the effect of one light is compensated by another; when used individually, the negative effect of one light decreases when combined with another light. In purple cabbage, yellow light treatment decreased anthocyanin content, whereas RBY treatment increased anthocyanin content. A similar effect was also documented in the content of flavonoids. Blue light treatment also detrimentally affected flavonoid content (Yang et al., 2016).

3.2. Macro and microelements

Each light spectrum significantly affected the accumulation of different mineral elements in different plant parts. Tomato plants grown under an integrated rooftop greenhouse did not show a significant difference in the content of micro and macro elements in leaves. Still, a significant difference was observed in stems. Under control, copper and phosphorus accumulation was higher (Appolloni et al., 2022). A higher accumulation of elements in the leaves of tomato plants grown under the supplemental green LED light was observed (Samuolienė et al., 2017). In cucumber seedlings grown under red light conditions, accumulation of elements like P, K, Mn, and Zn was high, whereas under RB treatment, P content was high and Mg content was decreased. An increase in specific mineral elements also has a negative effect on plant activity. For example, Plesničar et al. (1994) observed that an increase in P reduced the efficiency of RuBP regeneration and decreased the carbon fixation process. Iron concurrently inhibited the photosynthetic electron transport chain, thereby diminishing carbon dioxide assimilation. Under red light, an excess of manganese may inhibit PS II. Another factor to take into account is the reduced photosynthetic rate observed in the presence of red light (Miao et al., 2019).

3.3 Carbon and nitrogen accumulation

Photosynthesis plays an essential role in plant carbon accumulation. Both carbon and nitrogen accumulation vary under different light treatments. Carbon concentration was higher under RB-CL treatment, which showed increased dry matter accumulation and high nitrogen concentration under W-12hrs treatment. Under RB-CL conditions, the concentration of nitrogen decreased. Nitrogen plays an essential role in the synthesis of amino acids. Due to decreased nitrogen concentration under RB-CL conditions, the protein content per unit leaf area also decreases (Proietti et al., 2021). In cucumber seedlings, blue light increases carbon, nitrogen and dry matter accumulation (Miao et al., 2019). It is possible to manipulate plants' carbon and nitrogen contents according to their type and LED spectrum. Conversely, this impacts the yield of vegetation.

4. Effect of LED light on gene expression

Single monochromatic light or combination of light has distinct effects on different plant characteristics. At the molecular level, this light spectrum alters gene expression in various plants. In the study on *Melissia officinalis,* they noted that genotype, light and drought stress had an interactive effect on the expression of various genes like 9-Cis-epoxycarotenoid dioxygenase *(NCED)*, ABA 8 hydroxylase *(ABA80x),* Rosmarinic acid synthase *(RAS)* and Respiratory burst oxidase homolog *(RBOH)*. Expression of genes varies between genotypes under different light treatments. Expression of the NCED gene was up-regulated in the Ilam genotype under RB treatment. In contrast, it was up-regulated under red light treatment in the Isafahan genotype of *Melissia officinalis*. Expression of ABA80x was more under white light in the Ilam genotype, which increased the synthesis of ABA and conferred tolerance to drought. In both the genotype the expression of RAS was more under RB treatment. This RA (Rosmarinic acid) can detoxify reactive oxygen species during drought stress. In this way, plants are protected from drought stress by manipulating the expression of genes under different light spectra (Ahmadi et al., 2019). Adding other monochromatic light, like green, purple etc., to RB treatment activates and inhibits different genes. In lettuce, expression of NiR is up-regulated under RBG treatment compared to under RB treatment. Nitrite Reductase (NiR) reduces nitrite to ammonium. Accumulation of nitrite is harmful to plants, whereas, under green light, more nitrite is accumulated, which makes the plant activate NiR, such that ammonium content increases in plants (Li et al., 2021).White LED treatment of Pakchoi increased gene expression of antioxidant enzymes like Peroxidase (POD), Catalase (CAT), and Ascorbate peroxidase (APX) during its seven-day storage. The expression of *BrHEMA1* was comparatively higher when exposed to LED treatment on the fifth day of storage. As a result, the synthesis of chlorophyll was enhanced. CAT and POD catalyze the decomposition of hydrogen peroxide in plants, while the detoxification of hydrogen peroxide in plants is facilitated by APX via the ascorbate glutathione cycle. In the interim, *Brchlase 1, Brchlase 2,* and *BrPPH* gene expression were reduced (Zhou et al., 2020).

5. Effect of LED light on the storage life of vegetables

There are various chemical treatments and heat treatments to increase the storage life of vegetables. Specific methods are costly and toxic to the consumer. A cheaper, safe and non-toxic method is needed to improve the storage life of vegetable products. LED treatment acts as an environment-friendly method to extend the shelf life of harvested produce. LEDs alter the ripening and senescence process in various vegetable products. LED irradiation with white, red and green light has helped to increase leafy lettuce's storage life (Kasim & Kasim, 2017). As a result of the white LED treatment, the respiration rate of pakchoi was considerably reduced, which impacted its shelf life. As a result of the decreased respiration rate and metabolism, the degree of leaf yellowing is diminished (Zhou et al., 2020). It exhibited a two to three-day delay in senescence and yellowing of pakchoi foliage. Similar findings were reported by Hasperué et al. (2016), who observed that LED irradiation caused a delay in the respiration rate and discoloration of Brussels sprouts. Broccoli treated under red LED PPFD 50 $\mu mol/m^2/s$ showed reduced chlorophyll degradation and delayed senescence (Jiang et al., 2019). Moreover, under red LED irradiation, membrane damage was reduced and membrane integrity of broccoli was maintained. Intermittent treatment cycles of low light intensity in lambs'lettuce under low temperatures of 6ºC decreased chlorophyll degradation and delayed senescence (Braidot et al., 2014).

6. Effect of LED light on post-harvest disease of vegetables

Light plays a vital role in enhancing the quality of the harvested produce. Post-harvest diseases cause 40 to 60 percent of post-harvest losses. The effect of light spectra varies based on the type of plants and pathogens. It has been found that red, blue, and green light can confer resistance in plants against fungal pathogens. Light can be used in integrated disease management. Red and far-red light has been shown to provide disease resistance by manipulating the expression of various genes through phytochromes (Griebel & Zeier, 2008). Red light treatment has also been found to increase the occurrence of diseases like *Alternaria tenuissima* and *Botrytis cinerea* in broad beans (Islam et al., 2008). Blue light can inhibit spore development. So, initially, red light can be used to stimulate spore germination and blue light can be used to kill the spores. White light was found to stimulate conidia formation. In cucumbers, under white light, powdery mildew occurrences were high (Schuerger & Brown, 1997). In contrast to this, under red light treatment (628.6nm), powdery mildew was significantly reduced in cucumber (Wang et al., 2010). Illumination with 405nm LED on tomatoes inoculated with *Botrytis cinerea* and *Rhizopus stolonifer* was more effective in reducing the infestation after 12 days of storage (Chua et al., 2021).

Conclusion

Vegetables are highly perishable commodities and are rich in nutrients. The productivity of vegetables can be increased under controlled conditions. The concept of indoor cultivation is popularized due to the decreased availability of land and changing climatic conditions. LEDs play an essential role in providing controlled light in protected cultivation. Various factors that affect the growth and nutritional properties of vegetables can be manipulated using different spectra of LED light. The LED light system is a novel technology that consumes less power, is highly durable and supplies narrow light spectra. The effect of LED varies based on the type of spectra, duration of exposure, type of plant, variety of crop, season of cultivation, stage of development etc. Further, they also alter the development of plants at the molecular level by regulating the expression of various genes. When different combinations of LED are used, the effect of one light is altered by the other. They also affect the storage life of vegetables and regulate the occurrence of post-harvest diseases. Only a limited number of studies have been carried out on different aspects of using LEDs. Still, more vegetable crops have to be explored to study the effect of different spectra and combinations of LED on their development, nutritional parameters, gene expression, and storage life. The nutrient content and quality of the produce can be enhanced, which helps not only to overcome problems related to malnutrition but also increases the market value of vegetables.

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Author contributions

RSH drafted the manuscript and completed the necessary revisions. AA, IA, and AR made corrections to the manuscript. SS was responsible for the framework, revision, and overall supervision of manuscript writing.

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Conflict of interest

Every author of this manuscript affirms that they do not have any conflicts of interest to disclose.

Ethics approval

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