Chapter

An Overview of the Recent Developments in the Postharvest Application of Light-emitting Diodes (LEDs) in Horticulture

Bonga Lewis Ngcobo and Isa Bertling

Abstract

The majority of losses in horticultural produce occur during postharvest storage, particularly due to poor handling. Most fruit, especially climacteric fruit, have a short postharvest life due to an increase in ethylene synthesis which signals ripening and, subsequently, senescence. Traditional practices for preserving the postharvest quality of horticultural crops are chemical-based, a practice which has lately received enormous criticism. Recently, the use of postharvest illumination with LEDs as a nonchemical and environmentally friendly technique to preserve fruit and vegetables has been reported by various authors. Unique properties of LEDs such as low radiant heat, monochromatic nature and low cost have made this lighting gain popularity in the food industry. This paper, therefore, reviews the recent development in the postharvest applications of LEDs in horticultural crops, while focusing particularly on physical characteristics, nutritional value, and overall quality alterations of fruit and vegetables. According to the recently published research, red and blue LED lights are most valuable in terms of usage, while other wavelengths such as purple and yellow are slowly gaining attention. Furthermore, LEDs have been shown to affect fruit ripening and senescence, enhance bioactive compounds and antioxidants in produce, and prevent disease occurrence; however, there are some limitations associated with the use of this novel technology.

Keywords: bioactive compounds, irradiation, LED technology, nutrition, postharvest preservation, senescence, shelf life

1. Introduction

The worldwide common challenge faced by farmers, especially in developing countries, is ensuring food security for a fast-growing world population. Recent predictions suggest that the demand for food will increase significantly as the predicted world population reaches about 9.7 billion people by 2050 [1]. On the other hand, about half (50%) of horticultural produce, mainly fruit and vegetables, is lost between harvest and consumption (postharvest) [2]. This, therefore, poses a threat and brings a serious concern to farmers to establish innovative methods and practices to increase the global food supply to provide sustainable living standards for humans by reducing the percentage of food lost in the value chain. Moreover, the consumption of fresh fruit and vegetables improves human health and well-being, because these commodities are rich sources of various vitamins, minerals, and antioxidant compounds that can prevent the occurrence of chronic diseases [3, 4]. As such, proper handling of horticultural crops is required, pre- and post-harvest, to improve product quality and yield, thereby ensuring food and nutrient security for all humans.

The most reliable techniques that are currently used to preserve fruit and vegetables are cold storage and chemical additives. These chemical additives have come lately under criticism [5, 6] as consumers are aware of the possible negative implications these compounds can have on their health; as a result, there are limitations on the use of chemical additives for the preservation of horticultural produce. Industries in the agricultural sector have, therefore, shifted to nonchemical-based approaches such as light-emitting diode (LED) technology [7, 8]. This technology was adopted after the use of lights, such as fluorescent, high-pressure sodium, and incandescent lights, came under criticism due to their large emission of radiant heat and energy inefficiency [9], whereas LEDs could provide several advantages, including durability, low emission of radiant heat, adjustable size, and cool emitting surface, resulting in an environmentally friendly technology that is also economically favorable [10]. Initially, the LEDs were only used in growth chambers and greenhouses, whereas, after some time, LED technology improved, as there was an incorporation of the new semiconductor materials and improvement of the crystal growth techniques as well

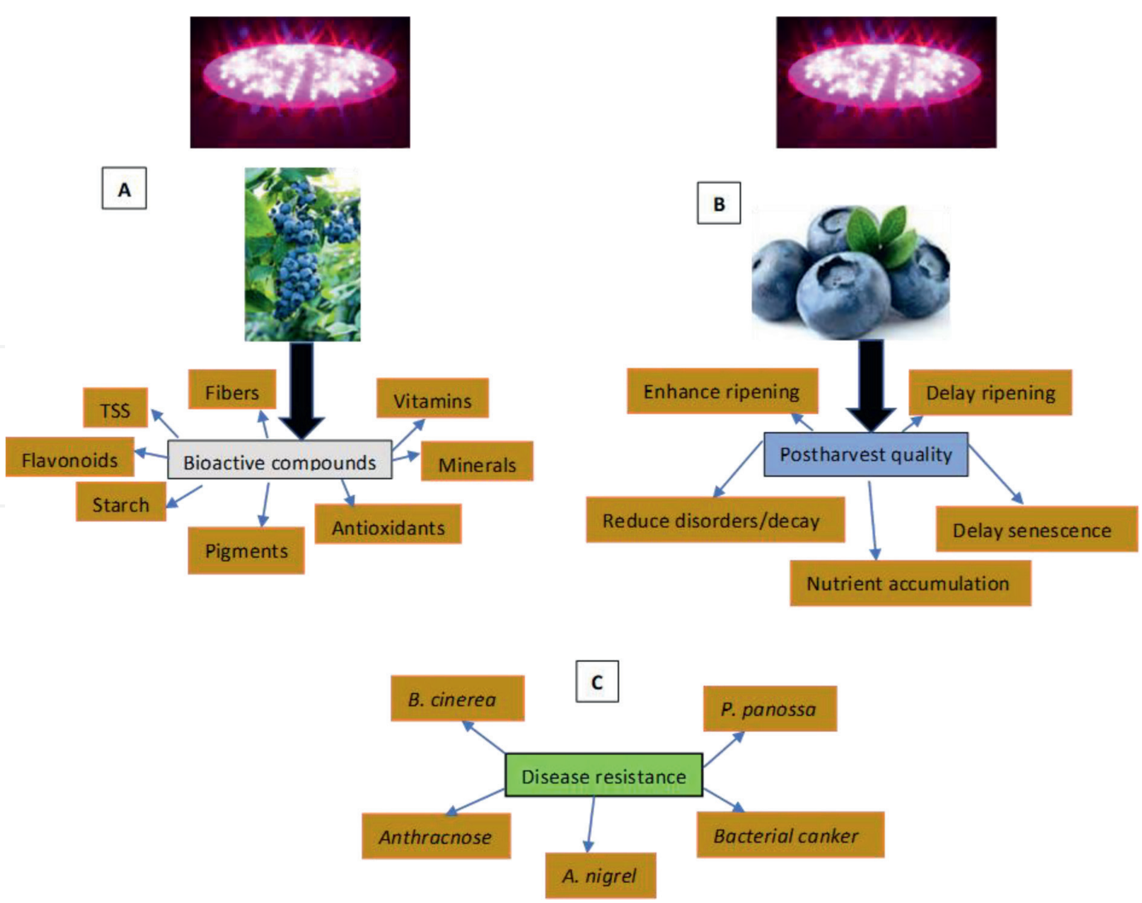

Figure 1.
Effect of LEDs on (A) the production of certain bioactive compounds, (B) postharvest quality, and (C) resistance to diseases affecting horticultural crops, adopted from] [12].

as of optics [11], resulting in LEDs being used in postharvest horticulture. Recently, research on postharvest preservation of fresh horticultural produce with the use of LEDs has gained popularity. Various studies revealed that LEDs have the potential to enhance ripening, particularly color development, as well as being able to suppress disease occurrence and improve the overall nutritional quality of fruit and vegetables exposed to various LED wavelengths [**Figure 1**] [7, 11, 13, 14]. This review, therefore, focuses on the potential of postharvest application of LED technology on horticultural crops, discussing the most significant, recent findings related to this technology. The technology and mechanism of action involved in irradiation with LEDs and the limitations of postharvest LED lighting will also be discussed.

2. Overview of LED technology used postharvest in horticultural crops

An LED consists of a semiconductor with a positive and negative junction, called p- and n-type, respectively. When an LED is connected to a power source, a flow of current starts from the positive (p-type) to the negative (n-type) junction, ultimately resulting in the flow of electrons, which causes light emission at a certain wavelength [7, 15]. The color of light emitted by the LED is determined by the band gap energy of the semiconductor material. **Figure 2** depicts the LED lighting system. Improved technology has enabled LEDs to be used in the postharvest preservation of fruit and vegetables. The unique and advantageous properties of LEDs have resulted in their use in postharvest storage of fresh fruit and vegetables [16]. The monochromatic nature, high photon efficiency, low radiant heat, durability, and prevention of thermal degradation of LEDs are favorable characteristics that make them beneficial in fruit and vegetable postharvest storage [17]. Moreover, the monochromatic nature of LEDs allows horticulturists to select specific wavelengths for the storage and preservation of horticultural produce [17]. Furthermore, LEDs operate at low direct current voltages and temperature, and their operation does not involve the use of toxic, environmentally unfriendly substances. As a result, the postharvest application of LEDs in the agricultural sector has expanded over the past years.

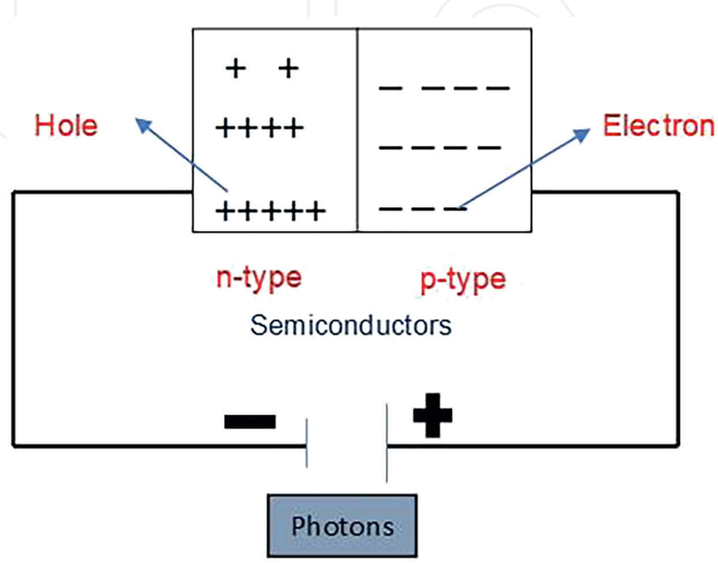

Figure 2.
Emission of photons by light-emitting diodes (LEDs), adopted from [7].

3. Mechanism of LED irradiation on horticultural crops

As mentioned above, due to their peculiar, distinctive properties, LEDs have gained popularity in the postharvest handling of horticultural crops. Even though the effect of various wavelengths, irradiation intensity, and exposure time of these LEDs on fresh fruit and vegetables has proved to be beneficial in enhancing color, bioactive compounds, antioxidants, shelf life, and overall quality [7, 11, 18–21], the mechanism(s) involved in LED irradiation technology is (are) still not clear. It is, however, known that the photosynthesis period of postharvest horticultural produce may be extended by illumination with LEDs. This can result in the long-term preservation of these commodities. The expression of genes and signaling of phytochrome may be inhibited or enhanced by irradiation with LED lights; this potentially affects fruit and vegetable senescence [22]. LEDs can reduce the breakdown of storage phytochemicals in the fruit/vegetable by delaying the emergence of ethylene and the respiratory peak [23]. Further, LED exposure can also cause a fluctuation in enzyme activity due to a change in the secondary structure of proteins. Other aspects involved in the mechanism of action of LED irradiation on fruit and vegetables require further investigations.

4. Postharvest application of LEDs in horticultural crops

The majority of horticultural crops, particularly fruit and vegetables, undergo rapid ripening postharvest due to an increase in respiration and metabolic activities, resulting in the deterioration in quality, softening, rapid water loss, tissue destruction, and senescence. This happens more so in climacteric fruit, as they continue the ripening process, even if removed from the mother plant. Postponing senescence, extending shelf life, and maintaining quality characteristics of horticultural produce are pivotal to reduce postharvest losses and ensure that appealing, high-quality produce reaches the consumer. This can be achieved by storing horticultural produce properly and exposing the produce to effective senescence-inhibiting treatments [24, 25]. The use of LED lights as a sustainable postharvest treatment offers unique opportunities to not only maintain but even improve produce characteristics.

The response of fruit and vegetables to irradiation with different spectral lights (wavelengths) varies and depends on the absorbing ability of the specific light wavelengths [10]. As such, the application of single-wavelength red and blue LEDs has been effective in enhancing bioactive compounds, phenolics, flavonoids, and other antioxidants in fresh fruits and vegetables, while maintaining their nutritional status and overall quality [7, 12] (**Table 1**). Recently, other wavelengths have started to gain interest and are producing promising results as a study by Xie et al. [30] demonstrated that purple LED light (40 $\mu mol\ m^{-2}\ s^{-1}$) enhances the concentration of ascorbic acid and carotenoids of broccoli florets, and a different study by Zhou et al. [31] revealed that irradiation with white LED light (10 $\mu mol\ m^{-2}\ s^{-1}$) is effective in maintaining postharvest quality and delaying senescence of pak choi during storage. On the other hand, mixed spectral light ratios, particularly blue:red at different ratios, have recently been adopted and proven to increase the efficiency of LED lighting [7, 12, 23, 26] (**Table 1**). Furthermore, research has shown that LED illumination can alter carotenoid accumulation and prevent fungal spoilage, which contributes

Crop investigated	LED Wavelength	Light Intensity	Effectiveness	Reference
Sweet cherries	Blue light and a ratio of white, blue, and green lights	—	Blue light enhanced the synthesis of anthocyanin and improved the quality of sweet cherries	[26]
Cherry tomatoes	Red and blue lights	Red (118 μmol m^{-2} s^{-1} at 638 nm) Blue LED light (118 μmol m^{-2} s^{-1} at 454 nm)	Both blue and red lights enhanced the health-related parameters of cherry tomatoes treated at the mature green stage	[20]
Tomatoes	Red light	—	Continuous red light irradiation accelerated ripening of green tomatoes. It also significantly increased lycopene, β-carotene, total phenolic content, and total flavonoid concentration	[27]
Tomatoes	Red light	113 μmol m^{-2} s^{-1}	Red light enhanced, color development lycopene, β-carotene, total phenolic, and total flavonoid concentration in both the outer and inner parts of tomatoes	[21]
Green chili	Red and blue lights	50 μmol m^{-2} s^{-1}	Exposure to red light accelerated color development and lycopene accumulation, whereas blue light was effective in enhancing vitamin C and total phenolics	[28]
Tomatoes	Blue light	100 μmol m^{-2} s^{-1}	30-min blue light exposure and 8-min pause enhanced lycopene, total phenolic compounds, total flavonoids, vitamin C, and soluble sugar more than other treatments	[29]
Broccoli	White, red, green, yellow, blue, and purple lights	40 μmol m^{-2} s^{-1} for each wavelength	Purple light delayed yellowing and maintained and improved the nutritional quality of broccoli during storage at 20°C.	[30]
Pak choi	White light	10 μmol m^{-2} s^{-1}	The treatment *delayed senescence* and maintained the quality of pak choi	[31]
Tomatoes	Blue and red lights	85.72 μ Einstein m^{-2} s^{-1} and 102.70 μ Einstein m^{-2} s^{-1} respectively	Blue wavelength was effective in extending the shelf life of tomatoes by delaying fruit softening and ripening	[32]
Strawberries	Blue light	—	Blue LED light prevented mold *spoilage* and preserved the physicochemical quality of strawberries	[33]

Crop investigated	LED Wavelength	Light Intensity	Effectiveness	Reference
Tomatoes	Blue light	87 W/m2	Blue light potentially maintained physicochemical quality and controlled mold growth on tomatoes during transportation and storage	[34]
Minimally processed broccoli sprouts	Red, blue, and far red	35 ± 2.5 μmol m^{-2} s^{-1}	Improved total antioxidant and decreased the microbial growth	[35]
Broccoli heads	Red light	50 μmol m^{-2} s^{-1}	The treatment delayed senescence and maintained the storage quality	[36]
Three apple cultivars: “Idared,” “Fuji,” and “Carjevič”	Blue light	—	Irradiation with blue light enhanced color development and nutritional quality of apples	[37]
Tomato	Red:far red (R:FR) light ratio	—	Exposure of tomato fruit to LED light with a high R:FR ratio enhanced the synthesis of lycopene	[23]

Table 1.
Postharvest effect of various LED lights on postharvest behavior of horticultural crops.

significantly to postharvest losses (**Table 1**) [11], a study by Dhakal and Baek [32] revealed that short-period exposure with blue wavelength to red tomatoes can extend the postharvest shelf life of tomatoes by delaying color development, and our recent study on cherry tomatoes also achieved the same results and documented improved phytochemical concentrations in blue-wavelength-treated tomatoes [20]. The postharvest effects of LEDs have also been tested on minimally processed food, and promising results have been achieved [35]; however, further research on such commodities is required to optimize exposure duration and type (wavelength).

5. Integration of LEDs with other treatments for postharvest quality alteration

The application of LEDs, as an environmentally sustainable and consumer-friendly approach, to preserve the quality and enhance the variety and concentration of antioxidant compounds in horticultural crops has been extensively investigated (**Table 1**). This technology has, however, some limitations depending on the wavelength used. As such, combining LEDs with other environmentally friendly treatments has recently gained attention. The aim of such combinations is to further improve the efficacy of LED treatments by generating unique properties that prevent LED limitations and contribute toward better postharvest preservation of fruit and vegetables. Hu et al. [38] investigated the combined effect of LEDs and UV light on the postharvest life of sweet oranges and revealed that different treatment combinations accelerated ripening and enhanced the nutritional quality of oranges; the study provided a potential regulation method for orange fruit quality. Hyun et al. [39] demonstrated that combining antimicrobials or photosensitizers with blue LEDs may be applied to extend the shelf life of fresh-cut apples and cherry tomatoes. LEDs can also be beneficial by reducing the occurrence of postharvest pathogens, and research conducted by [40] highlights two important mechanisms of controlling postharvest pathogens using LEDSs: one of these mechanisms is inducing the biosynthesis of specific secondary plant metabolites in fruit tissues, thereby improving the fruit/tissue resistance against pathogens, while also preventing pathogen or spore development due to the presence of photosensitizers in their cells. Zhang et al. [41] further revealed that combining blue light exposure and salicylic acid application maintained the sensory and nutritional quality of strawberries by maintaining bioactive component concentrations. Other studies also explored the effects of combining LEDs with other innovative and nonchemical-based treatments, such as heat and ethylene treatments [42–44].

6. Challenges and limitations associated with the postharvest use of LEDs

The postharvest use of LEDs has various benefits in maintaining and preserving the quality of horticultural crops (**Table 1**). However, some negative impacts are aligned with the use of this technology. Irradiation with LED lights has been reported to slightly reduce the mass of fruit and vegetables due to enhanced moisture loss [45]. The reason behind this moisture loss could be the selection of a specific, harmful wavelength and long duration or exposure of LEDs to horticultural crops. The opening of stomata can also be induced by postharvest irradiation with LED lights, and that may result in treated fruit and vegetables losing moisture. Most studies, including our recent ones, have demonstrated that postharvest application of either red or blue LED lights can improve nutritional quality and preserve the quality of horticultural crops without negatively affecting their mass [19, 20, 46]. The higher intensity, longer daily exposure, and continuous illumination have been reported to cause abiotic stress, resulting in higher mass loss; this, however, depends on the wavelength or LED light spectra used [47]. It is, therefore, very important to pay special attention when selecting the intensity, duration of exposure and spectral composition, or wavelength of LEDs to apply to a specific horticultural crop.

7. Conclusions

This review has demonstrated why LEDs are considered a novel technology in the food industry. This technology is constantly improving, and its application holds great potential in horticulture for food preservation. Importantly, LEDs are cost-effective and environmentally friendly, release minimal radiant heat, and have a monochromatic nature, which allows the selection of specific wavelengths, while excluding unwanted wavelengths that sometimes result in producing radiant heat. The application of LEDs postharvest has been shown to accelerate or delay ripening, improve color development, enhance the phytochemical concentration, improve nutritional quality, extend shelf life, and prevent fungal spoilage of various horticultural crops. It has, however, been noted that the recent research is focusing only on carotenoid-accumulating crops, such as pepper and tomato, with minimal focus on other crops. A deeper understanding of how various light spectra affect various crops and how the intensity of light and the duration of illumination affect various fruit and vegetables, especially highly perishable ones, is required. Merging of certain wavelengths still requires serious attention; it is also important to investigate the response of various crops to various ratios of wavelengths to decide on the combination that yields better results. Further studies are required to reduce moisture loss as a result of LED illumination; in this case, the application of edible coatings in different formulations after LED illumination may potentially mitigate this effect. The sensory acceptability of fruit and vegetables treated with LEDs postharvest, as well as a deeper understanding of the mechanism involved in the postharvest irradiation of LED lights, still needs to be further investigated. Lastly, research revealed that LEDs can enhance health-related compounds present in fruit and vegetables; however, further studies need to be conducted to determine optimal ratios or combinations of LEDs and investigate which one achieves this optimally without negatively affecting other quality parameters of these commodities.

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None.

Conflict of interest

The authors declare no conflict of interest.

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