PLANT SCIENCE TODAY
Vol 12(2): 1-13
https://doi.org/10.14719/pst.7318

eISSN 2348-1900

REVIEW ARTICLE

The role of LED lighting in enhancing post-harvest fruit and vegetable quality

Kavipriya S[1], Beaulah A[1*], Sundharaiya K[2], Anitha T[1] & Sivakumar K P[3]

[1]Department of Postharvest Technology, Horticultural College and Research Institute, Tamil Nadu Agricultural University, Periyakulam 625 604, India
[2]Department of Fruit Science, Horticultural College and Research Institute, Tamil Nadu Agricultural University, Periyakulam 625 604, India
[3]Department of Family Resource Management and Consumer Science, Community Science College and Research Institute, Tamil Nadu Agricultural University, Madurai 625 104, India

*Correspondence email - krrthanmayi@yahoo.co.in

Received: 20 January 2025; Accepted: 08 March 2025; Available online: Version 1.0: 17 May 2025; Version 2.0 : 27 May 2025

Cite this article: Kavipriya S, Beaulah A, Sundharaiya K, Anitha T, Sivakumar KP. The role of LED lighting in enhancing post-harvest fruit and vegetable quality. Plant Science Today. 2025; 12(2): 1-13. https://doi.org/10.14719/pst.7318

Abstract

Improper handling practices often aggravate post-harvest losses in horticultural produce. Due to ethylene production, climacteric fruits have a short shelf life, which triggers ripening and senescence. Traditionally, post-harvest preservation has relied on chemical methods, which can pose health risks. In contrast, Light-Emitting Diode (LED) treatment has emerged as an effective, residue-free alternative to conventional light sources for maintaining the quality of fruits and vegetables during storage. LED treatment has enhanced the accumulation of important phytochemicals such as vitamins, chlorophyll, total soluble solids and carotenoids in fruits and vegetables. It also leads to changes in anthocyanin, carotenoids, phenols and flavonoids. These beneficial effects are linked to the interaction of LED light with plant physiology, which can help regulate ripening, improve nutritional content and control microbial growth. Combining different LED wavelengths at varying intensities during post-harvest storage has been found to promote fresh produces' nutritional value, slow` ripening and reduce pathogenic microbial load. While research on using LEDs for post-harvest quality preservation is still in its early stages, initial findings are promising. This review examines the applications of LED treatment in preserving the post-harvest quality of fresh horticultural produce, highlighting its role in extending shelf life, maintaining nutritional value and reducing post-harvest losses.

Keywords: bioactive compounds; non-destructive; postharvest treatment; preservation; shelf-life

Introduction

Fresh fruits and vegetables are the sources of vital nutrients and fibre. Consumers have been paying more attention in recent years to the quality of vegetables, especially those that are nutritious. However, food loss is more likely due to their short shelf life and high perishability. Recently, several researchers have identified the reasons for post-harvest food losses and methods to mitigate them. According to data from the Food and Agriculture Organisation (FAO), the most wasted commodities are fruits and vegetables, especially in developing countries, primarily due to insufficient storage facilities in horticulture. Consequently, post-harvest losses occur, characterised by overripe, senescence, softening, firmness, weight loss and pest and disease attacks (1).

Globally, post-harvest losses of fruits and vegetables are significant, estimated to be between 28 % and 55 % of total production, amounting to approximately USD 750 billion annually. In some instances, these losses can reach up to 60 %, varying depending on the specific type of produce. These losses account for over 40 % due to various factors, which include mechanical damage and biological factors such as pests and diseases (2).

A recent study by NABARD Consultancy Services (NABCONS) revealed that post-harvest losses in 54 different crops in India lead to a financial loss of 1.5 trillion rupees annually (USD 18.5 billion). This loss represents roughly 2.35 % of the national GDP, calculated based on the current prices for the first quarter of 2022-23, exceeding the previous years' Ministry of Agriculture and Farmers Welfare (MoAFW) budget. Livestock products such as milk, meat, fish and eggs contribute the most to this economic loss (21.70 %), followed by fruits (19.34 %) and vegetables (17.97 %) (3).

Utilising Light Emitting Diodes (LEDs) for lighting emerges as one of the key new agricultural technologies to extend the shelf-life of horticultural crops. In recent years, visible light treatments have emerged as an innovative post-harvest method. (4). Vegetables are typically stored in the dark after harvest, which hastens and causes post-harvest senescence. Harvested plant parts, such as leaves and vegetables, respond to light even after harvest. Leaves continue light-dependent biological processes such as photosynthesis if there is enough light (5). LED lighting is superior to traditional post-harvest storage techniques due to its low radiant heat emissions, which minimise thermal damage and degradation, making it suitable for cold storage. LEDs offer control over the spectral composition of emitted light, enhancing the nutritive quality of foods, manipulating fruit ripening and reducing fungal infections. UV LEDs provide a non-thermal method of pathogen inactivation without chemical sanitisers or accelerating bacterial resistance. Furthermore, LEDs are cost-effective, with long life expectancies, robustness and compactness. They are a promising technology for reducing food waste by improving food quality and safety during post-harvest preservation. Unlike traditional lighting, LEDs offer greater control over UV or infrared (IR) radiation emissions and do not contain mercury, avoiding the risk of toxic heavy metal leakage (6, 7).

Post-harvest illumination with LEDs is a non-chemical technique to preserve vegetables, impacting their physical, nutritional and microbial qualities. Studies often favour continuous LED treatment, with different wavelengths improving nutritional content like chlorophyll, lycopene, vitamin C and phenolic compounds while stimulating antioxidant enzyme activity and maintaining membrane integrity. Red, blue and white LEDs are effective in various vegetable physiological processes and can inactivate foodborne pathogens (8). LED lighting enhances plant physiology, improving photosynthesis, chlorophyll and antioxidant activity, leading to better nutrition and longer shelf life. Cold storage and Modified Atmospheric Package (MAP) mainly slow deterioration without enhancing quality. Ozone treatment reduces microbial load but may cause damage to produce if not controlled. Unlike these methods, LED lighting offers targeted effects using specific wavelengths. This makes it a versatile and practical approach to vegetable preservation (8). The freshness of vegetables and fruits can be preserved through an innovative and environmentally friendly technique, such as exposure to visible light. This review focuses on exploring LEDs to extend the quality of fruits by slowing down senescence, enhancing ripening and improving their nutritional properties and secondary metabolites.

An Overview of Light Emitting Diode (LED)

In developing a more effective crystal detector for radio waves, British scientist Henry Josef Round of Marconi Company made the unintentional discovery that an artificial silicon carbon (SiC) crystal was emitting light when current passed through it. In the 2000s, LEDs were first used in plant cultivation (9). Furthermore, LEDs are favoured over conventional light sources because of their compact size, low heat emission, durability, extended lifespan and capability to select specific wavelengths for desired plant responses (6). Compared to traditional light sources, LEDs have a longer lifespan and are more efficient for energy use. The highest efficiency of Photosynthetic Active Radiation (PAR) is given by LEDs (80-100 %; refer to the electronic supplementary material). Significant progress has been made in creating specialised light techniques, particularly for horticultural crop production under controlled surroundings in recent years.

Working principle of LED

When an electric current flows through a certain kind of solid-state semiconductor diode, called an LED, the diode emits light. P-type and n-type semiconductors are two processed materials directly interacting to form an LED chips' p–n junction. Only the p-side (anode) to the n-side (cathode) is where current flows. An electron loses energy as a photon when it comes into contact with a hole, which lowers its energy level. The substances employed in producing an LED possess energies that correspond to near-ultraviolet, visible, or near-infrared light. The semiconductors' energy gap determines the colour (wavelength) of the emitted light (10). Due to their compact size, longevity and relatively cool emitting surfaces, LEDs are perfect for using lighting systems in plants (11). The term used to describe light produced by a solid-state process is electroluminescence. LED operates through a non-thermal process of electroluminescence, which occurs when an electric current passes through a semiconductor (12).

Mechanism of LED technology in plants

Plants react to their complex light environment using a range of photoreceptors sensitive to different wavelengths. Light signals are monitored by these receptors, which also control plant behaviour (13). Plants can sense various aspects of light, including its direction, duration, intensity and specific wavelengths. They accomplish this through four main types of photoreceptors. Phytochromes (phys) are chiefly responsible for detecting red (R) and far-red (FR) wavelengths (600-750 nm), while three other types of photoreceptors- cryptochromes (crys), phototropin (phots) and another receptor-sensitive to blue (B) and ultraviolet-A (UV-A) light play roles in perceiving the blue/UV-A region of the spectrum (320-500 nm) (14).

At least four photoreceptor families can distinguish between light wavelengths: UVR8 absorbs ultraviolet B (UVB) wavelengths, cryptochromes and phototropins recognise blue and ultraviolet A (UVA) wavelengths. In contrast, phytochromes essentially absorb red and far-red wavelengths (15).

LED lighting influences post-harvest vegetable quality by activating specific photoreceptors (phytochromes, cryptochromes and phototropins), triggering downstream signalling pathways. Phytochromes (absorbing red and far-red light) regulate chlorophyll metabolism, delaying senescence by upregulating chlorophyll synthesis genes and downregulating degradation genes (16, 17). Cryptochromes (sensitive to blue/UV-A light) affect antioxidant activity and metabolite accumulation by modulating gene expression in antioxidant pathways, thus reducing oxidative stress (17). Phototropins (also blue light receptors) may optimise light capture, potentially enhancing photosynthetic activity (18, 19). By understanding these photoreceptor-mediated responses, lighting strategies can be tailored to improve post-harvest preservation and enhance vegetable quality (6).

Among the metabolic changes that highlight stress are the xanthophyll cycle, non-photochemical quenching,

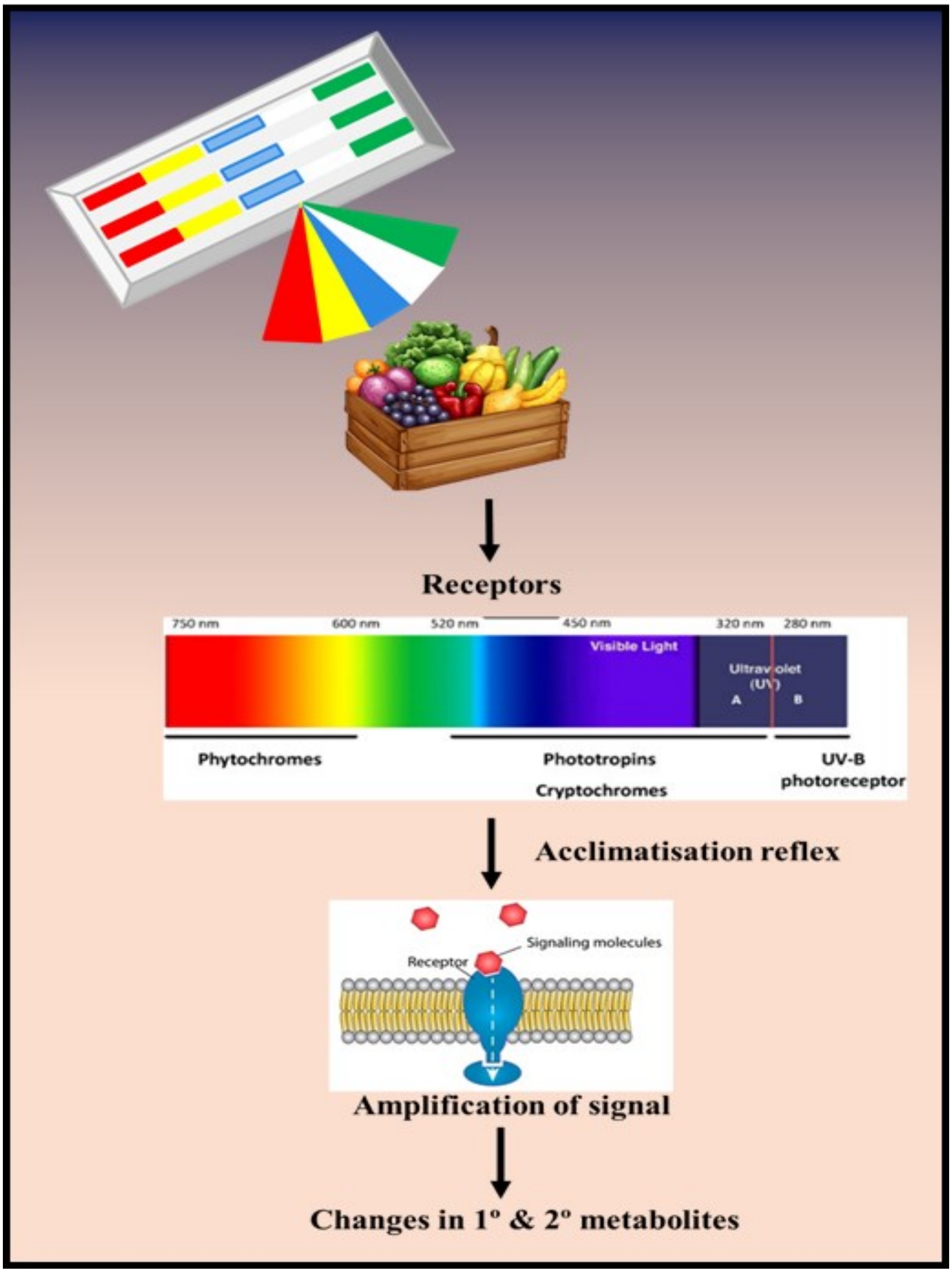

Fig. 1. Mechanism of LED technology in plants.

photorespiration, malate valve and antioxidant activity. These shifts create storage compounds, shielding, quenching of reactive oxygen species and repair mechanisms. Terpenoids and phenylpropanoids are examples of metabolites whose production occurs in or involves plastids (20). The depiction of the LED technology mechanism is shown in Fig. 1.

The role of LED in horticulture

LEDs possess the potential to extend the shelf life of horticulture crops. The monochromatic nature, extended lifespan, resistance to temperature degradation and high photon efficiency of LEDs are further benefits. LEDs have become more widely used post-harvest because of their many advantages over traditional light sources (Fig 2). LEDs enable non-thermal operations, thus reducing the potential for heat-related deterioration that could impact the quality of fresh produce. LED lighting offers unique opportunities to preserve and enhance food quality as a sustainable post-harvest treatment.

Research on *Arabidopsis* has also revealed that darkness accelerates the process by stimulating the genes involved in ethylene biosynthesis (21). It is widely recognised that darkness causes plants to express genes related to the breakdown of proteins, chloroplasts and chlorophyll, as well as an increase in reactive oxygen species (22). Nevertheless, post-harvest storage is frequently uncontrolled by light, with commodities kept in complete darkness for commercial purposes. This accelerates the development of senescence. Commonly utilised additional light for greenhouses is metal halide and fluorescent lighting. Research has shown that exposure to light improve the shelf-life and visual quality of microgreens such as spinach, radish and lettuce (23, 24). However, mixed spectrum light ratios at various ratios have been adopted recently and found to improve LED lighting efficiency.

Effect of LED Light on Physiochemical Characters of Fruits and Vegetables During Storage

LEDs release particular light wavelengths that can impact a range of physiological and chemical processes in plants, including ethylene generation, pigment synthesis, respiration rates and nutritional content. The most significant benefits of LED treatments are mentioned in Fig. 2.

Colour

Light significantly impacts the colour of fruits and vegetables, which controls their shelf-life. After harvest, fruits develop colour due to the concentration of several compounds like anthocyanin, chlorophyll and lycopene (25, 26);(27). On the second day of storage, the amount of chlorophyll in the broccoli florets treated with green (520 nm) and fluorescent lights (400-700 nm) was 39.8 % and 59.1 % higher, respectively, than in the control group. The LED green light treatment kept the Hue value higher and prevented the colour decline of broccoli (11). Table 1 below shows the effect of LED light on the colouration of fruits and vegetables

Total soluble solids (TSS)

Total soluble solids (TSS) in fruits and vegetables determine their maturity index. Increased TSS indicates faster ripening, while decreased TSS indicates slower ripening and longer shelf life. Research indicates that during 15 days of treatment, green (525 nm) LED light had lower TSS values than red (630 nm), blue (470 nm) and the control samples. LED treatment for 4 days at 5 °C shows a significant increase in sugar level, vitamin C and glycogen accumulation (28). The rise in TSS is due to the solubility of cell wall compounds such as polyuronides and hemicelluloses during fruit development.

Disputation, Blue light (470 nm) treatment significantly increased TSS content and ethylene production in post-harvest peaches. The highest ethylene production was postponed to 9 days. During post-harvest storage, pigment synthesis and internal ethylene could accelerate the ripening of blue LEDs (29).

Weight loss

A significant issue with post-harvest fruit and vegetable storage is weight loss. For vegetables like Brussels sprouts (*Brassica oleracea gemmifera*) and broccoli (*Brassica oleracea*), LED light treatment has been shown to mitigate weight loss. After 10 days of treatment at 22 °C, brussels sprouts with white and blue light at a rate of 20 W m^{-2} showed increased weight loss. The blue light interacts with stomatal cells, which influences stomatal opening. Consequently, higher respiration rates occur, impacting the metabolic pathway of fruits and vegetables (19). Light also affects transpiration, another process linked to stomatal opening (30). Similarly, both treated and untreated broccoli samples experienced higher weight loss during storage. Compared to the treated broccoli after 4 and 5 days, the control group exhibited a notably lesser increase in weight loss (11). Additionally, research demonstrates that treatment with red and blue LED at wavelengths of 456 nm and 655 nm, respectively, at 23 °C, initially led to an increase in lettuce weight, followed by a subsequent decline after 10 days of storage (31).

Effect of LED light on the synthesis of bioactive compounds

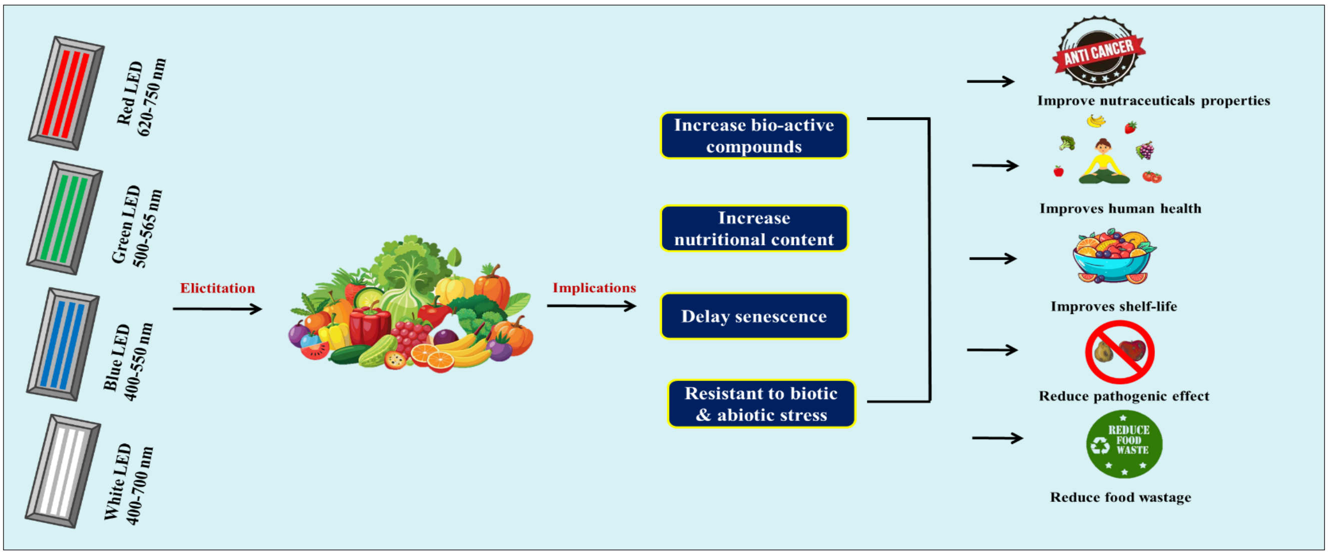

Fig. 2. Effects of LED lights in postharvest storage.

Table 1. Effect of LED light on the colour of fruits and vegetables

Fruits & Vegetables	Colour of LED Light	Wavelength range and intensity of light	Remarks	Reference
Broccoli *(Brassica oleraceae var. italica)*	White	463 nm and 50 Wm^{-2}	After 12 days of treatment at 22 °C, the light (L) value increases.	(26)
Broccoli *(Brassica oleraceae var. italica)*	Red	630 nm and 50 Wm^{-2}	Compared to the untreated control samples, increasing the L value was prevented by red light, resulting in a greater chlorophyll content of 59.1 %. of 5 days treatment at 20 °C	(11)
Lettuce *(Lactuca sativa)*	White, Green, Red, Blue	400-700 nm 516 nm 630 nm 450 nm and 10 Wm^{-2}	After 21 days at 5 °C, all LED treatments substantially reduced yellowing in the lettuce; chlorophyll content was raised by white LED light, but blue light inhibited the pathogenic effect and total soluble solids were raised.	(78)

of fruits and vegetables

The synthesis of antioxidants and bioactive substances can be induced by exposure to various LED wavelengths (Table 2), enhancing horticultural crops' nutritional value. Using blue LEDs (400-470 nm) has been associated with changes in several metabolic pathways and the buildup of anthocyanin, polyphenols, phenolic compounds and carotenoids (32). White light enhances nutritional quality by stimulating chlorophyll metabolism, increasing chlorophyll synthetase gene expression and downregulating chlorophyll-degrading genes (17, 33). Red light increases carotenoid content (16), whereas Green light helps preserve or improve chlorophyll content in vegetables like broccoli and cabbage (11, 33, 34). Light intensity plays a crucial role, with low-intensity LED light (4.3 Wm^{-2}) minimising abiotic stress, while high-intensity exposure can increase reactive oxygen species (ROS) production, potentially counteracting benefits (33, 34). UV-B light strongly induces stress responses, upregulating antioxidant enzyme activity and gene expression in the phenylpropanoid and flavonoid pathways, leading to flavonoid accumulation for UV protection (30).

The treatment with white-blue LEDs on brussel sprout leaves and after 10 days of storage at 22°C exhibited decreased respiration rate and increased chlorophyll content, antioxidants and flavonoids in leaves by 10 times compared to the control group (19). Research indicates that LED lights affected the overall nutritional composition of cabbage, resulting in increased levels of ascorbic acid, total phenolic content and total chlorophyll content and decreasing the presence of reactive oxygen species (35).

LED treatments for 9 days with the intensity of 29.2 Wm^{-2} at 24 °C, red light (650 nm) increases lycopene concentration in tomatoes by 41 % compared to dark conditions. Still, blue light (440 nm) slows the maturation

Table 2. Effects of LEDs on bioactive compounds of fruits and vegetables

Fruits & Vegetables	Colour of LED Light	Wavelength range and intensity of light	Remarks	Reference
Citrus *(Citrus sp.)*	Red Blue	660 nm 470 nm and 50 Wm^{-2}	Red and blue LED treatment increases antioxidant content, phenolics, total soluble sugar content, ascorbic acid content and enzymatic activity for 6 days at 20 °C.	(25); (27)
Tomatoes *(Lycopersicum esculentum)*	Blue Red	440 nm 450 nm and 85.72 Wm^{-2}	Red LED-treated tomatoes increased red colour, while blue light made them yellowish. Firmness decreased with storage time, while blue light maintained higher levels. Lycopene content increased with storage time, reaching levels similar to red and blue light. TSS content remained constant after 14 days at 25 °C.	(79)
Strawberry *(Fragaria ananassa)*	Blue	470 nm and 40 Wm^{-2}	The influence of blue LED treatment in strawberries for 12 days at 45 °C resulted in a decrease in the sugar content and an increase in the acidity level, phenolics, antioxidants, ascorbic acid and DPPH radical scavenging activity.	(80)
Blueberry *(Vaccinium sp.)*	Red Blue Green	630 nm 463 nm 520 nm and 20 Wm^{-2}	LED treatment for 3 days at 20 °C increased non-flavonoid content in blueberries, including rutin, ascorbic, caffeic, chlorogenic acid and phenolic compounds.	(28)
Strawberry *(Fragaria ananassa)*	Blue	470 nm and 40 Wm^{-2}	After four days of LED treatment, there was a 13 % increase in the phenolic compound content observed at 5°C.	(28)
Broccoli *(Brassica oleraceae var. italica)*	Blue	525 nm and 20Wm^{-2}	After seven days at 2 °C of LED therapy, there was a 1.8 % increase in total phenolic content compared to the untreated control sample.	(30, 61)
Garden Pea *(Pisum sativum)*	UV-A	375 nm and 33 Wm^{-2}	A more significant rise in quercetin-glycoside content was noted compared to the untreated control sample after 5 days of treatment.	(81)
Cabbage *(Brassica oleraceae var. capitata)*	Blue Green	436 nm ; 1.455 Wm^{-2} 524 nm; 1.515 Wm^{-2}	Both LED treatments increased total phenolics, chlorophyll and vitamin C content at 5 °C after 18 days of treatment. Blue LED treatment enhanced vitamin C levels, whereas green LED increased chlorophyll content.	(33, 82)
Satsuma orange *(Citrus sp.)*	Red	660 nm and 50 Wm^{-2}	All-trans-violaxanthin, total carotenoids, 9-cis-violaxanthin lutein, beta -cryptoxanthin and beta-carotenoid content increased significantly after red LED treatment for 4 days at 20 °C when compared to the non-treated (control) sample.	(80)
Mandarin orange *(Citrus reticulata)*	Red- Blue (60:40)	630 nm 460 nm and 32.6 Wm^{-2}	Citrus fruits treated with red-blue light at 20°C for 7 days showed increased phenolic compounds, carotenoids, ascorbic acid and antioxidant activity.	(83)
Muscat grapes *(Vitis vinifera.)*	Red Blue	660 nm 470 nm and 21.7 Wm^{-2}	Compared to grapes grown in the dark, grapes exposed to red, blue and red-blue light at 20 °C for 9 days had skin higher in carotenoids and less chlorophyll. Monoterpene levels, including linalool, limonene and geraniol, were more effectively maintained and increased by blue and red-blue light.	(84)
Indian pennywort (*Centella asiatica)*	White Blue	400-500 nm; 5.8 Wm^{-2} 450 nm; 6.4 Wm^{-2}	The application of white and blue LED light to *C. asiatica* leaves for 3 days at 25±2 °C increased the genes such as CaSQS, CaβAS and CaUGT involved in the triterpenoid pathway, which in turn accelerated the production of centellosides, specifically madecassoside and asiaticoside.	(85)
Tomato *(Lycopersicon esculentum)*	Red Blue	660 nm 470 nm and 10.8 Wm^{-2}	After 7 days of red LED treatment at 26°C, phytoene, lycopene and β-carotene levels were ten times greater than those in the control and blue LED-treated groups.	(86)
Cherry tomato *(Solanum lycopersicum var. cerasiforme)*	Blue	454 nm and 25.6 Wm^{-2}	The fruits were illuminated for 2 days at 21°C, which increases lycopene and β-carotene levels, especially in green-mature fruit, along with total soluble solids (% TSS), improving nutritional quality.	(87)

process (36). In comparison to red (630-670 nm), blue(455 nm) and white (400-500 nm) LED lights, red LED efficiently increased phenolic content and antioxidant activities. It maintained the ascorbic acid in cabbage (*Brassica oleraceae*), rocket *(Eruca vesicaria) and* radish *(Raphanus sativus)* after post-harvest storage for 6 h for 5 days at 5 °C and 85 % RH (37).

Flavonoid compounds

Changes in light quality have a significant impact on the synthesis of flavonoids. Blue and ultraviolet wavelengths are exceptionally efficient in enhancing flavonoid accumulation by upregulating the expression of genes involved in the flavonoid pathway (38). Essential photochemical processes in horticulture crops, such as synthesis and assimilation of secondary metabolites and photosynthesis, are regulated by light at different wavelengths (25, 27).

Red light can promote flavonoid accumulation by upregulating genes in the phenylpropanoid pathway, leading to increased enzyme activity, such as phenylalanine ammonia-lyase (PAL), chalcone synthase (CHS) and flavanone 3-hydroxylase (F3H), which enhance flavonoid biosynthesis. Blue light is particularly effective in activating the flavonoid pathway by increasing the expression of key regulatory and structural genes, significantly boosting flavonoid levels. UV light is a strong elicitor of flavonoid production, upregulating genes in the phenylpropanoid and flavonoid pathways, resulting in flavonoid accumulation that protects plant tissues from UV-induced damage (8).

Plants have abundant secondary metabolites called phenolic and flavonoid chemicals, which help them cope with biotic and abiotic stresses (39). Most flavonoids are well-known antioxidants, including ascorbate and α-tocopherol (40). Additionally, the biosynthesis of secondary metabolites is influenced by light intensity; higher light intensity causes herbs to produce more polyphenols (41). The phenylalanine ammonia-lyase (PAL) enzyme appears to function in the induction of secondary metabolites in crops when LEDs are present. Secondary metabolites are produced at higher rates when blue light and red LEDs upregulate PAL (42). There hasn't been sufficient research done on how LEDs affect secondary metabolites.

Phenolic content

LEDs cause abiotic stress by altering the phenolic metabolites of fruits and vegetables. Utilising photoreceptors sensitive to blue light and phytochrome responsive to red light plays a role in accumulating compounds such as flavonoids, quercetin glycosides and kaempferol (30). LEDs act as a light source, which causes high photosynthetically active radiation efficiency and generates responses. Thus, phenolic compounds are produced in fruit by a biosynthetic route partially activated by blue light. It controls and activates the enzymes linked to the synthesis and breakdown of phenylalanine ammonia-lyase (PAL), among others. After 2 days of green LED treatment with broccoli florets, total phenolic content increased to 40.4 % and 29.6 % more than those in control and fluorescent (400-700 nm) treated broccoli florets (11). Vitamin C and total phenol content were increased in baby leaf lettuce in green LED light (505 or 535 nm) than in blue LED light (455 or 470 nm) LED light (23). The okra treated with blue and white LED lights of 630 nm for 8 hours with an intensity of 17.28 Wm^{-2} had the highest total phenolic content. The elevated activities of chorismate mutase (CM), anthranilate synthase (AS) and AHP synthase (DS) were positively linked with the elevated phenolic content of the samples (43).

Anthocyanin

During the post-harvest phase, the anthocyanin concentration of fruits and vegetables can be altered by the varying intensity and LED wavelengths (Table 3). In strawberries, an investigation of the gene expression of the flavonoid pathway revealed that exposure to blue light raised the gene expression. When compared to dark control, it was discovered that all light sources cause anthocyanin accumulation. However, strawberries had the highest anthocyanin concentration when exposed to blue LED light (465 nm) followed by white light (405 nm) LED irradiation. Fruit exposed to green light (535 nm) had anthocyanin contents that were 1.5 and 3 times higher than those of white (405 nm) and red light (660 nm), respectively. White light produced a twofold anthocyanin accumulation compared to red light (15). The production of anthocyanin is triggered by blue light through the action of phototropins and cryptochromes (15, 44). Broccoli samples exposed to low-intensity white light showed a rise in carotenoid, while anthocyanin was preserved by 43 % of control leaves, 67 % by white light and 71 % by red light (45).

Carotenoids

One of the essential secondary plant compounds is carotenoid, which has various uses. When light intensity exceeds the

Table 3. Effects of LEDs on anthocyanin content of fruits and vegetables

Fruits & Vegetables	Colour of LED Light	Wavelength range and light intensity	Remarks	Reference
Blueberry *(Vaccinium sp.)*	Blue Red Green	470 nm 525 nm 630 nm and 60 Wm^{-2} at 2°C; 40Wm^{-2} at 21°C	Blueberry fruits treated for 10 days with red, blue and green LEDs at 2 °C and 21 °C had higher anthocyanin contents.	(91)
Sweet cherry *(Prunus avium)*	UV-B Blue	310 nm; 23 Wm^{-2} 450 nm ; 0.046 Wm^{-2}	Treatment with blue LEDs for 10 days had a considerably higher anthocyanin content at 1 ± 0.5 °C.	(92)
Grapes *(Vitis sp.)*	Blue	445 nm and 80 Wm^{-2}	Treating with blue LED light enhances anthocyanin levels and genes involved in anthocyanin biosynthesis over 9 days at 15-20 °C without impacting berry weight or acidity levels.	(93)
Immature strawberries (*Fragaria ananassa)*	Green	500-600 nm and 33 Wm^{-2}	Anthocyanin content was produced faster with green LED treatment for 5 days, which boosted the deep red hue at 4 °C.	(81)

photosynthetic capacity, light collection, structural elements stabilisation, excess energy dissipation and defence against free radicals are created (46). Cryptochromes, activated by blue light, inhibit the COP1-based ubiquitin ligase, thereby protecting the HY5 transcription factor from degradation, while phytochromes, activated by red light, suppress the PIF1 transcription factor. Both mechanisms regulate phytoene synthase (PSY), the key rate-limiting enzyme in the carotenoid biosynthesis pathway. Light intensity and quality also influence photosystem excitation through pH changes within the lumen and the balance of reduced and oxidised plastoquinones (47).

The transcript levels of the carotenoid biosynthesis genes phytoene synthase (PSY), β-cyclase (βLCY) and β-carotene hydroxylase (βOHASE1) increased under blue and white LEDs (max 453 nm) in most Brassica sprouts, with pak choi showing a 14 % rise in carotenoid levels compared to white LEDs (404-789 nm) and ~19 % compared to red and white LEDs (633 nm) under photosynthetically active radiation of 19.5 Wm^{-2} for 7 days (48). Plants use pigments called carotenoid and chlorophyll for photoprotection and light harvesting. Chl a and Chl b pigments have maximum absorption in the visible light spectrum at red (663 and 642 nm, respectively) and blue (430 and 453 nm, respectively). Conversely, the blue zone exhibits the most prominent absorption of beta-carotene (BC) and lutein (LUT) carotenoid pigments, with respective wavelengths of 454 and 448 nm (49).

The capsicum increased its total carotenoid content (more than 3.5 times the initial value) following a 24-hour red light (630 nm) irradiation. After being exposed to far-red light radiation for 72 hours, the amount of capsaicin alkaloid increased significantly (more than 8 times compared to the initial value). It has been proposed that a reduction in phytochrome activity caused by either low temperatures or far -red light (FRL) exposure (730 nm) at 25 °C with 15.2 Wm^{-2} intensity could lead to heightened expression of the caffeoyl-CoA 3-O-methyltransferase (CAM), phenylalanine ammonia lyase (PAL) genes (50). After 6 days of treatment in sweet orange at 20°C, blue light (470 nm; 43.4 Wm^{-2}) and red light (660 nm; 3.2 Wm^{-2}) significantly increased citric acid accumulation. Notably, dark shade and red light treatments most effectively promoted carotenoid accumulation. This included different carotenoid concentrations, including lutein, total carotenoid, neoxanthin, isolutein, all-trans-violaxanthin, zeaxanthin, phytofluene, cis-carotene and β-carotene (51).

Effect of LED Light in Ripening of Fruits and Vegetables During Storage

LEDs impact the rapid ripening of certain crop species through respiration and increased ethylene production (25, 27). LED light can induce ethylene synthesis in the yang cycle and cause ethylene production throughout this phase (29). This metabolic pathway involves receptors that alter the expression of genes associated with auxin or photosynthetic processes, limiting the ripening process (52). To seek the complete ripening phase of horticultural crops, LED light can cause light signal transduction and photo-oxidation processes by gene modification (53). Mechanistic diagrams of LED Light Interaction with Plant Metabolism Post-harvest are illustrated in Fig 1. Fruit exposed to blue light (470 nm) showed a considerable rise in ethylene synthesis because of increased activity of ethylene response factors, 1-aminocyclopropane-ethylene sensors, 1-carboxylic acid, lipoxygenase and ethylene receptors (29). Genes like PpACS3 and PpACO1 are stimulated to express when exposed to blue light, suggesting the molecular process behind LED-mediated fruit ripening. Table 4 illustrates how LED light affects the ripening process in different fruits and vegetables.

Effect of LED Light on Senescence of Fruits and Vegetables During Storage

Nutrient distribution throughout the tissue and changes to the biochemical and structural properties of the cell are the

Table 4. Effects of LEDs in ripening of fruits and vegetables

Fruits & Vegetables	Colour of LED Light	Wavelength range and light intensity	Remarks	Reference
Peach *(prunus persica)*	Blue	470 nm and 40 Wm^{-2}	Peaches with 15 days of treatment showed the highest ethylene production was delayed from 6 to 9 days, their TSS level increased and their acidity decreased at 10 °C.	(29)
Sweet Orange *(Citrus sinensis)*	Blue	450 nm and 60-630 Wm^{-2}	Citrus fruits ripened more quickly when exposed to high blue LED treatment at 20°C for 18 days because they increased ethylene synthesis.	(94)
Immature tomatoes *(Solanum lycopersicum)*	Blue Red	450 nm ; 22.3 Wm^{-2} 650 nm ; 18.62 Wm^{-2}	When tomatoes were exposed to blue LED light instead of red light, the development of the red hue slowed down. Blue light and red light treatments postponed the ripening and softening of green tomatoes for 21 days at 25 °C.	(79)
Strawberry *(Fragaria ananassa)*	Blue	470 nm and 40 Wm^{-2}	In comparison to the control, Blue LED treatment showed rapid red colour development, increased respiration and ethylene generation, total antioxidant activity and enzyme activity after 12 days at 5 °C	(25, 27)
Broccoli (*Brassica oleraceae*)	Blue Red	470 nm 660 nm and 50 Wm^{-2}	Red LED treatment delayed senescence by avoiding yellowing and ethylene formation for four days at 20 °C, while blue LED treatment did not affect retaining green colour.	(56)
Broccoli (*Brassica oleraceae*)	Green	520 nm and 2.6 Wm^{-2}	The shelf-life of broccoli was nearly three times longer than that of the control group by 2 days of treatment at 25 °C	(11)
Banana *(Musa sp.)*	Red	655 nm and 6.32 Wm^{-2}	Banana fruits treated with red LED light for 8 days at 20 °C speed up the production of carotenoid pigments and the breakdown of chlorophyll. It also controls ATP levels and energy metabolism, accelerating fruit ripening and senescence.	(95)

two main mechanisms behind the senescence process (54). Overproduction and buildup of ROS promote enzymatic alterations, membrane lipid, protein and macromolecule breakdown, ultimately destroying cells (55). LED lights (420–700nm) can regulate senescence by reducing pigment degradation and influencing respiration and transpiration processes (45). Both red and blue LEDs postpone fruit and vegetable senescence by controlling other hormones to facilitate the synthesis of ethylene and ascorbates (56).

The main concern with maintaining broccoli at room temperature is that it causes yellowing and senescence, lowering its quality (57). Broccolis' shelf life after harvest is considerably extended by green and fluorescent light treatment. The genetic expression of the gene, including zeaxanthin epoxidase, lycopene beta-cyclase (LCYb) and phytoene synthase (PSY), was also increased by blue and white LEDs (420-700 nm and 460 nm) in broccoli (58).

Several studies have demonstrated that the utilisation of LEDs delays turning yellow and ageing in certain fruits and vegetables, such as cabbage, spinach leaves, mandarin fruit, kiwifruit and Chinese kale (30, 59-61).

Ammonium buildup is significant during senescence and one key enzyme involved in its management is glutamine synthetase (GS). GS plays a crucial role in reassimilating ammonium and converting it into glutamine, which can be used in various metabolic processes. During senescence in darkness, the ammonium concentration increased 2.5 times; however, after 5 days of treatment with red or white light, there was no ammonium accumulation in basil leaves. Consequently, the senescence of basil leaves delayed by the red light pulses had the same effect as white light. In contrast to red light, far-red light did not lead to protein retention or a decrease in ammonium accumulation. Moreover, GS activity declined significantly under far-red light pulses than red light pulses (62).

Effect of LED Light on the Pathogenic Effect of Fruits and Vegetables During Storage

Several agricultural fields have used light-induced inactivation of microorganisms as a crop protection technique. LED illumination causes light to be absorbed by photosensitisers or photoreceptors, which then cause an effect by interacting with the biomolecules. The structure of microbial cells is disrupted by reactive oxygen species, leading to disintegration and preventing spoilage (63). Phospholipases D and A2 (PLD and PLA2) are integral components of lipid signalling in plants, essential for their immune response mechanisms (64). Overexpression of trans-phospholipases D and A2 (PLD and PLA2) in sPLA2 gene encoding, as well as the enzymatic substrates and products derived from them, play critical roles in the lipid signalling system and plant immune responses (64).

Near ultraviolet light stimulates sporulation in *B. cinerea*. Several fungal species, such as Penicillium, Aspergillus, Alteraria and others, have their toxic metabolism significantly inhibited by blue light (65, 66, 67). Endogenous porphyrins mediate the photoinactivation of *Candida albicans* by treatment with blue light (407-420 nm) and ALA (δ- aminolevulinic acid) of 0.03-600 mmol/l and precursors of endogenous porphyrins such as ALA methyl ester, enhances this process (68). Studies revealed that adding ALA to the light treatment would increase the 405 nm lights' inhibitory effect on *B. cinerea* spore germination (69). According to recent reports, the emission of LED light between 390 and 450 nm changes the process by which *Penicillium normycium* metabolises its toxins and impacts the proliferation of fungi (65). The antimicrobial effect of LED on fresh horticultural products has been mentioned (Table 5)

Effect of LED light on food preservation

Visible LEDs generate photodynamic processes, which give antibacterial characteristics. In response to specific wavelengths of light, endogenous porphyrins in bacteria promote the production of reactive oxygen species (ROS), ultimately resulting in bacterial cell death. (70). According to research conducted by (71), LEDs with 460 nm had a substantial effect on reducing bacterial activity and that effect increased with temperature. Liquid meals (Orange juice) were negatively impacted by the blue LEDs (460 nm), which also significantly changed the colour of food products. Blue LED lights primarily prevent bacterial activity by photodynamically inactivating microorganisms (PDI). When pineapples infected with *Salmonella enterica* were exposed to a 460 nm LED for 16°C illumination, the antibacterial effects were observed in *Eschercia coli O157:H7*, *Salmonella typhimurium*, *Eschercia. coli K12* and *Salmonella enteritidis*, with the highest decline of 1.72 log CFU/g (72). A 405-nm LED decreased Salmonella in freshly cut papaya by 1-1.2 log CFU/ cm^2 (73). Three Listeria monocytogenes and five Salmonella

Table 5. Effects of LEDs on mitigating pathogenic impact of fruits and vegetables

Fruits & Vegetables	Colour of LED Light	Wavelength range and light intensity	Remarks	Reference
Citrus (*Citrus sp.)*	Blue	461 nm and 152 Wm^{-2}	After 18 hours of blue LED treatment at 25 °C, *Penicillium italicum* and *Penicillium digitalatum* fungal infections were inhibited in citrus fruits.	(96)
Tangerines *(Citrus reticulate)*	Blue	456 nm and 8.6 Wm^{-2}	Compared to continuous dark conditions, fungal colonisation in "Fallglo" tangerines was significantly decreased by alternating cycles of 12 hours of 456nm blue light and 12 hours of darkness at 5 °C.	(97)
Tomato (*Solanum lycopersicum)*	Blue	405 nm and 630 Wm^{-2}	Prevent spoilage of harvested produce after 8 hours of treatment; lower the outbreak of *A. niger* spores.	(98)
Green grapes (Vitis vinifera)	UV	405 nm and 37.2 Wm^{-2}	The control samples are prone to fungal infection from *Guignardia bidwellii*. However, testing the LED-48h at 29 °C showed remarkable effectiveness in inhibiting fungal growth, as observed through colour development and morphology.	(98)

types on fresh-cut mangoes were reduced to less than 1.6 log CFU/cm^2 after 36-48 h of LED exposure (74). LED treatment with 405 nm on *Salmonella enteritidis* inoculation in cooked food (75). A combined exposure of 3.8 kJ/cm^2 at 4 °C decreased to 0.8-0.9 log CFU/cm^2. Fresh-cut broccoli florets stored at 5 °C for seven days treatment, LEDs improved the sulforaphane content concerning darkness, reporting over 40 % increases for blue (465 nm) and far red (670 nm) treatments with 10.4 Wm^{-2} light intensity (76).

Challenges and Future Prospects of LED Technology

Over the past ten years, LED technology has significantly expanded worldwide, rapidly displacing conventional lighting systems like incandescent bulbs, fluorescent lamps and high-intensity discharge (HID) lights in various sectors. Researchers have explored non-thermal methods as alternatives to chemical treatments. LED technology is becoming increasingly popular due to its superior characteristics to traditional lighting.

Implementing LED treatments in commercial supply chains is cost-effective due to their energy efficiency, significantly reducing power consumption compared to traditional lighting. This energy savings, combined with the longevity of LEDs, lowers overall maintenance and replacement costs, making them financially advantageous for extensive storage facilities. Additionally, LEDs can enhance the shelf life and nutritional quality of produce, thereby reducing waste and increasing market acceptability, leading to higher financial returns. The technologys' adaptability allows for scalability across various operational sizes, ensuring that it remains effective as demand for sustainable food production rises. While the initial investment may be higher, long-term savings and improved yields make LED systems a viable and attractive option for large-scale agricultural operations.

LED research is focused mainly on red and blue combinations, which are just beginning to achieve their future potential. Still, additional spectra besides the red and blue ones are valuable for research purposes. Green light has been claimed to reduce the harmful effects of continuous lighting. However, most of the research in this area is laboratory-based and must be implemented in actual food distribution processes. Retail stores can link this technology with additional factors, including packing or temperature, to boost effectiveness (77).

In developed nations, LED technology offers the potential to enhance safety and reduce post-harvest fruit and vegetable losses. However, risk assessment is a significant issue when utilising LEDs in post-harvest management. Research indicates that LEDs can influence the amount of phytochemicals in fruits and vegetables, which have positive and negative effects. Notably, the quality of light, particularly during artificial lighting, plays a vital part in regulating production, such as nitrate, a potentially toxic substance. The influence of light on consumer health and eye safety, especially during the installation of LED lighting on retail shelves, requires further investigation. Some studies have suggested a potential influence of blue light on retinal health and associated risks. Consequently, additional research is necessary to fully understand and address the implications of using LEDs to handle horticultural crop products after harvest.

Conclusion

LED lighting is emerging as a valuable tool in horticulture, enhancing post-harvest handling and storage of fruits and vegetables. LEDs regulate produce quality by emitting specific wavelengths, influencing bioactive compounds, nutritional value and secondary metabolites. Research highlights their ability to boost antioxidants, extend shelf life and reduce waste by modulating ripening rates. Additionally, LEDs inhibit microbial growth, improving food safety and minimising spoilage. LEDs offer sustainability benefits in commercial storage and distribution by reducing energy consumption and enhancing food preservation. Their integration into packaging, precooling and refrigerated transport can further optimise supply chains. Moreover, LEDs improve market display conditions, maintaining freshness and increasing consumer appeal. However, careful spectrum selection is essential, as some wavelengths may increase harmful substances like nitrate. There are also concerns about prolonged blue light exposures' impact on retinal health, particularly in retail environments. Future research should focus on identifying optimal wavelengths for microbial control and maximising energy savings. In conclusion, while the advantages of LEDs in post-harvest practices are significant, further research is needed to understand potential risks to both produce quality and consumer health. The continued adoption of LED technology promises a more efficient and sustainable horticultural industry.

Acknowledgements

The authors are very grateful to thank the Faculties, Department of Postharvest Technology, Horticultural College and Research Institute, Periyakulam, Tamil Nadu Agricultural University for their insightful discussions and feedback that helped strengthen this review article.

Authors' contributions

KS was responsible for writing the original draft, conceptualization, revising the draft including tables and figures and proofreading.

BA contributed to writing the original draft, conceptualization, revising the draft including tables and figures, and proofreading.

KS, BA, SK, AT and SP were involved in the revision of the manuscript, formatting, and supervision. All authors read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

References

1. Dou H, Niu G, Gu M, Masabni JG. Effects of light quality on growth and phytonutrient accumulation of herbs under controlled environments. Horticulturae. 2017;3(2):36. https://doi.org/10.3390/horticulturae3020036
2. Karoney EM, Molelekoa T, Bill M, Siyoum N, Korsten L. Global research network analysis of fresh produce post-harvest technology: Innovative trends for loss reduction. Post-harvest Biol Techno. 2024;208:112642. https://doi.org/10.1016/j.postharvbio.2023.112642
3. Sharma C, Pathak P, Yadav SP, Gautam S. Potential of emerging all-natural edible coatings to prevent post-harvest losses of vegetables and fruits for sustainable agriculture. Progress Organic Coat. 2024;193:108537. https://doi.org/10.1016/j.porgcoat.2024.108537
4. Charles F, Nilprapruck P, Roux D, Sallanon H. Visible light as a new tool to maintain fresh-cut lettuce post-harvest quality. Post-harvest Biol Techno. 2018;135:51-56. https://doi.org/10.1016/j.postharvbio.2017.08.024
5. Liebsch D, Keech O. Dark-induced leaf senescence: new insights into a complex light-dependent regulatory pathway. New Phytologist. 2016;212(3):563–70. https://doi.org/10.1111/nph.14217
6. Dsouza C, Yuk HG, Khoo GH, Zhou W. Application of light-emitting diodes in food production, post-harvest preservation and microbiological food safety. Compr Rev Food Sci Food Saf. 2015;14(6):719–40. https://doi.org/10.1111/1541-4337.12155
7. Koutchma T, Popović V, Green A. Overview of ultraviolet (UV) LED technology for applications in food production. In: Koutchma T, editor. Ultraviolet LED technology for food applications. New York: Academic Press; 2019. p. 1–23. https://doi.org/10.1016/B978-0-12-817794-5.00001-7
8. Perera WP, Navaratne S, Wickramasinghe I. Impact of spectral composition of light from light-emitting diodes (LEDS) on post-harvest quality of vegetables: A review. Post-harvest Biol Techno. 2022;191:111955. https://doi.org/10.1016/j.postharvbio.2022.111955
9. Piovene C, Orsini F, Bosi S, Sanoubar R, Bregola V, Dinelli G, et al. Optimal red: blue ratio in LED lighting for nutraceutical indoor horticulture. Sci Hortic. 2015 Sep 22;193:202–08. https://doi.org/10.1016/j.scienta.2015.07.015
10. Dutta GS, Jatothu B. Fundamentals and applications of light-emitting diodes (LED) in in vitro plant growth and morphogenesis. Plant Biotech Rep. 2013 ;7:211–20. https://doi.org/10.1007/s11816-013-0277-0
11. Jin P, Yao D, Xu F, Wang H, Zheng Y. Effect of light on quality and bioactive compounds in post-harvest broccoli florets. Food Chem. 2015;172:705–09. https://doi.org/10.1016/j.foodchem.2014.09.134
12. Lai ML, Tay TY, Sadhanala A, Dutton SE, Li G, Friend RH, Tan ZK. Tunable near-infrared luminescence in tin halide perovskite devices. J Phys Chem Lett 2016;7(14):2653–58. https://doi.org/10.1021/acs.jpclett.6b01047
13. Mawphlang OI, Kharshiing EV. Photoreceptor-mediated plant growth responses: implications for photoreceptor engineering toward improved performance in crops. Front Plant Sci. 2017;8:1181. https://doi.org/10.3389/fpls.2017.01181
14. Li J, Li G, Wang H, Wang Deng X. Phytochrome signaling mechanisms. *Arabidopsis* Book. 2011;9:e0148. https://doi.org/10.1199/tab.0148
15. Kadomura-Ishikawa Y, Miyawaki K, Noji S, Takahashi A. Phototropin 2 is involved in blue light-induced anthocyanin accumulation in *Fragaria* x *ananassa* fruits. J Plant Res. 2013;126:847–57. https://doi.org/10.1007/s10265-013-0582-2
16. Pennisi G, Orsini F, Castillejo N, Gómez PA, Crepaldi A, Fernández JA, et al. Spectral composition from LED lighting during storage affects nutraceuticals and safety attributes of fresh-cut red chard (*Beta vulgaris*) and rocket (*Diplotaxis tenuifolia*) leaves. Post-har Biol Technol. 2021;175:111500. https://doi.org/10.1016/j.postharvbio.2021.111500
17. Zhou F, Zuo J, Xu D, Gao L, Wang Q, Jiang A. Low intensity white light-emitting diodes (LED) application to delay senescence and maintain quality of post-harvest pakchoi (*Brassica campestris* L. ssp. *chinensis* (L.) Makino var. communis Tsen et Lee). Sci Hortic. 2020;262:109060. https://doi.org/10.1016/j.scienta.2019.109060
18. Wang XY, Xu XM, Cui J. The importance of blue light for leaf area expansion, development of photosynthetic apparatus and chloroplast ultrastructure of *Cucumis sativus* grown under weak light. Photosynthetica. 2015;53(2):213–22. https://doi.org/10.1007/s11099-015-0083-8
19. Hasperué JH, Rodoni LM, Guardianelli LM, Chaves AR, Martínez GA. Use of LED light for Brussels sprouts post-harvest conservation. Sci Hortic. 2016;213:281–86. https://doi.org/10.1016/j.scienta.2016.11.004
20. Darko E, Heydarizadeh P, Schoefs B, Sabzalian MR. Photosynthesis under artificial light: the shift in primary and secondary metabolism. Philosophical Transactions of the Royal Society B: Biol Sci. 2014 Apr 19;369(1640):20130243. https://doi.org/10.1098/rstb.2013.0243
21. Wang H, Ma LG, Li JM, Zhao HY, Deng XW. Direct interaction of *Arabidopsis* cryptochromes with COP1 in light control development. Sci. 2001;294(5540):154–58. https://doi.org/10.1126/science.1063630
22. Wada S, Ishida H, Izumi M, Yoshimoto K, Ohsumi Y, Mae T, Makino A. Autophagy plays a role in chloroplast degradation during senescence in individually darkened leaves. Plant Physiol. 2009;149(2):885–93. https://doi.org/10.1104/pp.108.130013
23. Samuolienė G, Sirtautas R, Brazaitytė A, Duchovskis P. LED lighting and seasonality effects antioxidant properties of baby leaf lettuce. Food Chem. 2012;134(3):1494–99. https://doi.org/10.1016/j.foodchem.2012.03.061
24. Toledo ME, Ueda Y, Imahori Y, Ayaki M. L-ascorbic acid metabolism in spinach (*Spinacia oleracea* L.) during post-harvest storage in light and dark. Post-harvest Biol Techno. 2003;28(1):47–57. https://doi.org/10.1016/S0925-5214(02)00121-7
25. Xu F, Cao S, Shi L, Chen W, Su X, Yang Z. Blue light irradiation affects anthocyanin content and enzyme activities involved in post-harvest strawberry fruit. J Agric Food Chem. 2014;62(20):4778–83. https://doi.org/10.1021/jf501120u
26. Büchert AM, Lobato GME, Villarreal NM, Civello PM, Martínez GA. Effect of visible light treatments on post-harvest senescence of broccoli (*Brassica oleracea* L.). J Sci Food Agri. 2011;91(2):355–61. https://doi.org/10.1002/jsfa.4193
27. Xu F, Shi L, Chen W, Cao S, Su X, Yang Z. Effect of blue light treatment on fruit quality, antioxidant enzymes and radical-scavenging activity in strawberry fruit. Sci Hortic. 2014;175:181–86. https://doi.org/10.1016/j.scienta.2014.06.012
28. Kim BS, Lee HO, Kim JY, Kwon KH, Cha HS, Kim JH. An effect of light-emitting diode (LED) irradiation treatment on the amplification of functional components of immature strawberry. Hortic, Environ Biotechnol. 2011;52:35–39. https://doi.org/10.1007/s13580-011-0189-2
29. Gong D, Cao S, Sheng T, Shao J, Song C, Wo F, et al. Effect of blue light on ethylene biosynthesis, signalling and fruit ripening in post-harvest peaches. Sci Hortic. 2015;197:657–64. https://doi.org/10.1016/j.scienta.2015.10.034
30. Zhan L, Hu J, Li Y, Pang L. Combination of light exposure and low temperature in preserving quality and extending shelf-life of fresh

-cut broccoli (*Brassica oleracea* L.). Post-harvest Biol Techno. 2012;72:76–81. https://doi.org/10.1016/j.postharvbio.2012.05.001

31. Shao M, Liu W, Zha L, Zhou C, Zhang Y, Li B. Differential effects of high light duration on growth, nutritional quality and oxidative stress of hydroponic lettuce under red and blue LED irradiation. Sci Hortic. 2020;268:109366. https://doi.org/10.1016/j.scienta.2020.109366
32. Taulavuori E, Taulavuori K, Holopainen JK, Julkunen-Tiitto R, Acar C, Dincer I. Targeted use of LEDs in improvement of production efficiency through phytochemical enrichment. J Sci Food Agriculture. 2017;97(15):5059–64. https://doi.org/10.1002/jsfa.8492
33. Lee YJ, Ha JY, Oh JE, Cho MS. The effect of LED irradiation on the quality of cabbage stored at a low temperature. Food Sci and Biotechnol. 2014;23:1087–93. https://doi.org/10.1007/s10068-014-0149-6
34. Loi M, Liuzzi VC, Fanelli F, De Leonardis S, Creanza TM, Ancona N, et al. Effect of different light-emitting diode (LED) irradiation on the shelf life and phytonutrient content of broccoli (*Brassica oleracea* L. var. *italica*). Food Chem 2019;283:206–14. https://doi.org/10.1016/j.foodchem.2019.01.021
35. Kang CH, Yoon EK, Muthusamy M, Kim JA, Jeong MJ, Lee SI. Blue LED light irradiation enhances L-ascorbic acid content while reducing reactive oxygen species accumulation in Chinese cabbage seedlings. Sci Hortic. 2020;261:108924. https://doi.org/10.1016/j.scienta.2019.108924
36. Nguyen QD, Huynh HN, Pham TT, Tran TN. Application of blue light led in the inactivation of pathogenic fungi on tomato fruit during natural storage. Proceed Inter Sym. 2023.5:99–103. https://doi.org/10.29007/x1sx
37. Ntsoane ML, Manhivi VE, Shoko T, Seke F, Sultanbawa Y, Sivakumar D. Brassica microgreens cabbage (*Brassica oleracea*), radish (*Raphanus sativus*) and rocket (*Eruca vesicaria*) (L.) Cav: Application of red-light emitting diodes lighting during post-harvest storage and *in vitro* digestion on bioactive compounds and antioxidant activity. Intern J Food Sci Technol. 2024;59(3):1432–42. https://doi.org/10.1111/ijfs.16890
38. Zoratti L, Karppinen K, Escobar LA, Häggman H, Jaakola L. Light-controlled flavonoid biosynthesis in fruits. Front Plant Sci. 2014;5:534. https://doi.org/10.3389/fpls.2014.00534
39. Ouzounis T, Fretté X, Rosenqvist E, Ottosen CO. Spectral effects of supplementary lighting on the secondary metabolites in roses, chrysanthemums and campanulas. J Plant Physiol. 2014;171(16):1491–99. https://doi.org/10.1016/j.jplph.2014.06.012
40. Hernández I, Alegre L, Van Breusegem F, Munné-Bosch S. How relevant are flavonoids as antioxidants in plants?. Trends in Plant Sci. 2009;14(3):125–32. https://doi.org/10.1016/j.tplants.2008.12.003
41. Manukyan A. Effects of PAR and UV-B radiation on herbal yield, bioactive compounds and their antioxidant capacity of some medicinal plants under controlled environmental conditions. Photochem and Photobiol. 2013;89(2):406–14. https://doi.org/10.1111/j.1751-1097.2012.01242.x
42. Hasan MM, Bashir T, Bae H. Use of ultrasonication technology for the increased production of plant secondary metabolites. Molecules. 2017;22(7):1046. https://doi.org/10.3390/molecules22071046
43. Wilawan N, Ngamwonglumlert L, Devahastin S, Chiewchan N. Changes in enzyme activities and amino acids and their relations with phenolic compounds contents in okra treated by LED lights of different colors. Food Bioprocess Technol. 2019;12:1945–54. https://doi.org/10.1007/s11947-019-02359-y
44. Zhang Y, Jiang L, Li Y, Chen Q, Ye Y, Zhang Y, et al. Effect of red and blue light on anthocyanin accumulation and differential gene expression in strawberry (*Fragaria× ananassa*). Molecules. 2018;23(4):820.https://doi.org/10.1016/j.resenv.2021.100023
45. Hasperué JH, Guardianelli L, Rodoni LM, Chaves AR, Martínez GA. Continuous white-blue LED light exposition delays post-harvest senescence of broccoli. Lebensmittel-Wissenschaft & Technologie. 2016;65:495–502. https://doi.org/10.1016/j.lwt.2015.08.041
46. Mortensen A, Skibsted LH, Truscott TG. The interaction of dietary carotenoids with radical species. Arch Biochem Biophysics. 2001;385(1):13–19. https://doi.org/10.1006/abbi.2000.2172
47. Kochetova GV, Avercheva OV, Bassarskaya EM, Zhigalova TV. Light quality as a driver of photosynthetic apparatus development. Biophysical Rev. 2022;14(4):779–803. https://doi.org/10.1007/s12551-022-00985-z
48. Frede K, Winkelmann S, Busse L, Baldermann S. The effect of LED light quality on the carotenoid metabolism and related gene expression in the genus *Brassica*. BMC Plant Biol. 2023;23(1):328. https://doi.org/10.1186/s12870-023-04326-4
49. Lefsrud MG, Kopsell DA, Sams CE. Irradiance from distinct wavelength light-emitting diodes affects secondary metabolites in kale. HortSci. 2008;43(7):2243–44. https://doi.org/10.21273/HORTSCI.43.7.2243
50. Pashkovskiy P, Sleptsov N, Vereschagin M, Kreslavski V, Rudometova N, Sorokoumov P, et al. Post-harvest red and far-red -light irradiation and low temperature induce the accumulation of carotenoids, capsaicinoids and ascorbic acid in *Capsicum annuum* L. green pepper fruit. Foods. 2023;12(8):1715. https://doi.org/10.3390/foods12081715
51. Hu L, Yang C, Zhang L, Feng J, Xi W. Effect of light-emitting diodes and ultraviolet irradiation on the soluble sugar, organic acid and carotenoid content of post-harvest sweet oranges (*Citrus sinensis* (L.) Osbeck). Molecules. 2019;24(19):3440. https://doi.org/10.3390/molecules24193440
52. Tadiello A, Longhi S, Moretto M, Ferrarini A, Tononi P, Farneti B, et al. Interference with ethylene perception at the receptor level sheds light on auxin and transcriptional circuits associated with the climacteric ripening of apple fruit (Malus x domestica Borkh.). The Plant J. 2016;88(6):963–75. https://doi.org/10.1111/tpj.13306
53. Adams-Phillips L, Barry C, Giovannoni J. Signal transduction systems regulating fruit ripening. Trends Plant Sci. 2004;9(7):331-38. https://doi.org/https://doi.org/10.1016/j.tplants.2004.05.004
54. Gan S, editor. Senescence processes in plants. Blackwell Pub.; 2007.
55. Drobot LB, Samoylenko AA, Vorotnikov AV, Tyurin-Kuzmin PA, Bazalii AV, Kietzmann T, et al. Reactive oxygen species in signal transduction. The Ukrainian Biochem J. 2013;86:209–17. https://doi.org/10.15407/ubj85.06.209
56. Ma G, Zhang L, Setiawan CK, Yamawaki K, Asai T, Nishikawa F, et al. Effect of red and blue LED light irradiation on ascorbate content and expression of genes related to ascorbate metabolism in post-harvest broccoli. Post-harvest Biol Techno. 2014;94:97–103. https://doi.org/10.1016/j.postharvbio.2014.03.010
57. Jia CG, Xu CJ, Wei J, Yuan J, Yuan GF, Wang BL, et al. Effect of modified atmosphere packaging on visual quality and glucosinolates of broccoli florets. Food Chem. 2009;114(1):28–37. https://doi.org/10.1016/j.foodchem.2008.09.009
58. Kopsell DA, Sams CE. Increases in shoot tissue pigments, glucosinolates and mineral elements in sprouting broccoli after exposure to short-duration blue light from light emitting diodes. J American Soc Hortic Sci. 2013;138(1):31–37. https://doi.org/10.21273/JASHS.138.1.31
59. Lester GE, Makus DJ, Hodges DM. Relationship between fresh-packaged spinach leaves exposed to continuous light or dark and bioactive contents: effects of cultivar, leaf size and storage duration. J Agri and Food Chem. 2010;58(5):2980–87. https://doi.org/10.1021/jf903596v

60. Liu JD, Goodspeed D, Sheng Z, Li B, Yang Y, Kliebenstein DJ, et al. Keeping the rhythm: light/dark cycles during post-harvest storage preserve the tissue integrity and nutritional content of leafy plants. BMC Plant Biol. 201515:1–9. https://doi.org/10.1186/s12870-015-0474-9

61. Zhan L, Li Y, Hu J, Pang L, Fan H. Browning inhibition and quality preservation of fresh-cut romaine lettuce exposed to high-intensity light. Innov Food Sci Emerging Technol. 2012;14:70–76. https://doi.org/10.1016/j.ifset.2012.02.004

62. Costa L, Montano YM, Carrión C, Rolny N, Guiamet JJ. Application of low-intensity light pulses to delay post-harvest senescence of *Ocimum basilicum* leaves. Post-harvest Biol Techno. 2013;86:181–91. https://doi.org/10.1016/j.postharvbio.2013.06.017

63. Luksienė Z, Zukauskas A. Prospects of photosensitisation in control of pathogenic and harmful microorganisms. J App Micro. 2009;107(5):1415–24. https://doi.org/10.1111/j.1365-2672.2009.04341.x

64. Munnik T, Irvine RF, Musgrave A. Phospholipid signalling in plants. Biochimica et Biophysica Acta (BBA)-Lipids and Lipid Metabolism. 1998;1389(3):222–72. https://doi.org/10.1016/S0005-2760(97)00158-6

65. Schmidt-Heydt M, Bode H, Raupp F, Geisen R. Influence of light on ochratoxin biosynthesis by Penicillium. Mycotoxin Res. 2010;26:1–8. https://doi.org/10.1007/s12550-009-0034-y

66. Purschwitz J, Müller S, Kastner C, Schöser M, Haas H, Espeso EA, et al. Functional and physical interaction of blue- and red-light sensors in *Aspergillus nidulans*. Current Biol. 2008;18(4):255–59. https://doi.org/10.1016/j.cub.2008.01.061

67. Häggblom P, Unestam T. Blue light inhibits mycotoxin production and increases total lipids and pigmentation in *Alternaria alternata*. App Environ Microbiol. 1979;38(6):1074–77. https://doi.org/10.1128/aem.38.6.1074-1077.1979

68. Oriel S, Nitzan Y. Photoinactivation of *Candida albicans* by its own endogenous porphyrins. Current Microbiol. 2010;60:117–23. https://doi.org/10.1007/s00284-009-9514-8

69. Imada K, Tanaka S, Ibaraki Y, Yoshimura K, Ito S. Antifungal effect of 405-nm light on *Botrytis cinerea*. Lett Applied Microbiol. 2014;59(6):670–76. https://doi.org/10.1111/lam.12330

70. Luksiene Z. Photodynamic therapy: mechanism of action and ways to improve the efficiency of treatment. Medicina (Kaunas, Lithuania). 2003;39(12):1137–50.

71. Ghate V, Kumar A, Zhou W, Yuk HG. Irradiance and temperature influence the bactericidal effect of 460-nanometer light-emitting diodes on Salmonella in orange juice. J Food Protect. 2016;79(4):553–60. https://doi.org/10.4315/0362-028X.JFP-15-394

72. Ghate V, Kumar A, Kim MJ, Bang WS, Zhou W, Yuk HG. Effect of 460 nm light-emitting diode illumination on survival of *Salmonella* spp. on fresh-cut pineapples at different irradiances and temperatures. J Food Engineer. 2017;196:130–38. https://doi.org/10.1016/j.jfoodeng.2016.10.013

73. Kim MJ, Mikš-Krajnik M, Kumar A, Ghate V, Yuk HG. Antibacterial effect and mechanism of high-intensity 405±5 nm light emitting diode on *Bacillus cereus*, *Listeria monocytogenes* and *Staphylococcus aureus* under refrigerated conditions. J Photochem Photobiol B: Biol. 2015;153:33–39. https://doi.org/10.1016/j.jphotobiol.2015.08.032

74. Kim MJ, Tang CH, Bang WS, Yuk HG. Antibacterial effect of 405 ± 5 nm light emitting diode illumination against *Escherichia coli* O157:H7, *Listeria monocytogenes* and *Salmonella* on the surface of fresh-cut mango and its influence on fruit quality. Int J Food Microbiol. 2017;244:82–89. https://doi.org/10.1016/j.ijfoodmicro.2016.12.023

75. Kim MJ, Ng BX, Zwe YH, Yuk HG. Photodynamic inactivation of *Salmonella enterica* Enteritidis by 405 ± 5-nm light-emitting diode and its application to control salmonellosis on cooked chicken. Food Control. 2017;82:305–15. https://doi.org/10.1016/j.foodcont.2017.06.040

76. Castillejo N, Martínez-Zamora L, Artés–Hernández F. A photoperiod including visible spectrum LEDs increased sulforaphane in fresh-cut broccoli. Post-harvest Biol Techno. 2023;200:112337. https://doi.org/10.1016/j.postharvbio.2023.112337

77. Dueck T, Ieperen WV, Taulavuori K. Light perception, signalling and plant responses to spectral quality and photoperiod in natural and horticultural environments. Environ Exp Bot. 2016;121:1–150. https://doi.org/10.1016/j.envexpbot.2015.06.012

78. Kasim MU, Kasim R. While continuous white LED lighting increases chlorophyll content (SPAD), green LED light reduces the infection rate of lettuce during storage and shelf-life conditions. J Food Processing Preserv. 2017;41(6):e13266. https://doi.org/10.1111/jfpp.13266

79. Dhakal R, Baek KH. Metabolic alternation in the accumulation of free amino acids and γ-aminobutyric acid in post-harvest mature green tomatoes following irradiation with blue light. Hortic Environ Biotechno. 2014;55:36–41. https://doi.org/10.1007/s13580-014-0125-3

80. Ma G, Zhang L, Kato M, Yamawaki K, Kiriiwa Y, Yahata M, et al. Effect of the combination of ethylene and red LED light irradiation on carotenoid accumulation and carotenogenic gene expression in the flavedo of citrus fruit. Post-harvest Biol Techno. 2015;99:99–104. https://doi.org/10.1016/j.postharvbio.2014.08.002

81. Kanazawa K, Hashimoto T, Yoshida S, Sungwon P, Fukuda S. Short photoirradiation induces flavonoid synthesis and increases its production in postharvest vegetables. J Agri Food Chem. 2012 May 2;60(17):4359–68. https://doi.org/10.1021/jf300107s

82. Lee SW, Seo JM, Lee MK, Chun JH, Antonisamy P, Arasu MV, et al. Influence of different LED lamps on the production of phenolic compounds in common and Tartary buckwheat sprouts. Industl Crops Prod. 2014;54:320–26. https://doi.org/10.1016/j.indcrop.2014.01.024

83. Costanzo G, Vitale E, Iesce MR, Spinelli M, Fontanarosa C, Paradiso R, et al. Modulation of antioxidant compounds in fruits of *Citrus reticulata* Blanco using post-harvest LED irradiation. Biol. 2023;12(7):1029. https://doi.org/10.3390/biology12071029

84. Li W, Zhang J, Sun J, Chen K, Guan X, Zhang K, et al. Light irradiation with different wavelengths modifies the quality traits and monoterpenes biosynthesis of post-harvest grape berries during the shelf life. Lebensmittel-Wissenschaft & Technologie. 2023;185:115164. https://doi.org/10.1016/j.lwt.2023.115164

85. Kamol P, Nukool W, Pumjaroen S, Inthima P, Kongbangkerd A, Suphrom N, et al. Harnessing post-harvest light emitting diode (LED) technology of *Centella asiatica* (L.) Urb. to improve centelloside content by upregulating gene expressions in the triterpenoid pathway. Heliyon. 2024;10(1):e23639:02–06. https://doi.org/10.1016/j.heliyon.2023.e23639

86. Xu Y, You C, Xu C, Zhang C, Hu X, Li X, et al. Red and blue light promote tomato fruit coloration through modulation of hormone homeostasis and pigment accumulation. Post-harvest Biol Techno. 2024;207:112588. https://doi.org/10.1016/j.postharvbio.2023.112588

87. Ngcobo BL, Bertling I, Clulow AD. Post-harvest alterations in quality and health-related parameters of cherry tomatoes at different maturity stages following irradiation with red and blue LED lights. J Hortic Sci Biotechnol. 2021;96(3):383–91. https://doi.org/10.1080/14620316.2020.1847696

88. Jin S, Ding Z, Xie J. Study of post-harvest quality and antioxidant capacity of freshly cut amaranth after blue LED light treatment. Plants. 2021;10(8):1614.https://doi.org/10.3390/plants10081614.

89. Song Y, Qiu K, Gao J, Kuai B. Molecular and physiological analyses of the effects of red and blue LED light irradiation on post-harvest senescence of pak choi. Post-harvest Biol Techno. 2020;164:111155. https://doi.org/10.1016/j.postharvbio.2020.111155

90. Castillejo N, Martínez-Zamora L, Gómez PA, Pennisi G, Crepaldi A, Fernández JA, et al. Postharvest LED lighting: effect of red, blue

and far red on quality of minimally processed broccoli sprouts. J Sci Food Agric. 2021;101(1):44–53. https://doi.org/10.1002/jsfa.10820

91. Shi L, Cao S, Chen W, Yang Z. Blue light induced anthocyanin accumulation and expression of associated genes in Chinese bayberry fruit. Sci Hortic. 2014;179:98–102. https://doi.org/10.1016/j.scienta.2014.09.022
92. Kokalj D, Zlatić E, Cigić B, Vidrih R. Post-harvest light-emitting diode irradiation of sweet cherries (*Prunus avium* L.) promotes accumulation of anthocyanins. Post-harvest Biol Techno. 2019;148:192–99. https://doi.org/10.1016/j.postharvbio.2018.11.011
93. Azuma A, Yakushiji H, Sato A. Post-harvest light irradiation and appropriate temperature treatment increase anthocyanin accumulation in grape berry skin. Post-harvest Biol Techno. 2019;147:89–99. https://doi.org/10.1016/j.postharvbio.2018.09.008
94. Ballester AR, Lafuente MT. LED Blue Light-induced changes in phenolics and ethylene in citrus fruit: Implication in elicited resistance against *Penicillium digitatum* infection. Food Chem. 2017;218:575–83. https://doi.org/10.1016/j.foodchem.2016.09.089
95. Zhou X, Cheng J, Sun J, Guo S, Guo X, Chen Q, et al. Effect of red visible lighting on post-harvest ripening of bananas via the regulation of energy metabolism. Hortic. 2023;9(7):840. https://doi.org/10.3390/horticulturae9070840
96. Lafuente MT, Alférez F. Effect of LED Blue Light on *Penicillium digitatum* and *Penicillium italicum* strains. Photochem Photobio. 2015;91(6):1412–21. https://doi.org/10.1111/php.12519
97. Murdoch LE, McKenzie K, Maclean M, Macgregor SJ anderson JG. Lethal effects of high-intensity violet 405-nm light on *Saccharomyces cerevisiae*, *Candida albicans* and on dormant and germinating spores of *Aspergillus niger*. Fungal Biol. 2013;117(7-8):519–27. https://doi.org/10.1016/j.funbio.2013.05.004
98. Pham TT, Nguyen TN, Le NT, Dang BT, Nguyen BQ. Post-harvest preservation of green grapes utilising 405 nm light emitting diode. Case Stud Chem Environl Engineer. 2023;8:100463. https://doi.org/10.1016/j.cscee.2023.100463

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.