REVIEW ARTICLE

Effect of Light-Emitting Diodes (LEDs) on the Quality of Fruits and Vegetables During Postharvest Period: a Review

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Abstract
Major losses of fresh horticultural produce transpire during postharvest storage due to prompt senescence and diseases. The traditional postharvest preservation techniques used after harvest are based on cooling and the application of chemical preservation techniques. As a residue-free physical sterilization and preservation method, light-emitting diode (LED) treatment, has recently been applied for postharvest storage of fruits and vegetables by numerous researchers. This paper reviews the recent applications of LEDs in postharvest storage of fresh produce, including its effect on physiological characteristics, secondary metabolism, nutritional attributes, ripening process, senescence, shelf-life improvement, and pathogenic microbial spoilage of fruits and vegetables. LED treatment has promoted the accumulation of different phytochemicals, such as phenolic compounds, vitamins, glucosinolates, chlorophyll, total soluble solids, and carotenoids. Changes in the nutritional content, anthocyanin content, antioxidant capacity, and ripening were also observed after the treatment. Reduction in microbial spoilage and delay senescence were evident after the LED exposure. The influence of LED light depended on the fruit and vegetable variety. Therefore, LED treatment is an efficient and promising strategy for extending the storage life of fruits and vegetables with enhanced nutritional values.

Keywords LEDs · Fruits and vegetables · Postharvest · Preservation · Light quality

Introduction

Fruits and vegetables are well known for their health-promoting properties due to their contents of vitamins, minerals, and antioxidants, which reduce the risk of chronic diseases and increasing their demand in the consumer diet (Aghdam et al. 2018; Pinela and Ferreira 2017; Slavin and Lloyd Beate 2012). The Food and Agriculture Organization (FAO) has reported that fruits and vegetables are the most wasted commodities (Dou et al. 2017; Miguel et al. 2008). The primary causes for this wastage are inefficient postharvest infrastructure and poor harvesting and storage techniques (Dou et al. 2017; Dueck et al. 2016; Kozai 2013; Kozai and Niu 2015; Regnier and Combrinck 2009). The postharvest problem is a major global issue, in both developed and developing countries. Many studies have shown that there are minimal storage facilities for various horticultural crops, especially in developing countries, which has influenced postharvest losses, including over-ripening, softening, decay, weight loss, senescence, firmness loss, and specific physiological disorders (Bantis et al. 2018; Dou et al. 2017). The shortening of fruits and vegetable loss is a leading issue for providing long-term storage across the global population (Capone et al. 2014). However, due to the speedy senescence and susceptible diseases of postharvest fruits and vegetables, the preservation technology has become the research focus (Mari et al. 2016; Usall et al. 2016).

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Currently, the techniques used for preserving fruits and vegetables are mainly chemical additives, such as the use of 1-methyl cyclopropane (Amornputti et al. 2014; Chiabrando and Giacalone 2011), ozone treatment (Song et al. 2016), application of a high oxygen atmosphere (Zheng et al. 2008), chitosan coating (Kerch 2015), and physical techniques, including controlled atmosphere storage (Skrovankova et al. 2015), forced air cooling air packaging (Castro et al. 2004), and UV-C (Amornputti et al. 2014; Wang et al. 2009), and biological techniques such as biocontrol agent (Amornputti et al. 2014) to reduce losses. As a result of limitations on chemical additives technologies, thus, the food processing industries have shifted toward nonthermal approaches, including irradiation, ultraviolet light (UV), pulsed light (PL), high-pressure processing (HPP), ultrasound (US), and cold plasma (Naveenkumar et al. 2017; Castillo et al. 2010; Osae et al. 2020; Pinela and Ferreira 2017).

Recently, greater emphasis has been paid to the influence of LEDs (narrow-bandwidth illumination) on the postharvest storage of fresh horticultural produce. Recent research has shown that LEDs enhance the traits of numerous postharvest fresh produce, including lettuce, cabbage, kale plants, white mustard, sweet pepper, cucumber and blueberries (Hung et al. 2016), peaches (Gong et al. 2015), strawberries (Xu et al. 2014a, 2014b), tomatoes (Dhakal and Baek 2014), citrus fruits (Ma et al. 2012), Chinese bayberries (Shi et al. 2014), Spinach and kale (Erwin and Gesick 2017), and grapes (Rodyoung et al. 2016).

In addition, there have been many researches on the application of LEDs in the field of postharvest fruits and vegetables and several reviews on plant physiology (D'Souza et al. 2015). However, there is a lack of usable information on the advantages of LED techniques when applied at the time of postharvest storage. There is also no synopsis of the influence of LEDs on quality attributes. This review provides information on the application of LEDs for the postharvest preservation of fresh horticultural crops. An overview of the effect of LEDs as a nonhazardous technique for improving the ripening process, nutritional parameters, and secondary metabolites, delaying senescence, and leading to quality improvement of fruit is discussed.

Overview of LED (NBI) Technology in the Postharvest Period of Fruits and Vegetables

LEDs are a solid-state (i.e., semiconductor-based) system that converts electrical energy to electromagnetic radiation (D'Souza et al. 2015; Schultz et al. 2008), typically in the infrared or visible regimes (Rodyoung et al. 2016), and occasionally in ultraviolet regimes (Bantis et al. 2018; Dou et al. 2017; Krames et al. 2007). A depiction of a LED system is shown in (Fig. 1). The LEDs comprised of a semiconductor with a p-n (positive-negative) junction, consisting of p-type (positive-doped) and n-type (negative-doped) semiconductor on the right and left, respectively. A depletion region, defined as the barrier between p-type and n-type regions that prevent the movement of electrons from n-type and holes from p-type semiconductors, is created due to diffusion currents. The depletion region left with positive and negative charged ions. Electrons and holes (being the absence of particles) recombine spontaneously when a forward bias (i.e., applied electric field) forces them to interact within the depletion region. This recombination process produces light (as photons) in a spontaneous emission process, defining the mechanism of the LEDs (Bantis et al. 2018; Folta et al. 2005; Hasan et al. 2017a, 2017b). This emitted light has a wavelength dictated by the bandgap energy of the semiconductor between the conduction and valence energy bands (D'Souza et al. 2015). The emission of light from LED can vary from a narrow band of single colors like red, green, or blue to the wider band for white light (Mitchell et al. 2012). A white LED is typically a blue LED that has been infused with phosphorous to broaden the emission spectrum. A phenomenon involved in the operation of LEDs is electroluminescence, which is a non-thermal process of emitting light when the electric current passes through the semiconductor (Lai et al. 2016). The electroluminescence phenomenon was first detected when H. J. Round was working with silicon carbide in 1907. However, the first patent based on the emission of infrared radiation from a semiconductor due to the passage of electricity was obtained by James Biard and Gary Pittman in 1962 (Taulavuori et al. 2017).

Fig. 1 LEDs showing the emission of photons
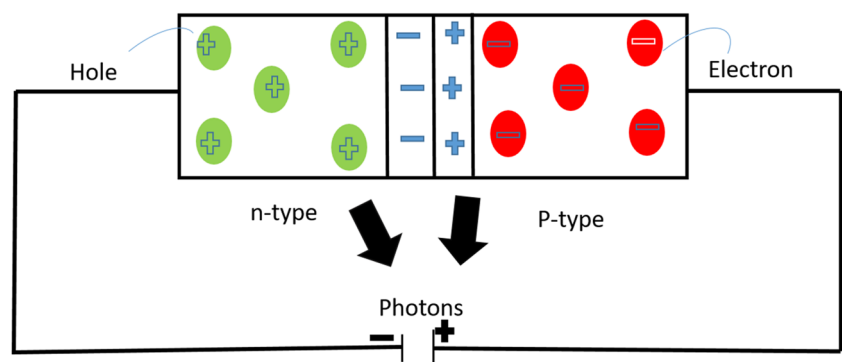
LEDs have many advantageous properties that mark their use in postharvest storage of fruits and vegetables (Bantis et al. 2018; Branas et al. 2013; Lee et al. 2014a, 2014b). LEDs have the potential to regulate senescence, lead to ripening, and improve fruit quality and nutritional attributes in fruits and vegetables (Dutta Gupta 2017; Bantis et al. 2018). The potential of LEDs to extend the storage life of horticultural crops is advancing. Other advantageous properties of LEDs include their monochromatic nature, long life, prevention of thermal degradation, and high photon efficiency. All these favorable characteristics make LED application beneficial for extended the storage life of fruits and vegetables (Krames et al. 2007; Yu et al. 2017). LEDs do not involve the use of heavy metals that are toxic and operate at a low temperature and low direct current (DC) voltages (Dutta Gupta et al. 2019; D'Souza et al. 2015; Yang et al. 2018). Furthermore, the monochromatic nature of LEDs allows for the selection of the wavelength-specific emission light spectra desired for the production, preservation, and storage of fresh horticultural produce (Krames et al. 2007; Yu et al. 2017). The application of LEDs in postharvest has expanded due to its numerous advantages over conventional light sources. LEDs have more efficient energy utilization and a longer lifespan (approximately 5×10^4 versus $7–15 \times 10^3$ h) compared with traditional light sources (Krames et al. 2007; Yu et al. 2017). Additionally, LED lights have some properties such as the capability to restrain spectral composition, adjustable sizes, durability, a longer operating time, and relatively cold emitting surfaces (Folta et al. 2005; Yu et al. 2020). LEDs facilitate nonthermal operations and therefore minimize thermal degradation that might have any detrimental influence on the quality of fresh produce. It is also mechanically robust, which prevents damage due to vibrations. LEDs do not present any mechanical damage as a result of transportation, thus enabling their use in cold storage (D'Souza et al. 2015).

Characteristics of LEDs (NBI)

LEDs emit low radiant heat and are highly effective at a low temperature. LEDs have long-term effects and can last for 50,000–100,000 h working against traditional lighting, which can last for 15000 h (Jatothu 2013; Zhmakin 2011). LEDs have a close-packed size that improves flexibility while designing lighting systems. LEDs can control ultraviolet (UV) and infrared (IR) LEDs, while both UV and IR LEDs cannot control high-pressure lamps (HPL) and fluorescent lights (Denbaars et al. 2013; Munthikote 2018). LED components can be assembled into a compact system of various shapes, but this cannot be achieved with HPL and fluorescent lights due to their bulkiness (Ibrahim et al. 2014; Munthikote 2018). LEDs have a color mixture of white of 100–150 lm/W, whereas high-pressure and fluorescent lamps have values of 45–80 lm/W, and 65–150 lm/W, respectively. Many properties of LEDs have facilitated their use over traditional light, such as sodium and xenon lamps (D'Souza et al. 2015), high-intensity discharge lamps (Dutta Gupta 2017). LEDs are energy efficient with high luminosity and high photon flux (Dutta Gupta 2017). They do not involve the use of heavy metals that are toxic in cases of leakage (D'Souza et al. 2015). Additionally, LEDs are safe to operate and have adjustable on/off properties.

Effects of LEDs (NBI) on Postharvest Physiochemical Characteristics of Fruits and Vegetables

During postharvest storage, the majority of fruits and vegetables undergo rapid age and deterioration in quality, such as a rise in respiration process, softening, tissue destruction, and lipid peroxidation, increases in water loss, and postharvest quality characteristics such as the visual scale, flavor, texture, aroma, and nutritional quality; therefore, the primary purpose of postharvest storage of horticultural crops is to postpone senescence and to maintain the trait of fruits and vegetables during storage (Hodges and Toivonen 2008; Martínez-Romero et al. 2007; Pinela and Ferreira 2017; Prasad and Chakravorty 2018; Sharma et al. 2017). LEDs have been proven to be an effective inhibitory treatment for postharvest senescence of fresh produce in recent years, by extending the shelf life and maintain the quality of fresh produce (Table 1) (Colquhoun et al. 2013; D'Souza et al. 2015; Dhakal and Baek 2014; Dutta Gupta 2017; Gong et al. 2015; Hodges and Toivonen 2008; Kader 2005; Lichtfouse 2015; Prasad and Chakravorty 2018; Xu et al. 2014a, 2014b). The most recent study mainly focused on the application of LEDs in horticulture, and some studies have explored the application of LEDs in the postharvest stage (Dutta Gupta 2017). The study of the effect of LEDs on postharvest quality is relatively recent but has resulted in important findings.

Color Development

The color of a fruit is an important attribute that defines fruit acceptability and quality. In most fruit such as blueberries, the presence of anthocyanins is responsible for their color. The color of the fruit is affected by multiple factors, such as temperature, pH, and fruit physiology (Casati et al. 2012). Similarly, light has a significant impact on the color indices of fruits and vegetables, which regulate their shelf life. The development of color in fruits after harvest is related to the accumulation of various pigments such as lycopene, chlorophyll, or anthocyanin (Büchert et al. 2011; Xu et al. 2014a,

Table 1 Effect of LED treatment on the physicochemical characteristics of fruits and vegetables during postharvest storage

Treated fruit/vegetable	LED types	Treatments	Results	Reference
Broccoli (*Brassica oleracea*)	White (463 nm) LEDs	12 days of treatment at a fluence rate of 12, 25, and 50 W m^{-2} at 22 °C	White LED treatment increased the L value after 12 days at 22 °C	(Büchert et al. 2011)
Strawberries (*Fragaria ananassa*)	Blue LEDs	12 days of treatment at 5 °C at a fluence rate of 40 W m^{-2}	After 4 days of blue LED treatment, the color development in strawberries increased. However, the respiration rate decreased during the initial 2 days of storage, followed by a gradual increase in the control and blue light treatment at 5 °C. Blue LED treatment increased the values of CRIG as compared with control samples.	(Xu et al. 2014a, 2014b)
Brussels sprouts (*Brassica oleracea gemmifera*)	White and blue LEDs	5 and 10 days treatment at a fluence rate of 20 W m^{-2} at 22 °C	Medium intensity LED treatment increased weight loss of Brussels after 10 days at 22 °C compared with control untreated samples kept in the dark.	(Hasperué et al. 2016a, 2016b)
Broccoli (*B. oleracea var. Italica*, *cv. You-xiu*)	Red (630 nm) LEDs	5 days of treatment at a fluence rate of 50 W m^{-2} at 20 °C	A higher increase in weight loss was observed in broccoli during storage in both groups. The level of increase in weight loss was significantly lower in the control group relative to treated broccoli on 4 and 5 days.	(Jin et al. 2015)
Broccoli (*B. oleracea var. Italica*, *cv. You-xiu*)	Red (630 nm) LEDs	5 days of treatment at a fluence rate of 50 W m^{-2} at 20 °C	The red light was able to inhibit the increase in L values, leading to the higher chlorophyll content of 59.1% compared with the control untreated samples. Likewise, the a/b value of broccoli generally decreased during storage, regardless of treatment; however, it was higher in LED-treated broccoli after 3 days until the end of the experiment.	(Jin et al. 2015)
Peaches (*Prunus persica cv.*)	Blue (470 nm) LEDs	15 days of treatment at a fluence rate of 40 W m^{-2} at 10 °C	Blue LED treatment significantly increased ethylene production, and the maximum ethylene production was delayed from 6 to 9 days, TSS content increased, and acidity decreased in peaches after 15 days of storage at 10 °C.	(Gong et al. 2015)
Citrus fruits (*Citrus sp.*)	Red (660 nm) and blue (470 nm) LEDs	6 days of treatment at a fluence rate of 50 W m^{-2} at 20 °C	After 6 days of red and blue LED treatment, the contents of antioxidants, phenolics, total soluble sugars, and ascorbic acid and enzymatic activities increased significantly at 20 °C.	(Xu et al. 2014a, 2014b)
Tomato (*Solanum Lycopersicum*)	White and red:far-red LEDs	6 days of treatment at a fluence rate of 476 W m^{-2} at 23 °C	Highest red: far-red ratios treatment positively affected the firmness parameters compared with other white LED light conditions. Furthermore, red: far-red ratio increased the TSS and TA of the tomato fruit compared with the white LED light and control sample after 6 days of storage at 23 °C.	(Nájera et al. 2018)

Table 1 (continued)

Treated fruit/vegetable	LED types	Treatments	Results	Reference
immature green tomatoes	Blue light (440) and red light (450 nm)	21 days of treatment at a fluence rate of 102.70 and 85.72 W m^{-2} at 25 °C	Both red LED, and dark (control) treatment increased the color of tomatoes, while those treated with blue light were yellowish color at 7 days. But no difference was observed after 21 days of storage. There was a gradual decrease in the firmness of tomatoes as the storage time increased. Tomatoes treated with blue light maintained significantly higher levels of firmness than those treated with red and darkness after 21 days of storage. Tomatoes treated under red light and darkness accumulated significantly higher amounts of lycopene than those treated under blue light after 7 days of storage. Tomatoes treated under blue light showed gradually increasing lycopene contents as the storage time in darkness increased, eventually reaching the same levels of lycopene as those treated under darkness and red light after 21 days of storage. The TSS content of tomatoes treated under darkness, red light, and blue light did not differ significantly after 7 days of storage and remained constant after 14 days of storage. Nevertheless, all treatment showed a significant decrease in TSS after 21 days of storage.	(Dhakal and Baek 2014)
Habanero pepper (*Capsicum chinense*)	Blue and UV-C LED light	30 days of treatment at 4–5 °C at a fluence rate and dosage of 0, 1.5 W m^{-2} and 0, 0.5 kJ m^{-2}	Blue and UV-C LED light both increased the content of all bioactive compounds and antioxidant capacity in habanero pepper vegetables for 30 days at 4–5 °C during storage. However, in some bioactive compounds such as chlorophylls and total carotenoids, the effect was evident only in the 1 days of storage.	(Pérez-Ambrocio et al. 2018)
Lettuce (*Lactuca sativa* L. cv. 'Zishan')	Red and blue LED (456 nm) and (655 nm)	20 days of treatment at a fluence rate of 500 W m^{-2} and 23 °C	Red and blue LED treatment increased the weight of lettuce first and then decreased after 10 days of storage. However, both the LEDs increased the content of soluble sugar, anthocyanin, flavonoid, total phenolic, and ascorbic acid compared with the untreated sample (control).	(Shao et al. 2020)
Chinese *bayberries* (*Myrica rubra*)	Blue (470 nm) LEDs	8 days of treatment at a fluence rate of 40 W m^{-2} at 10 °C	After 8 days of blue LED treatment, the content of total soluble sugar, consisting of fructose, sucrose, and glucose, in the Chinese bayberries significantly increase as a result of an increase in gene expression (hexokinase genes, cryptochrome genes, glucose sensor genes).	(Shi et al. 2016)
				(Kim et al. 2011)

Table 1 (continued)

Treated fruit/vegetable	LED types	Treatments	Results	Reference
Strawberry (*Fragaria ananassa*)	385 nm (violet, 470 nm (blue), 525 nm (green) and 630 nm (red)	4 days of treatment at 5 °C	After 4 days of LED treatment at 5 °C, the content of soluble sugars, acidity, total phenol, vitamin C, and anthocyanin in immature strawberry increased.	
Strawberry (*Fragaria ananassa*)	Blue (470 nm) LEDs	12 days of treatment at 5 °C at a fluence rate of 40 W m^{-2}	Blue LED treatment enhanced the levels of phenolics, ascorbic acid, and acidity in strawberry for 12 days at 5 °C compared with the control samples, and blue LED treatment significantly decreased the total sugar content during the initial 6 days of storage in both the control and treated samples; however, the contents of antioxidant and DPPH radical scavenging activity in strawberries was increased.	(Ma et al. 2012)
Grape berries (*Vitis labruscana Bailey cv'Campbell Early' and 'Kyoho'*)	Blue LED light (445 nm)	9 days of treatment at a fluence rate of 80 W m^{-2} at 15–25 °C	After blue LED treatment, firmness was not influenced by any of the treatments for 9 days at 25 °C. TSS content was reduced in the dark compared with the treated sample. At the same time, the titratable acidity was significantly enhanced and gradually decreased with an increase in temperature under both light and dark conditions. The percentage of berry weight loss was progressively increased with increasing temperature under both light and dark conditions.	(Azuma et al. 2019)
Red Chinese sand pears fruit (*Pyrus pyrifolia*Nakai)	White LEDs (765 nm) and UV-B LED (315 nm)	10 days of treatment at a fluence rate of 532 and 270 W m^{-2} at 32 °C	White and UV-B LED treatment improved red color, firmness, and TSS of the fruit for 10 days at 32 °C compared with the control untreated sample.	(Sun et al. 2014)

2014b). The accumulation and production of pigments are affected mainly by light (Xu et al. 2014a, 2014b).

In brussels sprouts (*Brassica oleracea gemmifera*) treated with white and blue LEDs for 10 days of storage, LEDs affect the color indices of the vegetables (Hasperué et al. 2016a, 2016b). Similarly, lower L (where L* lightness-darkness color) values also reported in broccoli florets exposed to red LEDs (630 nm) at a fluence rate of 50 W m^{-2} for 5 days. The red light was able to inhibit the increase in L values, leading to the higher chlorophyll content of 59.1% compared with the control untreated samples; likewise, the a/b (where the positive a* represents the redness and the negative a* represents the greenness whereas the positive b* represents the yellowness and the negative b* represents the blueness) value of broccoli generally decreased during storage, regardless of treatment; however, it was higher in LED-treated broccoli after 3 days until the end of the experiment (Jin et al.

2015). It has been reported that blue LED treatment (85.72 W m^{-2}) in green tomatoes fruit was able to prevent red color development as compared with red light (102.70 W m^{-2}) and untreated samples after 7 days of storage. The L values were significantly lower for tomatoes treated with blue light with less reddish tomatoes visually. However, tomato treated with the red light turned red at room temperature for given intensity (Dhakal and Baek 2014). Also, when the treatment of strawberries was carried out with blue light at a fluence rate of 40 W m^{-2} for 12 days at 5 °C and evaluated for color changes, no significant differences were observed. Also, there was an increase in CRIG values during postharvest storage as compared with control samples (Xu et al. 2014a, 2014b). In another study conducted by Büchert et al. (2011), there was an increase in L value for broccoli when treated with white light using fluorescent tubes at a fluence rate of 12, 25, and 50 W m^{-2} at 22 °C. This increase

explained that with an increase in the treatment period, fruit or vegetable heads towards the senescence stage. However, broccoli heads remained green under treatment with light than those kept in the dark, implying that treated samples showed a lower increase in L value as compared with untreated ones (Büchert et al. 2011).

The influence of light at different wavelengths (463, 520, and 630 nm) and fluence rates (20, 40, and 60 W m^{-2}) at two different temperatures of 21 °C and 2 °C on blueberries showed variable responses (Zhou et al. 2014). At 21 °C, the lowest L value was observed for 20 and 40 W m^{-2}, respectively, under blue light treatment for 15 days. In contrast, at 2 °C, red light resulted in the lowest L value under the same conditions. However, with an increased influence rate to (60 Wm^{-2}), green light had the lowest L value for 15 days at 21 °C and 2 °C, followed by blue and red light. At higher fluence rates, blue and red (40 and 60 W m$^{-2)}$ light exhibited an increased L value compared with the control samples at 21 °C, which was inconsistent with the 2 °C (control samples) with the highest L values. Overall, enhanced L values were reported for red light treatment for all three fluence rates at 21 °C. However, a decrease in the L value was observed under blue light treatment followed by green light. At 2 °C, green light showed a decrease in L value with an increased influence rate (Zhou et al. 2014).

Total Soluble Solids

The content of total soluble solids in both climacteric and non-climacteric fruit determines the maturity index of fruits and vegetables. Increased levels of total soluble solids (TSS) in fruit indicate an acceleration of the ripening process, while a decrease in TSS content indicates slow ripening and enhanced shelf life of fruit (Gong et al. 2015). Similarly, the application of LED treatment in brussels sprouts (Brassica oleracea gemmifera) inhibited the increase in TSS within the first 5 days of storage; however, after 10 days of storage, the TSS content significantly decreased (Hasperué et al. 2016a, 2016b; Shi et al. 2014). Likewise, the application of blue, green, and red LEDs in blueberry fruit inhibited the maximum increase in TSS content during postharvest storage (Taulavuori et al. 2017). At 21 °C, red light showed a maximum increase in TSS for 5, 10, and 15 days, followed by blue and green light at a fluence rate of 20 Wm^{-2}. Equivalently, for 40 and 60 W m^{-2}, red light showed a maximum increase in TSS for 5 and 10 days. However, over 15 days, blue light had maximum TSS values. At 2 °C, blue light resulted in enhanced levels of TSS at 20, 40, and 60 W m^{-2} during the 15-day treatment period. However, the TSS content of blueberries should remain constant as an increase in TSS results in ripening and reduces the shelf life of fruit. Green LED light showed lower values for TSS compared with red and blue light and control samples over 15 days

of treatment at 20, 40, and 60 Wm^{-2} at both 21 °C and 2 °C (Taulavuori et al. 2017). Also, after 4 days of LED treatment at 5 °C in strawberry fruit, the contents of vitamin C and sugar significantly increased during postharvest storage. However, the significant increase in TSS in strawberries could be associated with the solubilization of cell wall components of crops, such as polyuronides and hemicelluloses, rather than the conversion of starch to sugars, as there is very little accumulation of glycogen during fruit development (Kim et al. 2011). There was an increase in TSS levels in Chinese bayberries (Myrica rubra Sieb) under the treatment of blue (470 nm) LEDs at 40 Wm^{-2} for 8 days at 10 °C. There were enhanced levels of glucose, fructose, and sucrose as compared with untreated samples (Shi et al. 2016). In addition, the application of white and red:far-red LED treatment at a fluence rate of 476 W m^{-2} significantly increased the firmness parameters compared with other white LED light conditions. Furthermore, the highest R: FR ratio increased the TSS and TA of the tomato fruit compared with white LED light and control sample after 6 days of storage at 23 °C (Nájera et al. 2018)

Conversely, the TSS content significantly increased under blue light treatment. A similar trend of enhanced ethylene production was observed in postharvest peaches treated with blue (470 nm) LEDs for 15 days at 10 °C (Gong et al. 2015). However, maximum ethylene production was delayed from 6 to 9 days of storage compared with the untreated control samples. The TSS content significantly increased, and the acidity decreased after treatment, in addition to color development in peaches; blue LEDs helped to regulate the synthesis of pigments and internal ethylene in fruit, accelerating the ripening during a postharvest period (Gong et al. 2015).

Weight Loss

Weight loss is an important problem of quality deterioration in fruits and vegetables during postharvest storage (Zhan et al. 2012a, 2012b). The weight loss of vegetables was inhibited when treated with LED light, including brussels sprouts (Brassica oleracea gemmifera) and broccoli (Brassica oleracea) (Hasperué et al. 2016a, 2016b), also brussels sprouts treated with a white and blue light at a fluence rate of 20 W m^{-2} for 5 and 10 days at 22 °C. There was higher weight loss under light treatment as compared with control untreated samples. Also, the weight losses increased with an increase in the treatment period. These clearly explain the interaction of blue light with stomatal cells. Blue light affects the opening of stomata leading to higher respiration rates, which in return affects the overall metabolism of fruits and vegetables (Hasperué et al. 2016a, 2016b). In addition to respiration, the other process affected by light is transpiration that is also associated with stomatal opening regulated by light (Zhan et al. 2012a, 2012b). In another study conducted by

Xu et al. (2014a, 2014b) found that levels of respiration rates were higher in strawberries treated with blue light after 4 days of storage at 5 °C. Treatment was carried out at a fluence rate of 40 W m^{-2} for 12 days.

Similarly, a higher increase in weight loss was observed in broccoli during storage in both treated and untreated samples. The level of increase in weight loss was significantly lower in the control group relative to treated broccoli on 4 and 5 days (Jin et al. 2015). Red and blue LED (456 nm) and (655 nm) treatment at a fluence rate of 500 W m^{-2} at 23 °C significantly increased the weight of lettuce first and then decreased after 10 days of storage (Shao et al. 2020).

Antioxidant Compounds

It is well known that plant senescence is mostly as a result of the production of reactive oxygen species which can provoke oxidative damage to lipids and protein of plant cells, thus controlling the production of ROS is a significant way to retard the senescence of fresh horticultural produce during postharvest storage (Skrovankova et al. 2015). The removal of ROS is classified into two categories: antioxidant substances (AS) and antioxidant enzymes (AE). AS comprising (carotenoids, polyphenols, vitamin E, and reduced glutathione), while AE mainly comprises (glutathione oxidase, catalase, ascorbate oxidase, superoxide dismutase, and glutathione oxidase) (Xu et al. 2014a, 2014b).

The antioxidant system of fruits and vegetables was significantly increased by LED treatment (Table 1). On the other hand, LED treatment increases the content of other antioxidants such as phenolic compounds (i.e., flavonols, anthocyanins, and ascorbic acid), carotenoids, and GSH, as shown in (Table 1). The increased content of antioxidant and DPPH (1,1-diphenyl-2-picrylhydrazyl) free radical scavenging activity was observed in immature strawberries treated with blue light (470 nm) at 40 W m^{-2} for 12 days at 5 °C compared with untreated samples (Xu et al. 2014a, 2014b). In addition, red (660 nm) and blue (470 nm) light treatment at a fluence rate of 50 W m^{-2} at 20 °C decreased the contents of carotenoid in citrus fruit compared with the control, demonstrating a gradual increase towards the end of treatment (Ma et al. 2017). However, blue (470 nm) LEDs did not have any significant effect (Ma et al. 2014). Similar results have been reported for fresh-cut broccoli using green light treatment (Jin et al. 2015) and strawberries with a blue light at (40 W m^{-2}) (Xu et al. 2014a, 2014b). Research showed that LED treatment increased the antioxidant activity of blueberries at 40 W m^{-2} at 21 °C and 2 °C (Dinardo et al. 2018). Similarly, the application of blue (470 nm) and red (660 nm) LED light in citrus fruits at 20 °C for 6 days at a fluence rateof 50 W m^{-2} both the light significantly increased the antioxidant present in citrus fruit such as ß-cryptoxanthin (Ma et al. 2012). Also, blue and UV-C LED light treatment at a fluence rate and dosage (0,

1.5 W m^{-2} and 0, 0.5 kJ m^{-2}) increased the content of all bioactive compounds and antioxidant capacity in habanero pepper vegetables for 30 days at 4–5 °C during storage. Also, in some bioactive compounds such as chlorophylls and total carotenoids, the effect was appreciable only in the 1 day of storage (Pérez-Ambrocio et al. 2018). Additionally, LED treatment increased antioxidant characteristics of many leafy vegetables such as tomato (*Solanum Lycopersicum*), Chinese kale (*Brassica* sp.), Chinese cabbage (*Brassica napus* L.), and pea (*Pisum sativum L.*), during storage as a result of ROS-scavenging enzymes, DPPH free radicals, β-carotene, and glucosinolates (Hee-Sun Kook 2013; Johkan et al. 2010; Ki Lee et al. 2016; Wu et al. 2007). The increased activity of this antioxidant helps in curing many diseases such as cancer and ultimately promotes the functional properties of citrus fruit (Ma et al. 2012).

Effects of LEDs (NBI) on Secondary Metabolites in Postharvest Fruits and Vegetables

Lights of different wavelengths regulate key photochemical processes include photosynthesis and the production/assimilation of secondary metabolites in horticultural crops (Xu et al. 2014a, 2014b). The increase in gene expressions such as MdMYB10 and MdUFGT under the effect of light aids in the accumulation of compounds such as vitamin C, soluble sugars, anthocyanin, or organic acids. Additionally, enzymes such as phenylalanine ammonia-lyase are responsible for the production of secondary metabolites (Hasan et al. 2017a, 2017b). The effect of light on various photoreceptors or the production of secondary metabolites is essential for its application of crop productivity and quality (Dutta Gupta et al. 2017). Crops respond to a natural light source, the sun, to carry out the process of photosynthesis. Also, plants react to other variables such as the light intensity, duration, wavelength, surrounding temperature, humidity, and carbon dioxide, among others, which leads to the initiation of signals that affect photoreceptors. For example, the phytochrome photoreceptor is responsible for the absorption of far-red and red light (Briggs and Olney 2001; Bentsink and Koornneef 2008; Brazaityte et al. 2006; Casal 2013; Cookson and Granier 2006; Dutta Gupta 2017; Ouzounis et al. 2014; Samuoliene et al. 2013; Reinbothe and Reinbothe 1996; Park and Runkle 2017), whereas cryptochrome and phototropin are responsible for the absorption of blue light (Kong and Okajima 2016; Wang and Folta 2013). The responses affect processes such as ripening, senescence, nutritional quality, and overall fruits and vegetable quality (Solovchenko and Merzlyak 2008; Seigler 2000; Wang and Folta 2013). Also, light exposure affects the production of secondary metabolites and the accumulation of phytochemicals (Ki Lee et al. 2016). Light sensors such as phytochrome, cryptochrome, and phototropin perceive light at variable wavelengths and affect the metabolic

pathways (Braidot et al. 2014; Jones 2018; Kong and Okajima 2016).

In fresh horticultural produce, secondary metabolites produced are different from primary metabolites such as carbohydrates and amino acids (Nhut et al. 2011). The role of LEDs in secondary metabolite induction in crops seems to be associated with the phenylalanine ammonia-lyase enzyme. The upregulation of PAL by blue light and red LEDs increases the production of secondary metabolites (Bian et al. 2014; Heo et al. 2012; Hasan et al. 2017a, 2017b). The major secondary metabolite is ginsenoside, which is generated via the isoprenoid pathway in ginseng. The effects of LEDs on secondary metabolites has not been well researched. However, studies have shown that blue LED treatment (450–470 nm) increases the concentration of flavonoids in Chinese foxglove (*Rehmannia* sp.) from 2–74% compared with the sample that is stored under dark conditions (Manivannan et al. 2015; Nhut et al. 2011).

Phenolic Compounds

Phenolic compounds are the main nutrient present in fruits and vegetables, which not only gives fruits and vegetables the function of promoting human health but also plays a vital role in plants themselves as secondary metabolites produced in response to biological and abiotic stresses. The significant phenolics found in fruits and vegetables are flavonoids (cyanidin, petunidin, delphinidin), flavonols (myricetin, quercetin, kaempferol, gallic acid), flavanols (catechins, epicatechin), and tannins (ellagitannins and phenolic acid) (Dutta Gupta et al. 2019; Skrovankova et al. 2015). Light stress promotes the biosynthesis of these compounds. As abiotic stress, LEDs induce the change of phenolic metabolism of postharvest fruits and vegetables (Table 2). For fruits and vegetables, this stimulatory influence was likely to increase the total phenolic content over a long time. LEDs as a source of light with high photosynthetically active radiation efficiency induces responses through photoreceptors (blue light) (Wang et al. 2009), as well as phytochrome (red light) (Zhan et al. 2012a, 2012b), which are involved in the accumulation of compounds such as flavonoids, quercetin glycosides, or kaempferol. So, blue light plays a significant role in activating a biosynthetic pathway to produce phenolic compounds in the fruit. It regulates and stimulates the enzymes such as phenylalanine ammonia-lyase (PAL) associated with the synthesis and accumulation of secondary metabolites (Wang et al. 2009). Red light helps in enhancing the photosynthetic ability and induces photophosphorylation for stomatal opening. It converts the phytochrome from an inactive state to active form and regulates the accumulation of phytochemicals such as tocopherols and terpenes (Zhan et al. 2012a, 2012b). Additionally, light affects the expression of genes encoding enzymes, including phenyl ammonia-lyase (PAL), chalcone

synthase, and flavanone-3-hydroxylase, among others, involved in various processes (Dutta Gupta 2017).

In blueberries fruit, treatment with LEDs blue light (470 nm) significantly increases the total phenolic content at a fluence rate of 40 W m^{-2} after treatment (Xu et al. 2014a, 2014b). In addition, After 3 days of red (630 nm), blue (463 nm), and green treatment (520 nm) at a fluence rate of 20 W m^{-2} in the blueberry (*Vaccinium*) fruit, the content of non-flavonoids including ascorbic, chlorogenic, caffeic acid, and rutin in blueberries showed a maximum increasing trend overall. However, the content of phenolic compounds was significantly increased (Kim et al. 2011). Similar results have been reported for immature broccoli treated with blue (660 nm) LEDs, showing a positive effect on the phenolic compounds within 7 days of storage (Zhan et al. 2012a, 2012b). Some recent studies have shown that LED treatment increases the phenolic content in blueberries at 12 and 24 h (Patel 2014). Also, several studies have reported that the application of blue (450 nm, 440 nm, 450 nm, 470 nm, 456 nm, 405 nm, 465 nm, and 460 nm) LED light enhanced the phenolic content during storage of Tartary buckwheat sprouts (*Fagopyrum* sp.) (Thwe et al. 2014), grape (*Vitis* sp.) (González et al. 2015), citrus fruit (*Citrus* sp.) (Ballester and Lafuente 2017a), Chinese foxglove (*Rehmannia* sp.) (Ahn et al. 2015), cherry tomato (*Solanum* sp.) (Kim et al. 2014), kalanchoe pinata (Nascimento et al. 2013), strawberry fruit (*Fragaria* sp.) (Choi et al. 2013), and lettuce (*Lactuca* sp.) (Son and Oh 2013). The increased contents of phenolic, ascorbic acid, and acidity were observed in immature strawberry fruits (*Fragaria* sp.) treated with blue (λ = 470 nm) LED light at a fluence rate 40 W m^{-2} for 12 days at 5 °C, as compared with control samples; also, the sugar content was significantly decreased during the initial 6 days of treatment in both the control and treated samples, followed by an increase in the later stage of storage (Kim et al. 2011). After 2 days of LED treatment in strawberries, the content of total phenol showed an increasing trend overall compared with the untreated samples (Kim et al. 2011; Wang et al. 2009). Furthermore, the significant increase in the phenolic compound could be attributed to the substantial decrease in acidity and organic acids over time, which aid in the provision of carbon skeletons for the formation of phenolic compounds (Wang et al. 2009). Similarly, the application of blue (436 nm), green (524 nm), and red (665 nm) LEDs on cabbage *Brassica oleracea* L.) vegetable inhibited the increase of phenolic content, total chlorophyll, and vitamin C during postharvest storage (Lee et al. 2014a, 2014b). On the other hand, UV-LED treatment increases the production of flavonoids content (Yang et al. 2019).

Anthocyanin Content

Different fluence rates and wavelengths affect the anthocyanin content of fruits and vegetables during the postharvest period

Table 2 Effect of LED treatment on the secondary metabolites of fruits and vegetables during postharvest storage

Treated fruit/vegetable	LED types	Treatments	Results	Reference
Blueberries (*Vaccinium*)	Red (630 nm), blue (463 nm), and green (520 nm)	3 days of treatment at 20 °C at a fluence rate of 20 W m^{-2}	After 3 days of LED treatment, the content of non-flavonoids, including ascorbic, chlorogenic, caffeic acid, and rutin in blueberries, showed a maximum increasing trend overall. However, the content of phenolic compounds was significantly increased.	Kim et al. 2011
Immature strawberries (*Fragaria ananassa*)	Blue (470 nm) LEDs	12 days of treatment at a fluence rate 40 W m^{-2}	After 4 days of LED treatment, the content of total phenolic was found to increase by 13% for 4 days at 5 °C	Kim et al. 2011
Immature broccoli	Blue (525 nm) LEDs	7 days of treatment at 2 °C at a fluence rate of 20 W m^{-2}	After 7 days of LED treatment, the content of total phenolic was increased by 1.8% than the control untreated sample	Zhan et al. 2012a, 2012b
Blueberries (*Vaccinium*)	Blue (470 nm), red (525 nm), and green (630 nm)	10 days of treatment at a fluence rate of 20 and 60 W m^{-2}at 2 °C and 40 W m^{-2} at 21 °C	Blue, red, and green LED treatment, both increased the content of anthocyanin in blueberries fruits for 10 days at 2 °C and 21 °C	Shi et al. 2014
Sweet cherries (*Prunus avium L.*)	UV-B (310 nm), blue (450 nm), a combination of white, blue and green LED light (450, 473, and 532 respectively)	10 days of treatment at a fluence rate of 23, 0.046, 3.6, and 0.02 W m^{-2} at 1 ± 0.5 °C	Blue LED treatment, increased the content of anthocyanin in sweet cherries for 10 days at1 ± 0.5 °C (cyaniding 3 Oglucoside, cyanidin 3-O-rutinoside) and significantly influenced the CIE color parameters. Furthermore, a Combination of white-blue-green light provoked similar but less pronounced effects, while UV-B light was similar to Control untreated sample. Blue and white-blue-green light treatment increased the phenylalanine ammonia-lyase activity. Light irradiation had no significant impact on ascorbic acid and the phenolic profile after 10 days of storage.	(Kokalj et al. 2019)
Grape berries (*Vitis labruscana Bailey cv 'Campbell Early' and 'Kyoho'*)	Blue LED light (445 nm)	9 days of treatment at a fluence rate of 80 W m^{-2}at 15–25 °C	Blue LED treatment enhances the content of anthocyanin for 9 days at optimal temperature 15–20 °C without a decline in titratable acidity and berry weight. The expression levels of anthocyanin biosynthesis-related genes also increased significantly and co-ordinately by light and temperature.	(Azuma et al. 2019)
Strawberry (*Fragaria × ananassa*) fruit	Red, yellow, green, blue, and white LED	7 days of treatment at a fluence rate of 520 W m^{-2}at 30 °C	Red and yellow LED treatment maintained high significant increased in total anthocyanin content at 7 days; green, blue, and white LED treatment both reduce the total anthocyanin content at 30 °C	(Miao et al. 2016)
Red Chinese sand pears fruit (*Pyrus pyrifolia*Nakai)	White LEDs (765 nm) and UV-B LED (315 nm)	10 days of treatment at a fluence rate of 532 and 270 W m^{-2} at 32 °C	White and UV-B LED treatment enhanced the accumulation of anthocyanin content for 10 days at 32 °C compared with the control untreated sample.	(Sun et al. 2014)

Table 2 (continued)

Treated fruit/vegetable	LED types	Treatments	Results	Reference
Grape Berries (*Gros Colman*)	White (352 nm) and UV (530 nm) LEDs	72 h of treatment at a fluence rate of 20, 24, and 60 W m^{-2} at 25 °C	After 72 h treatment, total anthocyanin content (TAC) was markedly increased by white light. However, Under UV LED, a considerable amount of TAC also accumulated relative to dark conditions. As white and UV LED intensities increased, TAC gradually enhanced, but this promoting the effect of light on the accumulation of anthocyanin was saturated at 60 W m^{-2} for white and 24 W m^{-2} for UV.	(Kataoka et al. 2004)
Octaploid strawberries (*Fragaria ananassa*) fruit	White LEDs	8 days of treatment at a fluence rate of 110 W m^{-2} at 23 °C	White LED treatment controlled the content of anthocyanin biosynthesis via activation of FaMYB10 expression. Furthermore, FaMYB10 accelerated anthocyanin synthesis of pelargonidin 3-glucoside and cyaniding 3-glucoside during strawberry fruit ripening for 8 days at 23 °C.	(Kadomura-Ishikawa et al. 2015)
Grape berries (*Vitis × labruscana*)	Blue (460 nm) and red (640 nm)	24 h of treatment at a fluence rate of 41 and 42 W m^{-2}	Blue and red LED treatment significantly increases the content of anthocyanin in berry grape for 24 h compared with the control sample; however, the content of the expression of anthocyanin biosynthesis-related genes, including VlMYBA1-3, VlMYBA2, F3'5'H, and UFGT, was higher in the treated sample than in control.	(Azuma et al. 2012)
Kyoho' grapevines (*Vitis labrusca × V. vinifera*)	Red (660 nm) and blue (450 nm) LEDs	10 days of treatment at a fluence rate of 50 W m^{-2} at 35 °C	Blue and red LED treatment increases the anthocyanin accumulation and enhanced the expressions of VvUFGT, VlMYBA1^{-2}, and VlMYBA2 for 10 days at 35 °C	(Rodyoung et al. 2016)

(Table 2). However, at the postharvest stage, minimal studies have examined the effect of light on anthocyanin content (Kim et al. 2011). LEDs modulate anthocyanin biosynthesis by controlling the expression of anthocyanin synthesis genes in some fruit such as Chinese bayberry fruit (*Myrica rubra Sieb*) and immature strawberry (*Fragaria* sp.) (Shi et al. 2014). In addition, the application of blue (470 nm), red (525 nm), and green (630 nm) LED treatment at a fluence rate of 20 and 60 W m^{-2} and 40 W m^{-2})increased the content of anthocyanin in blueberries fruits for 10 days at 2 °C and 21 °C (Shi et al. 2014). Similarly, the application of UV-B (310 nm), blue (450 nm), a combination of white, blue and green LED light (450, 473, and 532 respectively) at a fluence rate of 23, 0.046, 3.6, and 0.02 W m^{-2} increased the content of anthocyanin in sweet cherries fruit for 10 days at 1 ± 0.5 °C (cyaniding 3 Oglucoside, cyanidin 3-O-rutinoside) and significantly influenced the CIE color parameters. Furthermore, a combination of white-blue-green light provoked similar but less pronounced effects, while UV-B light was similar to the control untreated sample (Kokalj et al. 2019). Also, some studies have reported for red-leaf cabbage (*Brassica oleracea L.*), buckwheat sprouts (*Fagopyrum* sp.), red leaf lettuce (*Lactuca* sp.), and Chinese kale sprouts (*Brassica* sp.) with red, blue light, and far-red light LEDs maintaining the green color during the postharvest period (Seo et al. 2015; Shi et al. 2014). In the strawberry fruit, anthocyanin content increased during LED treatment compared with the control samples (Xu et al. 2014a, 2014b). Similar results were also reported for Chinese bayberries (*Myrica rubra Sieb*) at 40 W m^{-2} for 8 days, where blue light treatment significantly increased the anthocyanin content (Shi et al. 2014). Conversely, blue LED treatment enhanced the anthocyanin content of strawberry fruit both at the ripening stage and during postharvest storage (Bantis et al. 2016; Kadomura-Ishikawa et al. 2013; Xu et al.

2014a, 2014b). In the previous study, treatment with blue light LEDs shown to induce anthocyanin accumulation and total flavonoid content in Chinese herbal medicine during storage (Ren et al. 2014) and Chinese kale fruit (*Brassica* sp.) (Qian et al. 2016). Nevertheless, it has been reported that LED treatment has a positive influence on the anthocyanin accumulation in grapes (*Vitis* sp.) and leaf baby lettuce (*Lactuca sativa*) (Kondo et al. 2014; Samuoliene et al. 2012).

The effect of different LED treatments blue, red, and green (385 nm, 470 nm, 525 nm, and 630 nm) in immature strawberries (*Fragaria ananassa*) at 5 °C for 4 days was reported compared with control samples (Kim et al. 2011). The anthocyanin content showed a significant increase by 21% in the treated strawberries during storage compared with the untreated controls, as a result of variable light wavelengths, which resulted in an increased of anthocyanin via the expression and enzymatic activities of genes such as chalcone isomerase (FaCHI), flavanone 3-hydroxylase (FaF3H), and anthocyanidin synthase (FaANS) (Kim et al. 2011). Additionally, when photoreceptors respond to light signals, they coordinate anthocyanin biosynthesis. compared with green and red LEDs, phototropin such as FaPHOT2 respond to blue LEDs mostly involved in inducing flavonoid pathway gene expression for the accumulation of anthocyanin and other flavonoids (Kadomura-Ishikawa et al. 2013). Similarly, the application of blue LED light at a fluence rate (40 W m^{-2}) for 8 days on Chinese bayberries fruit (*Myrica rubra*) inhibited the increased of anthocyanin content by 1.8% compared with the untreated control samples (Gupta et al. 2017; Shi et al. 2014). Blue light induces the expression of genes involved in the synthesis of pigments such as anthocyanin, including MrMYB1, MrANS, MrF3H, and MrDFR1 (Gupta et al. 2017; Shi et al. 2014).

Influence of LEDs (NBI) on Nutritional Parameters in Postharvest Fruits and Vegetables

Light stimulates the making of several secondary metabolites, nutrients content as well as an antioxidant which supply (ROS) in the course of photosynthesis (Darko et al. 2014). LEDs intensify the redolent characteristics of fresh horticultural products (Colquhoun et al. 2013), also improve the nutritive value of horticultural crops at the postharvest level, and increase the accumulation of vitamin C, anthocyanin, and total phenolic compounds (Table 3) (Dutta Gupta et al. 2017a; D'Souza et al. 2015). Thus, the treatment of fruit with LEDs of different light (wavelength) helps to maintain the nutritional quality in the postharvest stage (Samuoliene et al. 2013). The effect of the different types of LEDs diverse for a variety of fruits and vegetables, affecting their nutritional value and thereby affecting their functional components and quality (Muneer et al. 2014). The use of LEDs has made the application of monochromatic light convenient with well-defined

wavelengths and emission intensities. Thus, blue (400-470 nm) and red (600-650 nm) LEDs reported having a significant effect on nutritional value (Colquhoun et al. 2013; Holopainen et al. 2018; Taulavuori et al. 2017). For instance, blue light is associated with its effect on various metabolic pathways and accumulation of phenolic compounds, carotenoid, anthocyanin, ascorbic acid, and polyphenols (Taulavuori et al. 2017). In contrast, red light regulates the concentration of phytochemicals like terpenes, sesquiterpenes, and tocopherols in fruits and vegetables (Holopainen et al. 2018). The influence of different types of LEDs (wavelength) on fresh horticultural produce varies because of the impact generated by the lights on the specific receptors in fruits and vegetables (Samuoliene et al. 2013). Kitayama et al. (2019), studied the effect of LED light superiority, fluence rate, and photoperiod on the nutritional increase in many fruits and vegetables in controlled conditions. In general, studies have shown that LED treatment of different colors red (665 nm), blue (436 nm), green (524 nm), and white (375 nm) improve the nutritional quality and other bioactive compounds of some harvested fruits and vegetables during the postharvest period such as Chinese bayberry fruit (*Myrica rubra Sieb*), cabbage (*Brassica oleracea L.*), broccoli (Brassica oleracea), romaine lettuce (*Lactuca* sp.), spinach *Spinacia oleracea*), and pea seedling (Kanazawa et al. 2012; Lee et al. 2014a, 2014b; Lester et al. 2010; Zhan et al. 2012a). It also reported that during postharvest storage, chlorophyll, vitamin C, and total phenolic content were significantly increased by LED light (Zhan et al. 2012b). Consequently, the use of a particular wavelength supports the initiation of responses in fruits and vegetables, which may lead to the enrichment of functional compounds (Table 3). These findings demonstrated that the nutritional value of fruits and vegetables is enhanced by the application of LEDs of different colors/wavelengths during postharvest storage. However, ultraviolet (UV) LEDs are not part of the visible spectrum; they are suited for postharvest storage, improving nutritive value and retarding microbial growth in fruits and vegetables (Yang et al. 2019). The higher increase in quercetin-glycoside was observed in garden pea sprouts and watercress by UV-A LED (375 nm) at a fluence rate of 33 W m^{-2} for 5 days (Kanazawa et al. 2012). Also, proper UV LED exposure improved phytochemical traits of fruits and vegetables (Luksiene and Zukauskas 2009).

The precise biological processes of how nutrients improved through light are not fully understood. But current studies seem to move towards tracing the modifications in terms of biochemical response and comparing in nutrition with an expression of the gene via techniques like real-time- quantitative reverse transcription-polymerase chain reaction (qRT-PCR) investigation (Park et al. 2020). Consequently, the tractability in modification LEDs (optimum spectral composition) would be convenient in discovery the (OSP) of light for fresh horticultural crops, and well understanding of biological responses

Table 3 Effects of LED treatment on the nutritional content of fruits and vegetables during postharvest storage

Treated fruit/vegetable	LED types	Treatments	Results	Reference
Garden pea sprouts (*Pisum sativum L.*) and watercress (*Nasturtium officinale R. Br.*)	UV-A LED (375 nm) LED	5 days of treatment at a fluence rate of 33 W m^{-2}	The higher increase in quercetin-glycoside was observed at the end of treatment compared with control untreated sample	(Kanazawa et al. 2012)
Broccoli (*Brassica Oleracea L. var. italica*)	Red (660 nm)	4 days of treatment at a fluence rate of 50 W m^{-2}	After 4 days red LED treatment, the content of ascorbic acid increased compared with control sample	(Ma et al. 2014)
Cabbage (*Brassica oleracea L.*)	White, Blue (436 nm), Green (524 nm) Red (665 nm)	Continues	Both LED treatments increased the content of total chlorophyll, vitamin C, and total phenolics compared with a dark control. Green LED was most effective for increasing chlorophyll content while blue LED increased vitamin C. All LED treatments increased phenolic content. Moisture content for all treatments decreased by less than 5% only, and pH increased at the same rate for all treatments	(Lee et al. 2014a, 2014b)
Grape berries (*Vitis labruscana Bailey cv 'Campbell Early' and 'Kyoho'*)	Blue (440 nm)	5 days of treatment at a fluence rate of 40 W m^{-2}	After 5 days of red LED treatment, the concentration of stilbene compounds in the skin increased significantly compared with non-treated (control) sample	(Ahn et al. 2015)
Lamb's lettuce (*V. olitoria L. Pollich*)	White LEDs	6 days of treatment at a fluence rate of 1.4 W m^{-2}	A slighter decrease of carotenoids content was observed at 5 °C after 6 days of storage compared with the dark control	(Braidot et al. 2014)
Lettuce (*Lactuca sativa*), Butterhead and iceberg	Red (660 nm) and Blue (455 nm)	14 of treatment at a fluence rate of 5 W m^{-2}	Red and blue LED treatment significantly increased the content of glucose, fructose, and sucrose in butterhead lettuce after 7 days, and iceberg lettuce with blue LED treatment after 14 d	(Woltering and Seifu 2015)
Peach (*Prunus persica cv. Jinli*)	Blue (470 nm)	20 days of treatment at a fluence rate of 40 W m^{-2}	After 20 days of blue LED treatment, the content of total carotenoids, zeaxanthin, and b-carotene, b-cryptoxanthin, and lutein content increased compared with control untreated.	(Shi et al. 2014)
Mature green tomatoes (*Solanum Lycopersicum L. cv. Dotaerang*)	Blue (440–450 nm) and red (600-650 nm) LEDs	21 days of treatment at a fluence rate of 85.7 W m^{-2}	After 21 days of blue LED treatment, the content of glutamic acid and c-butyric acid significantly increased compared with the control untreated sample and red LED light.	(Dhakal and Baek 2014)
Satsuma mandarins (*Citrus unshiu Marc.*)	Red (660 nm)	4 days of treatment at a fluence rate of 50 W m^{-2}	After 4 days of red LED treatment, the content of total carotenoids, beta-cryptoxanthin, all-trans-violaxanthin, 9-cis-violaxanthin lutein, and beta-carotenoid were simultaneously increased compared with non-treated (control) sample.	(Ma et al. 2014)
Satsuma mandarin (*Citrus unshiu Marc.*)	Blue (470 nm) LED	28 days of treatment at a fluence rate of 50 W m^{-2}	Blue LED treatment increased the content of total carotenoid compared with the control sample. However, the content of beta-carotene, beta-cryptoxanthin, 9-cis-violaxanthin, alpha-carotene, lutein, and total carotenoid were decreased by 14 days and increased after 28 days of storage.	(Zhang et al. 2015)

Table 3 (continued)

Treated fruit/vegetable	LED types	Treatments	Results	Reference
Valencia orange (*Citrus sinensis* Osbeck)	Blue (470 nm) LED	28 days of treatment at a fluence rate of 100 W m^{-2}	Blue LED treatment increased the content of total carotenoid in the first 12 days of storage and kept constant after that. Furthermore, after 28 days, the content of beta-cryptoxanthin increased, while the contents of beta-carotene, 9-cis-violaxanthin, alpha-carotene, lutein, and total carotenoid content decreased.	(Zhang et al. 2015)
Tatsoi (*B. Rapa var. rosularis*, Rozetto)'	Blue (445 nm) and red (640 nm) LEDs	20 days of treatment at a fluence rate of 300 W m^{-2} at 21 °C	Both the treatment increased the chlorophyll content, total protein, and essential amino acid contents after 20 days of the storage period.	(Viršilė et al. 2019)
Green asparagus spears (*A. officinalis* L. var.)	Green (550 nm, blue (440 nm) and red (630 nm) LEDs	9 days of treatment at a fluence rate of 100, 116, and 117 W m^{-2} at 4 °C	Both the LED treatment and intensities increased the content of ascorbate, chlorophyll a and b, carotenoids, anthocyanins, and lignin for 9 days at 4 °C.	(Mastropasqua et al. 2016)
kale sprouts (*Brassica oleracea* L. var. *sabellica* L.)	Combination of red, green and blue (RGB) LED, fluorescent bulb (2715 K), cold white (10278 K) and warm white (3073 K) LEDs, Traditional (incandescent) light bulb (2612 K) and	24 h of treatment	After 24 h treatment, The highest concentrations of chlorophylls, β-carotene, lutein, neoxanthin ascorbic acid, and violaxanthin were found in cotyledons of sprouts treated under RGB LED light. The highest contents of protein and total thiocyanates were observed in sprouts treated with incandescent light. However, the conventional bulb led to the lowest yield as well as the smallest amounts of chlorophylls, β-carotene, lutein, and neoxanthin after storage.	(Fiutak and Michalczyk 2020)

to various spectral composition (SP) of light. This will permit growers and vendors to exploit the light schemes that increase the nutritive trait of their fresh produce in the future.

Influence of LEDs (NBI) on the Ripening Process in Postharvest Fruits and Vegetables

Ripening is the most evident phenomenon defining the storage life of fresh produce during the postharvest period. Providing palatability in fruits and vegetables, a proper ripening stage is a critical step in the growth phase (Aked 2002). However, it causes changes in acidity, firmness, sweetness, color, aroma, and nutritional composition of fruits and vegetables, which can be both desirable (consumer acceptability) and undesirable (towards senescence). Factors such as the respiration rate, chlorophyll loss, degradation of complex molecules (organic acids, pectin, cellulose, etc.), and changes in biochemical and physiological properties of tissue cells affect this process (Lichtfouse 2015). Similarly, light is also an important parameter affecting the ripening of fruits and vegetables. Light accelerate or postpone the maturation of fruits and vegetables by controlling the amount of ethylene production.

LEDs influence the rapid ripening of crops species as a result of respiration and ethylene output amplification (Xu et al. 2014a, 2014b). Throughout this process, ethylene production is triggered by various parameters, including LED light, which can affect the yang cycle of ethylene synthesis (Gong et al. 2015). In this metabolic pathway, receptors cause an increase or decrease in the expression of auxin-related or photosynthetic genes that interfere with the ripening process (Tadiello et al. 2016). In addition to ethylene production, pigment accumulation is another relevant regulatory event associated with fruit ripening. An increase in gene expression and corresponding mutations in fruit resulted in an intensification of carotenoid and flavonoid concentrations. LED light interacts with these gene modifications through light signal transduction and photo-oxidation processes, targeting the overall ripening phase of horticultural crops (Adams-Phillips et al. 2004). The influence of LED light depends on the type of fruits and vegetables, light intensity, wavelength, and treatment parameters. Many studies suggested the use of LED sources increased the ripening process of fruits and vegetable during storage (Table 4), which aid in enhancing the storage life and quality of fresh produce for consumers.

The effects of blue and red LED treatments (440–450 nm and 650–660 nm) on green tomatoes (*Solanum Lycopersicum*) at 85.72 and 102.70 $\mu E\ m^{-2}\ s^{-1}$ for 7, 14, and 21 days, respectively, have been reported (Dhakal and Baek 2014). The blue light treatment was able to retard the red color in tomatoes compared with the control and the red light. After 14 days of treatment, the maturation of red color in green tomatoes treated with blue LEDs was reduced compared with the red light (Dhakal and Baek 2014). However, after 21 days of storage, almost the same observations were obtained irrespective of the type of treatment. Similar results have been obtained for lycopene, where blue LEDs was effective in delaying the development of pigment in tomatoes compared with those kept in the dark and those treated with red LEDs, demonstrating higher levels of lycopene (Dhakal and Baek 2014). This sequence of trials performed by (Dhakal and Baek 2014) confirmed that yellow color was more prominent in tomatoes treated with blue light.

Additionally, with fruit ripening, firmness tends to decrease, making fruit more palatable but reducing the storage life. In this research, firmness has been reduced significantly with the increase in storage time for all treatments. These findings showed that blue light was able to delay firmness compared with red light and control samples, helping to increase the shelf life of fruit during storage (Dhakal and Baek 2014). In another study conducted by Xu et al. (2014a, 2014b), blue LED light (470 nm) treatment was applied to immature strawberries (*Fragaria ananassa*) at 40 W m^{-2} for 12 days, which resulted in an increase in color development after 4 days of storage, implying that the ripening process accelerated in strawberries. The respiration rate was significantly decreased during the initial 2 days of storage, followed by a gradual increase in the control and blue light treatment groups when compared with the control untreated samples. Also, ethylene production and higher respiration process were significantly enhanced in the samples treated with blue light LEDs (Xu et al. 2014a, 2014b).

The effect of blue light (470 nm) on the ripening process of peaches (*Prunus persica cv.*) was evaluated by Gong et al. (2015), who observed that 15 days of treatment at 10 °C at a fluence rate of (40 W m^{-2}) accelerated the ripening process during storage. Ethylene synthesis was significantly increased in fruit after illumination with blue light due to an increase in the activity of lipoxygenase, 1-aminocyclopropane-1-carboxylic acid, ethylene response factors, ethylene sensors and ethylene receptors (Gong et al. 2015). Similar results also reported for sweet oranges, in which blue (450 nm) LED treatment at a fluence rate between 60 and 630 (W m^{-2}) at 20 °C led to an enhancement of ethylene production during postharvest storage (Ballester and Lafuente 2017). This result implies that blue light treatment accelerated the ripening process in citrus fruits (*Citrus* sp.) by increasing the synthesis of ethylene at higher intensities, as in the case of peaches (Gong

et al. 2015) and strawberries (Xu et al. 2014a, 2014b). Blue LED treatment enhances the ripening of fruit during storage in conjunction with the initiation of synthesis of gama-tocopherol, alper-tocopherol, lutein, and beta-carotene compared with the control untreated samples (Xu et al. 2014a, 2014b). Also, blue LED treatment stimulates the expression of genes, like PpACS3 and PpACO1, which indicates the molecular mechanism of LED-mediation fruit ripening (Gong et al. 2015). Overall, the studies suggest that the application of LEDs at specific wavelengths and fluence rates is an effective approach for regulating the processes of ripening and is also used to accelerate or retard the ripening process during the postharvest stage. In conclusion, the influence of other LEDs of different wavelengths and fluence rates should be studied on other climacteric fruits and equated the impact of secondary ripening in fruit presented in the literature.

Influence of LEDs (NBI) on Delaying Senescence in Postharvest Fruits and Vegetables

Senescence is an undesirable phenomenon in some horticultural crops, instigating deterioration of fresh produces, thus results in a loss of nutritional and commercial value (Pogson and Morris 2003). The mechanism of the senescence process involves the allocation of nutrients from one part of the tissue to another and modification in both the physical characteristics and biochemical attributes of the cell structure (Aked 2002; Buchanan-Wollaston 2007). Moreover, oxidative metabolism results in the production of (ROS) in fruits and vegetables. Overproduction and accumulation of ROS facilitate the degradation of membrane lipids, proteins, macromolecules, and enzymatic changes, causing cell death (Drobot et al. 2013). Additionally, structural changes, chlorophyll degradation, protein and macromolecule breakdown, and gene expression in horticultural crops cells are the factors responsible for the trait, texture, and shelf life deterioration of fruit. Simultaneously, these lead to the death of cells (Aked 2002; Buchanan-Wollaston 2007). Cytokinins, gibberellins, and some auxins slow down senescence while other phytohormones such as ethylene, abscisic acid, and jasmonates increase senescence during postharvest storage of fruits and vegetables (Pogson and Morris 2003).

LEDs have significant utility in delay senescence as the optimum amount of light of a specific wavelength and frequency affects stress conditions in fruits and vegetables (Noodén and Schneider 2003). The point at which the light required for the pace of photosynthesis and respiration becomes adequate is called the light compensation point, which defines this optimum level of light intensity. Senescence occurs below or above this illumination level of brightness (D'Souza et al. 2015). Mostly, blue LEDs (460 nm) and white

Table 4 Effects of LED treatment on the accelerating/ delaying of ripening in postharvest fruits and vegetables

Treated fruit/vegetable	LED types	Treatments	Results	Reference
Sweet oranges (*Citrus × Sinensis*)	LED (450 nm)	3 to 18 days of treatment at a fluence rate between 60-630 W m^{-2} at 20 °C	High intensities of blue LED treatment accelerated the ripening process in citrus fruits by increasing the synthesis of ethylene.	(Ballester and Lafuente 2017)
Peaches (*Prunus persica cv.*)	Blue LED (470 nm)	15 days of treatment at a fluence rate of 40 W m^{-2} at 10 °C	Blue LED treatment accelerated the ripening process of peaches and increased ethylene synthesis, and it significantly increased gene expression, including lipoxygenase, 1-aminocyclopropane-1-carboxylic acid, ethylene response factors, ethylene sensors, and ethylene receptors, for 15 days at 10 °C.	(Gong et al. 2015)
Green tomatoes (*Solanum Lycopersicum*)	Blue (400- 450 nm) and red (600-650 nm) LEDs	7, 14 and 21 days of treatment at fluence rates of 85.72 and 102.70 μE m^{-2} s^{-1} at 25 °C	Blue LED treatment retarded the red color in tomatoes compared with the red light and control. After 21 days both blue and red LED, delaying the ripening and softening of green tomatoes.	(Dhakal and Baek 2014)
Satsuma Fruit (*C. unshiu Marc. Aoshimaunshu'*)	Red LEDs (660 nm)	4 days of treatment at a fluence rate of 12 W m^{-2}	Red LED treatment accelerated the color development in the rind of irradiated fruit compared with those stored in darkness.	(Ma et al. 2014)
Green Tomato (*Solanum Lycopersicum L.*)	Red LED (400–700 nm) and UV LED (5.53 kJ m^{-1})	20 days of treatment at a fluence rate of 113 W m^{-2} at 20/ 19 °C	After treatment, non-treated (control) fruit ripened within 15 days while fruit exposed to the red light and a combination of red light with UV radiation required 5 days less to reach the same maturity level. However, the exposure to red light alone or in combination with UV significantly increased the content of lycopene, β-carotene, total flavonoids, and phenolics for 20 days at 20 °C.	(Panjai et al. 2017)
Green Tomato (*Solanum Lycopersicum L.*)	Red LEDs (665 nm)	20 days of treatment at a fluence rate of 113 W m^{-2} at 20/ 19 °C	After 20 days of red LED treatment, the content of lycopene, β-carotene, total phenolic content, total flavonoid concentration and antioxidant activity in green tomato showed a significantly increased trend overall compared with non-treated sample (control). However, continuous red light irradiation accelerated the ripening of green tomatoes during the storage period.	(Panjai et al. 2019)
Immature strawberries (*Fragaria ananassa*)	Red (385 nm), blue (470 nm), green (525 nm), and white (630 nm)	4 days of treatment at 5 °C	Red, green and white LED treatment significantly increased the content of anthocyanins after 3 to 4 days at 5 °C, which was slightly less than the effect of blue LED treatment and control untreated samples. Blue LED was more effective in increasing the content of anthocyanin and the color intensity of strawberries.	(Kim et al. 2011)
Unripe strawberries (*Fragaria ananassa*)	Green LED (500–600 nm)	6 days of treatment at a fluence rate of 98 W m^{-2}	Green LED treatment improved a deep red color faster due to the production of anthocyanins content.	(Kanazawa et al. 2012)
Strawberry (*Fragaria ananassa*)	Blue (470 nm) LEDs	12 days of treatment at 5 °C at a fluence rate of 40 W m^{-2}	Blue LED treatment, increased in respiration, ethylene production, faster development of red color, total antioxidant activity, and antioxidant enzyme activity compared with control for 12 days at 5 °C	(Xu et al. 2014a, 2014b)

LED (420–700) lights are known to control the senescence by lowering the pigment degradation and affecting the transpiration and respiration processes (Hasperué et al. 2016a, 2016b). Blue LED light reduces the moisture content of fresh produce during postharvest storage of crops, while the red LED light supports the moisture of tissues of horticultural crops (Dutta Gupta 2017; Muneer et al. 2014; Massa et al. 2010). Both blue and red LEDs delay the senescence of vegetables and fruit by decreasing the production of ethylene and ascorbates by regulating other hormones (Ma et al. 2014; Xu et al. 2014a, 2014b). Light intensities below the light compensation point resulted in a net loss of sugar in fruits and vegetables, but not under all circumstances (Eldeen Nour Eldaime Elgimabi 2017). The study showed that irradiated horticultural crops with a light intensity below light compensation resulted in better storage conditions than those in the dark. In another study, a light intensity below the light compensation point below (30 W m^{-2}) was irradiated on Chinese kale, basal leave, and fresh-packaged spinach leaves recorded higher nutrients and bioactive compounds in the light than in the dark (Costa et al. 2013; Lester et al. 2010).

Light quality increases the production of nutrients and delay senescence during the storage of fruits and vegetables (Braidot et al. 2014). Low intensity has been reported to improve the postharvest attribute of fruits and prevent senescence during storage than those stored in the darkness (Braidot et al. 2014). Senescence may vary in criteria with different vegetables, and loss of chlorophyll and wilting usually indicates senescence in leafy vegetables. Also, in broccoli and Mature kale, treatment with blue LEDs (21.8 W m^{-2}) within 1 to 2 days at 20 °C reduces the senescence as compared with those in the dark (control) (Zhan et al. 2012a). Furthermore, several studies have reported that the application of LEDs postpone senescence and prevent yellowing in some fruits and vegetables including cabbage (*Brassica oleracea L.*), mandarin fruit (*Citrus reticulate*), spinach leaves (*Spinacia oleracea*), Chinese kale (*Brassica* sp.) and kiwifruit (*Actinidia deliciosa*) (Liu et al. 2015; Lester et al. 2010; Zhan et al. 2012a, 2012b). Many studies have been performed in this area to examine the effect of light (variable wavelengths) from LED systems on the rate of senescence and, ultimately, control the quality attributes of fresh horticultural produce (Table 5).

In Brussels sprouts, (*Brassica oleracea gemmifera*), treatment with white and blue LEDs (420–700 nm and 460 nm) significantly increase the contents of chlorophyll and total soluble sugars and weight loss compared with untreated samples of outer leaves after 10 days of treatment (Hasperué et al. 2016a, 2016b). Moreover, Newman and Sherman (1978) reported that illumination with blue light causes maximum absorption of chlorophyll b as light signals are gathered by phototropin, namely phot-1 and phot-2, creating the stimulus. Likewise, the total soluble sugar content was significantly higher in treated internal and external foliage compared with untreated samples. Also, a decrease in sugar content can be due to starvation in leafy vegetables, implying that high sugar content enhances green vegetables (Hasperué et al. 2016a, 2016b). The effect of white and blue LEDs on broccoli (*Brassica oleracea L.*) was studied under the same treatment conditions mentioned above at (20 W m^{-2}) LED treatment showed the smallest quantity of yellowing. At the same time, chlorophyll a/b and carotenoid contents significantly increased in the treated sample and maintained until the end of the storage period, facilitating the preservation of the green color of broccoli (Hasperué et al. 2016a, 2016b). Also, withholding of sucrose, fructose, and glucose was experimental during storage treatment. This phenomenon can be attributed to the ability of blue light to maximize the absorption of lutein and beta-carotene.

Additionally, white and blue LEDs (420–700 nm and 460 nm) also enhanced the expression of genes such as phytoene synthase (PSY), lycopene beta-cyclase (LCYb), and zeaxanthin epoxidase in broccoli (Dean Kopsell and Carl Sams 2013). Moreover, the sucrose content was significantly increased after 35 days in both 5 °C and 22 °C storage, which means that white-blue LEDs were able to regulate the metabolic process. The higher sucrose was detected in the 5 °C storage treatment compared with the elevated temperature of 22 °C because of the lower temperature and lower rate of metabolic activities. All eminence pointers of senescence were better for broccoli irradiated by LEDs compared with the one stored under darkness even up to 42 days when stored at 5 °C. In general, low fluence rates can prevent senescence from continuing, and also can keep the sample as fresh as possible in good commercial value. The study showed that white-blue light treatment of broccoli was effective in delaying yellowing and regulating senescence during postharvest storage (Hasperué et al. 2016a, 2016b).

The effect of red (λ = 660 nm) and blue LED (λ = 470 nm) lights on broccoli (*Brassica oleracea*) have been studied over 4 days of treatment at 20 °C. The samples were compared with those treated with white light (control) to study the effect of different colors. After treatment, the red light was effective in controlling the yellowing of leaves, but the blue light showed no impact on preserving the green color (Ma et al. 2012). The effect of light varies with the absorption effect on chlorophyll, as red and blue light promotes the absorption of chlorophyll a and b, respectively contributing to the accumulation of chlorophyll levels and optimal photosynthetic efficiency (Dean Kopsell and Carl Sams 2013). Also, the effect of red light was more prominent in decreasing ethylene production and increasing in ascorbic acid content compared with the blue LEDs and control samples, demonstrating that as ethylene reduced, the respiration rate also decreased (Ma et al. 2014). Similarly, a rise in ethylene production and respiration rate was reported in strawberries by Xu et al. (2014a, 2014b).

Table 5 Effects of LED treatment on the Senescence in postharvest fruits and vegetables

Treated fruit/vegetable	LED types	Treatments	Results	Reference
Brussels sprouts (*Brassica oleracea gemmifera*)	White (420-700 nm) and blue (460 nm) LEDs	5-10 days of treatment at 22 °C and fluence rates of 20 W m^{-2}	Both white and blue LED treatment increased the chlorophyll content, green leaves, and total soluble sugar content and delayed yellowing in brussels sprouts, and higher weight loss was observed in both treatments for 5 to 10 days at 22 °C.	(Hasperué et al. 2016a, 2016b)
Broccoli (*Brassica oleracea*)	White and blue LED (wavelength not mentioned)	0, 35 and 42 days at 5 °C and 0, 2, 3, and 4 days at 22 °C at a fluence rate of 20 W m^{-2}	Both white and blue light treatment increased the content of chlorophyll and carotenoids in broccoli, increased the total sugar content at 5 °C and 22 °C, and increased the activity of genes such as phytoene synthase (PSY), lycopene beta-cyclase (LCYb), and zeaxanthin epoxidase.	(Hasperué et al. 2016a, 2016b)
Lettuce (*Lactuca sativa*)	White (400-700 nm), green (516 nm), red (630 nm), and blue (450 nm) LEDs	21 days of treatment at 5 °C at a fluence rate of 10 W m^{-2}	All LED treatments significantly reduced yellowing in lettuce after 21 days at 5 °C; white LED treatment significantly increased the chlorophyll content, and blue LED treatment reduced microbial damage and enhanced total soluble sugar after 21 days at 5 °C.	(Kasim and Kasim 2017)
Broccoli (*Brassica oleracea*)	Red (660 nm) and blue (470 nm) LEDs	4 days of treatment at 20 °C at a fluence rate of 50 W m^{-2}	Red LED treatment delayed senescence by controlling yellowing and ethylene production for 4 days at 20 °C, and blue LED treatment showed no effect on preserving green color.	(Ma et al. 2014)
Pakchoi (*Brassica campestris L.* ssp. *Chinensis (L.) Makino var. communis Tsen et Lee*)	White LEDs (448 nm)	7 days of treatment at 20 °C at a fluence rate of 10 W m^{-2}	White LED treatment significantly increased the changes in respiration rate and maintained higher chlorophyll and vitamin C content in pakchoi stored at 20 °C. Furthermore, white LED treatment maintained the levels of gene expression and enzyme activity of peroxidase, catalase, and ascorbate peroxidase and also inhibited the activity expression of several enzymes such as chlorophyllase, chlorophyll-degrading peroxidase, Mg-dechelatase, pheophytinase, and chlorophyll-degrading genes (BrChlase1, BrChlase2, and BrPPH), and increased the expression of the chlorophyll synthetase gene, BrHEMA1 for 7 days 20 °C.	(Zhou et al. 2019)
Pak- choi (*Brassica rapa* ssp. *Chinensis*)	Red and blue LEDs	24 h of treatment at 20 °C at a fluence rate of 0, 10, 35, and 70 W m^{-2}	After the treatment, red LEDs inhibited its senescence, as shown by slower loss of photochemical efficiency and higher contents of chlorophyll, vitamin C, and total soluble proteins. At the same time, blue LED light had a much weaker effect. However, Red light inhibited the expression of putative chlorophyll degradation and senescence-associated genes, while promoting the expression of putative vitamin C biosynthetic genes.	(Shezi et al. 2020)
Broccoli (*B. oleracea var. Italica, cv. You-xiu*)	Red LEDs	5 days of treatment at 20 °C at a fluence rate of 50 W m^{-2}	Red LEDs inhibited yellowing and the degradation of chlorophyll and decreased weight loss and malondialdehyde content in broccoli for 5 days at 20 °C. Red LED treatment significantly increased the activity of the antioxidant enzymes, peroxidase, catalase, and ascorbate peroxidase in broccoli while the expression of the chlorophyll degrading genes, chlorophyllase II, chlorophyllase III, pheophorbide, and oxygenase was suppressed in the early stages of storage. In contrast, no effect on chlorophyllase I observed after 5 days.	(Jiang et al. 2019)

Table 5 (continued)

Treated fruit/vegetable	LED types	Treatments	Results	Reference
Basil (*Ocimum basilicum L.*)	White LEDs	5 days of treatment at 20 °C at a fluence rate of 30–37 W m^{-2}	After 5 days white LED treatment, the low-intensity light (30–37 W m^{-2} during storage at 20 °C is an effective treatment to delay postharvest senescence of basil leaves.	(Costa et al. 2013)
Lettuce (*Lactuca sativa L.*)	White LEDs	7 days of treatment at a fluence rate of 150 W m^{-2} at 6 °C	White LED treatment maintained the high quality of lettuce for 7 days at 6 °C by reducing browning, minimizing weight loss and respiration, and keeping a higher level of photosynthetic capacity compared with untreated samples (control).	(Charles et al. 2018)
Purple kale (*Brassica oleracea var. sabellica*)	White and red LEDs	3 days of treatment at 20 °C at a fluence rate of 20–25 W m^{-2}	White and red LED treatment significantly increase the chlorophyll, protein, antioxidant capacity, and soluble sugar content than non-irradiated (control), maintained high anthocyanins retention and carotenoids during postharvest senescence of kale, decrease the content of phenols for 3 days at 20 °C	(Bárcena et al. 2019)
Broccoli (*Brassica oleracea L. var. italica Plenck*)	White and red LEDs	4 days of treatment at 20 °C at a fluence rate of 20^{-2}5 W m^{-2}	White and red LED treatment reduce chlorophyll *a* and protein degradation, but the red light was insufficient to retained chlorophyll b and phenolics compared with white light treatment for 4 days at 20 °C.	(Favre et al. 2018)

The fruit was illuminated with blue (470 nm) LED light at 5 °C for 12 days and compared with strawberries kept in the dark. A decrease in ethylene production was observed upon an initial treatment, followed by a significant increase from 2 to 6 days of storage.

In lettuce (*Lactuca sativa*), treated with blue ($\lambda = 450$ nm), green ($\lambda = 516$ nm), white ($\lambda = 400\text{-}700$ nm), and red ($\lambda = 630$ nm) LEDs, the red and white light was more effective than the other two colors in preserving the greenness of lettuce leaves (Kasim and Kasim 2017). This finding showed that red light significantly affected the associated receptors. Since red light is part of white light, the effect of preservation for red and white color was observed during the postharvest period. All the treated samples showed reduced yellowing during postharvest storage. After treatment, the content of chlorophyll *a* and *b* showed an increasing trend overall beyond the initial ratio and slowly decreased in pheophytin, hence suggesting a postponed in senescence. However, the degradation of pigment was less when treated with white and red LEDs, lights compared with green, blue LEDs, and control samples. After the experiment, the content of glucose was significantly enhanced during storage with a maximum effect of white LEDs, followed by blue and green LEDs, light (Kasim and Kasim 2017). These studies showed that LEDs, light colors were effective in enhancing the shelf life of lettuce leaves and delaying the senescence compared with control samples during the storage period. Similar results were reported in lettuce at 1.4 W m^{-2} for 8 days, where white LED significantly increased chl *a* and *b* ratio above the initial rate and pulsed

lighting using 16 cycles of 30 min pulses where reduced the degradation of chl *a* and *b* resulted in a slower decline of carotenoids content in lettuce, thereby delaying the loss of postharvest nutritional quality and postponed senescence (Braidot et al. 2014). Also, the application of red LEDs, at a wavelength of 660 nm on lettuce, delayed yellowing during postharvest storage (Holopainen et al. 2018), while the yellow LEDs, suppressed the growth of lettuce, suggesting that the yellow LEDs, decreased photosynthesis (Dean Kopsell and Carl Sams 2013; Ma et al. 2012).

Influence of LEDs (NBI) on Pathogenic Microorganisms in Postharvest Fruits and Vegetables

The diseases caused by fungi during the storage period of fresh horticultural produce will cause a lot of economic losses, which has been the focus of attention among researchers. Currently, chemical synthesizes fungicides are still the best ones, but the application is limited to its safety (Assefa 2019; Xu et al. 2019). LEDs are among the several techniques developed and introduced to reduce pathogenic microorganisms in fruits and vegetables. Upon illumination with LEDs, photosensitizers or photoreceptors absorbs light to form reactive oxygen species that react with the biomolecules to trigger the effect. These reactive oxygen species interfere with the microbial cell structure, causing breakdown and preventing spoilage (Luksiene and

Zukauskas 2009). Moreover, the application of LEDs triggers defense-related gene expression or the accumulation of defense hormones in fruits and vegetables, providing resistance to microbial growth and damage. However, different LED wavelengths initiated different molecular responses in microbial cells (Hasan et al. 2017a, 2017b).

As a residue-free physical sterilization technique, LEDs have been related to the postharvest anti-fungal effects of fruits and vegetables (Table 6) (D'Souza et al. 2015). All along, LEDs have always been exhibited an improved impact on postharvest fungal infections of fruits and vegetables during postharvest storage (Liao et al. 2013). Liu et al. (2011) reported that LED treatment inhibits fungal spoilage conidial germination and sporulation of Colletotrichum on mango fruit. Research showed that blue LEDs at a fluence rate of 40 W m^{-2} decrease rotten areas, mycelial growth, and the formation of various fungi including *Penicillium digitatum*, *Penicillium italicum*, and *Phomopsis citri*, when compared with white LED and dark control (Alferez et al. 2012; Liao et al. 2013). LED treatment with blue (450 nm), red (630 nm), white (400–700 nm), and green (516 nm) light at a fluence rate of 10 W m^{-2} significantly inhibit the decay rate of lettuce during storage (Kasim and Kasim 2017). Likewise, LEDs of blue (410–540 nm), green (47–620 nm), and red (580–670 nm) light at a fluence rate of 40 W m^{-2} for 1 to 2 days inhibit fungal pathogenic microorganisms, including *Penicillium citri*, *Penicillium italicum*, and *Penicillium digitatum* in Fallglo, sweet orange (*Citrus* sp.), tomato (*Solanum Lycopersicum*), and tangerine fruits (*Citrus reticulate L.*) during postharvest storage (Alferez et al. 2012; Ghate et al. 2013; Imada et al. 2014; Liao et al. 2013). Alferez et al. (2012)

reported that the application of blue LEDs during postharvest storage of fruits and vegetables minimize postharvest losses by reducing fungal infections and fruit decay. Also, another study showed that blue LEDs at a fluence rate (40 W m^{-2}) in tangerine fruit (*Citrus reticulate L.*) reduced fungal infection against *Penicillium digitatum* (Alferez et al. 2012). Blue LED treatment of citrus fruits (*Citrus* sp.) for 18 h at a fluence rate of 120 W m^{-2} and 700 W m^{-2} controlled fungal infections by *Penicillium digitatum* and *Penicillium italicum*, thereby inhibiting the germination of spores during storage (Lafuente and Alférez 2015). The study has shown that LED treatment at 461 nm (blue), 521 nm (green), and 642 nm (red) of fruits and vegetables enhanced the antibacterial activity against *Staphylococcus aureus*, *Salmonella typhimurium*, and *Escherichia coli* during storage (Ghate et al. 2013; Koutchma and Popović 2019). Additionally, blue LED treatment (405 nm) at a fluence rate of 50 W m^{-2} for 15 days inhibited bacteria (*Botrytis cinerea*) growth on the leaves of tomato fruit during postharvest storage (Imada et al. 2014).

Trends and Future Perspectives of LED Use During Postharvest Storage

A growing interest in research related to postharvest fruits and vegetables exposed to LEDs has occurred from 2000 to 2019. A review of Science direct databases showed increased use of LEDs in the postharvest preservation of fresh produce (Fig. 2), implying that LEDs are serviceable in the postharvest storage of horticultural crops. The use of nonthermal techniques has been studied to avoid the use of chemicals. The application of

Table 6 Effect of LED treatment on the Microbial Spoilage metabolites of fruits and vegetables during postharvest storage

Treated fruit/vegetable	LED types	Treatments	Results	Reference
Fallglo fruits	Blue (410–540 nm), green (470 – 620 nm), and red (580–670 nm) LEDs	3 days of treatment at 5 °C at a fluence rate of 40 W m^{-2}	LED treatment significantly inhibited the decreased of fungal pathogenic microorganism including *Penicillium digitatum*, *Penicillium italicum*, and *Penicillium citri* in fallglo fruits for 3 days at 5 °C	Alferez et al. 2012
Citrus fruits (*Citrus* sp.)	Blue (461 nm) LEDs	18 h of treatment at 25 °C at a fluence rate of 120 W m^{-2} and 700 W m^{-2}	Blue LED treatment controlled the fungal infections against *Penicillium digitatum* and *Penicillium italicum* in citrus fruits *for* 18 h	Lafuente and Alférez 2015
Satsuma mandarins (*C. unshiu Marc. 'Aoshimaunshu'*)	Blue (465 nm)	8 days of treatment at a fluence rate of 8 and 80 W m^{-2}	Blue LED treatment, decreased the fungal colonization and disease incidence of *Penicillium italicum* on the surface of Satsuma mandarins fruit compared with the dark control	(Liao et al. 2013)
Strawberries (*Fragaria ananassa*)	Deep ultraviolet (272, 289, 293 nm)	9 days of treatment at a fluence rate of 20 W m^{-2}	Mold growth suspected to be *Botrytis cinerea*, was absent in LED-treated samples after 9 days, whereas those stored in the dark had extensive growth after 6 days	(Papoutsis et al. 2019)

LEDs in the postharvest stage has dramatically increased due to its advantages over other types of conventional light (Taulavuori et al. 2017).

The application of LED technology is widely gaining interest due to its enhanced properties over conventional light (Gatamaneni et al. 2020). Moreover, the effects of LED technology on processes such as senescence, ripening, nutritional aspects, improved shelf life, and pathogenic microbial prevention have enormous potential during the postharvest period. Consequently, the approach of the LED system for postharvest activities is in a phase of continuous growth (Abewoy 2018). However, most works in this field are lab-based and need to be applied in the actual food supply chain. Such studies are important to harness the potential of the technology for extended shelf life, provision of quality and safe, fresh produce over long-term storage, as well as long-distance transportation (Taulavuori et al. 2017).

Additionally, with advancements and further studies, the application of LED technology could be a promising approach in developing countries where critical issues are involved in the delivery of quality and safe, fresh produce to consumers. In developed countries, this technology can aid in ensuring wholesomeness and reducing fruit and vegetable losses. This technology can be implemented in retail locations and linked with other parameters, such as temperature or packaging, to increase efficiency (Dueck et al. 2016). Ultimately, further development and scaling up of the LED system to the food industry level swill be of great benefit and importance for postharvest management. Another primary concern for the application of LEDs for postharvest management is the risk assessment of the technology. Studies have revealed that LEDs stimulate the accumulation of phytochemicals in vegetables and fruits, which can be both harmful and beneficial. The production of nitrate, a toxic substance, is primarily
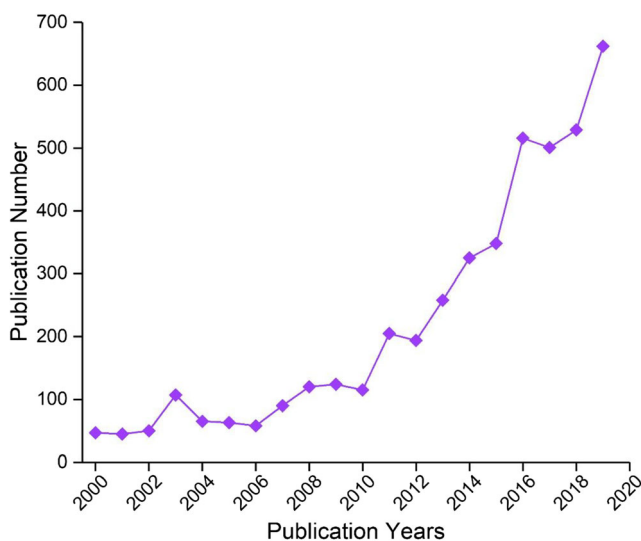
regulated by light quality, especially during artificial lighting in greenhouses (Bian et al. 2014). The effect of light on consumer health and eyes while installing in-store shelves remains to be explored. However, some studies have revealed an influence of blue light (450–475 nm) on the retina and toxicity associated with its use (Bian et al. 2014). Similarly, the effect of light at other wavelengths also needs to be studied to examine the influence on consumer health. Further studies are required in this field to address the emerging concept of applying LEDs in postharvest handling of horticultural crops.

Conclusion

Growers and vendors currently face challenges in maintaining the quality of fresh produce after harvest. Possible ways to circumvent these challenges are to increase the production rate of fruits and vegetables and prevent waste to ensure the provision of quality and safe, fresh produce to consumers. LEDs play an essential role in agriculture and also crucial in the postharvest stage to fulfill the above requirements. The distinctive properties of LEDs make them an outstanding choice. Lights of different wavelengths regulate key photochemical processes in fruits and vegetables, such as photosynthesis and secondary metabolite yields. Similarly, the use of LEDs regulates senescence, controls ripening rates, affect the nutritional quality, and reduce pathogenic microbial spoilage in fresh produce during the postharvest period. The application of LEDs holds the potential for life-enhancing storage and handling during postharvest activities, also can assist growers and vendors in reducing waste as well as aid in the provision of long-term storage and transportation.

Compliance with Ethical Standards

Conflict of Interest   The authors declare that they have no conflicts of interest.

Fig. 2 Publications of LEDs based on the Science direct database, December 26, 2019

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