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Impact of spectral composition of light from light-emitting diodes (LEDs) on postharvest quality of vegetables: A review

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ABSTRACT

Postharvest illumination with light-emitting diodes (LEDs) is an emerging, non-chemical, residue-free technique used to preserve plant commodities. This paper aimed to review current knowledge on postharvest LED illumination on vegetables while focusing on their effect on the physical, nutritional, and microbial quality of vegetables. Most of the studies on postharvest illumination have concentrated on continuous LED treatment over photoperiod/cycle illumination. LED illumination from different wavelengths preserved or improved the nutritional value (ex: chlorophyll, lycopene, vitamin C, and phenolic compounds), stimulated antioxidant enzyme activity in some vegetables while effectively reducing the membrane damage, and maintaining membrane integrity. According to the available research data, light from red, blue, and white LEDs is ostensibly effective on the physiological process of a variety of vegetables. Further, LEDs can be used in non-thermal means to inactivate foodborne pathogens considerably. Therefore, postharvest LED lighting with different wavelengths can be considered an excellent alternative lighting system to preserve safe and nutritious fresh vegetables.

1. Introduction

Vegetables are rich in phytochemicals, minerals, vitamins (C, A, B-6, E, folate, riboflavin, niacin, thiamin), and dietary fiber (Dias, 2012; Ambuko et al., 2017). Phytochemicals (ex: polyphenols, carotenoids, glucosinolates, ascorbic acid) are associated with many health-promoting effects, such as protection against cardiovascular diseases, cancers, diabetes, inflammation, and asthma (de Kok et al., 2008; Alothman et al., 2009). Hence, apart from visual quality, consumers nowadays are more concerned about nutritional quality and food safety regarding the microbial and chemical-residual effects on fresh produce (ex: fresh vegetables). Depending on the storage condition, many physiological processes (ex: respiration, senescence, and ripening) can affect the quality and shelf life of fruit and vegetables (Ziv and Fallik, 2021). Physiological deterioration (ex: water loss, color loss, and softening) and microbial decay due to yeasts/molds and pathogenic bacteria are two main processes that cause fruit and vegetable deterioration (Ziv and Fallik, 2021). Thus proper postharvest management is required to preserve the fresh commodities from physical, nutritional, and microbial quality degradation and extend shelf life, reduce postharvest loss and ensure food security. Many researchers have focused on postharvest preservation by adjusting or developing different preservation methods to replace chemical preservation techniques (Vicente et al., 2005). Alternative methods capable of controlling physiological disorders and decay without altering postharvest quality attributes could help extend postharvest life (Vicente et al., 2005).

The light intensity and spectra can affect the physiological responses of plants (Kokalj et al., 2016). Harvested plant leaves can continue photosynthesis like light-dependent biological processes (Liu et al., 2015). Therefore, taking advantage of this active responsiveness may be a powerful perspective to promote postharvest quality (Liu et al., 2015). Hence, it is worthwhile studying the impact of visible light on the quality and nutritional value of vegetables during storage. Under this circumstance, postharvest illumination is a non-chemical non-thermal preservation technique that holds growing interest in postharvest studies. Recently, research interest has increased in using light-emitting diodes (LEDs) during postharvest storage and preservation of vegetables. Generally, LEDs consist of high energy-conversion efficiency, relatively cool surfaces with minimum heating, and small mass and volume with long life expectancy (Wu et al., 2007; Massa et al., 2008; Xu et al., 2012; Lin et al., 2013; Kokalj et al., 2016). The main advantage of using LED is controlling its spectral composition (Kokalj et al., 2016). Hence, it

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allows for matching their wavelengths with plant photoreceptors (Massa et al., 2008; Lin et al., 2013; Hasperué, Guardianelli, et al., 2016; Kokalj et al., 2016). Few authors have gathered results of previous studies regarding postharvest LED lighting application on both vegetables and fruit and discussed based on the type of commodity. It is appropriate and economically beneficial if the vegetables can be presented based on the suitable spectral composition of the LED lighting. However, a summary focused on the effect of LED light treatment solely on postharvest vegetables is hardly available. As such, this review provides an insight into the effect of postharvest illumination on the physical, nutritional, and microbial quality of vegetables based on the spectral composition of LEDs. Physiological responses of postharvest vegetables discussed here include photosynthesis, senescence, antioxidant activity, membrane integrity, lycopene, vitamin C, phenolic compounds content, and chlorophyll metabolism. It also presents future aspects, practical applicability, and limitations for opening an avenue for LED light application on postharvest vegetables.

2. Effect of postharvest LED lighting on vegetables

Understanding the relationship between light and postharvest quality to a greater extent is essential to a better postharvest application (D'Souza et al., 2015). Certain plants and their parts (fruit and edible flowers) have been subjected to postharvest LED lighting to preserve and improve the quality. These plant parts include leafy and non-leafy vegetables such as; amaranth- *Amaranthus dubius* L. (S. Jin et al., 2021), bell pepper- *Capsicum annuum* L. (Kokalj et al., 2016), broccoli- *Brassica oleracea* L. var. *italica* (Ma et al., 2014; P. Jin et al., 2015; Hasperué, Guardianelli, et al., 2016; Loi et al., 2019), brussels sprouts- *Brassica oleracea* var. *gemmifera* (Hasperué, Rodoni, et al., 2016), cabbage (Lee et al., 2014), red chard- *Beta vulgaris* (Pennisi et al., 2021), lamb's lettuce- *Valerianella olitoria* L. (Braidot et al., 2014), okra- *Abelmoschus esculentus* L. (Wilawan et al., 2019), pak choi- *Brassica rapa* L. Chinensis (Zhou, Zuo, et al., 2019; Song et al., 2020; Zhou et al., 2020; Zhang and Xie, 2021), mature green tomatoes- *Solanum lycopersicum* L. (Dhakal and Baek, 2014a, 2014b; Ntagkas et al., 2016; Panjai et al., 2017), red tomato (Kokalj et al., 2016; Nájera et al., 2018), and wild rocket- *Diplotaxis tenuifolia* (Pennisi et al., 2021). In current research studies, broccoli, tomato, and pak choi have gained more attention. More studies related to tomatoes have focused on the mature green stage. The impact of postharvest LED lighting on the quality of leafy and non-leafy vegetables is summarized in Table 1 based on spectral composition. The vegetables most suitable for a particular LED wavelength can be identified in Table 1. The postharvest LED treatment, which is most suitable for a particular type of vegetables, can be identified based on the nutrient or the quality attributes (ex: visual, textural) expected to preserve as well.

2.1. Impact on photosynthesis

The available studies have been carried out with constant and light: dark cycles of LED lighting to evaluate the impact of light on the quality and shelf-life of harvested commodities. More studies have focused on continuous LED treatment over photoperiod/cycle illumination. Loi et al. (2019) have confirmed the low-intensity LED lighting (20 μmol m^{-2} s^{-1}) as a nonchemical method sufficient to reduce biochemical alterations of phytonutrients in postharvest storage and to preserve broccoli from postharvest senescence; because low LED light intensities cause no abiotic stress, unlike high-light conditions which induce a strong increase in reactive oxygen species (ROS) production in plants. Braidot et al. (2014) highlighted the importance of low-intensity white LED light cycles (8 cycles of 1 h per day; 16 cycles of 0.5 h per day) along with low-temperature storage on the quality of lamb's lettuce (*Valerianella olitoria* [L.] Pollich). Though it resulted in a loss of glucose after 6 d in both light and dark treated samples (at both 6 and 4 ^{0}C), light-treated samples (at 6 ^{0}C) were reported to have more glucose concentration and still be capable of inducing the production of the pigments (chlorophylls and carotenoids especially in 16 cycles at 6 ^{0}C) compared to the lettuce samples stored in darkness (Braidot et al., 2014). Therefore, they concluded that low-intensity intermittent light cycles are insufficient for occurring photosynthesis to a substantial amount as photosynthesis was only partially activated. However, Hasperué et al. (2016) observed maintained glucose and fructose levels and increased sucrose levels in broccoli with continuous white-blue (WB) LED (20 μmol m^{-2} s^{-1}) treatment.

A study conducted by Woltering and Seifu (2015) stated that increased carbohydrate levels in fresh-cut butterhead lettuce exposed to continuous or a 12 h photoperiod of red LED lighting (5 μmol m^{-2} s^{-1}) contribute to extending the shelf-life. Over this study, 7.5 d of shelf-life resulted in samples stored in darkness and 12 d in red light treated samples. Woltering and Seifu (2015) also observed similar results with fresh-cut butterhead lettuce when exposed to continuous illumination (5 μmol m^{-2} s^{-1}) of 50% red + 50% blue (RB) LED light. When the photon flux is below the light compensation point, it causes a net loss of sugars (D'Souza et al., 2015). However, based on the outcome of Woltering and Seifu (2015), the involvement of gluconeogenesis can be possible. The quantity of light used was well below the light compensation point, and it indicates that photosynthesis may not be the primary process caused for sugar accumulation (Woltering and Seifu, 2015). Sugars on postharvest cherry tomatoes (at the mature green stage) were enhanced by both red and blue LED treatments of 118 μmol m^{-2} s^{-1} (Ngcobo et al., 2021). Therefore it opens up a new research avenue to explain the accumulation of sugars depending on the postharvest LED light treatment.

2.2. Impact on chlorophyll content

Generally, massive degradation of chloroplast proteins and chlorophylls occurs in the senescence of harvested green organs (Pennisi et al., 2021). The low-level white LED (10 μmol m^{-2} s^{-1}) illumination stimulated the chlorophyll metabolism compared to the dark-treated samples of pak choi (Zhou, Zuo, et al., 2019). The presence of a higher level of divinyl chlorophyllide *a*, which is a major precursor in the biosynthesis of chlorophyll (Nagata et al., 2007; Zhou, Zuo, et al., 2019), in the white light treated samples than the samples kept in the dark was reported as may be partially responsible for the delay of leaf yellowing in pak choi plants (Zhou, Zuo, et al., 2019). As proven by Zhou et al. (2020), the effect of white LED illumination (10 μmol m^{-2} s^{-1}) on chlorophyll-related genes and enzymes was responsible for higher chlorophyll content in LED illuminated pak choi samples. Higher expression values of chlorophyll synthetase gene, BrHEMA1 resulted in LED treated samples in the first 5 d of storage than the control samples, suggesting that the chlorophyll synthesis was promoted by LED lighting (Zhou et al., 2020). Furthermore, the expression of chlorophyll-degrading genes (BrChlase1, BrChlase2, and BrPPH) was downregulated in LED-treated samples (Zhou et al., 2020). Continuous white LED illumination (35 ± 2.5 μmol m^{-2} s^{-1}) preserved the chlorophyll content in the postharvest wild rocket as well (Pennisi et al., 2021).

In addition to white light illumination, green LED light was reported to impact the chlorophyll content of postharvest vegetables positively. The postharvest illumination with green LED light effectively preserved (P. Jin et al., 2015) or improved (Loi et al., 2019) chlorophyll in broccoli heads. Continuous postharvest illumination with green LED light improved total chlorophyll content in cabbage (Lee et al., 2014) and preserved chlorophyll content in wild rocket (Pennisi et al., 2021). Therefore postharvest green LED lighting may have an impact on preserving or improving the chlorophyll content. Blue LED light extends the duration of active photosynthesis and increases the photosynthetic capacity (X. Y. Wang et al., 2015; Hasperué, Rodoni, et al., 2016) and the chlorophyll content (Hogewoning et al., 2010). Hence, blue LED lighting can be an alternative method to extend shelf-life by delaying senescence (Hasperué, Rodoni, et al., 2016). For example, Jin et al. (2021) observed

Table 1
Effectiveness of postharvest illumination on leafy and non-leafy vegetables based on the spectral composition of LED.

LED color	Wavelength (nm)	Leafy and non-leafy vegetable	Light intensity and treatment condition (PFD/ Irradiance)	Storage condition	Suitable application	References
White light	–	Broccoli (*Brassica oleracea* L. var. *italica*)	40 µmol m^{-2} s^{-1}	4 ± 0.5^{0}C and 68 ± 2% RH[a]	For preserving from postharvest senescence	Loi et al. (2019)
	–	Cabbage (Dongdori)	Continuous illumination	4–5^{0}C	For improving nutritional quality (total chlorophyll, vitamin C, and total polyphenolic content) while maintaining the visual quality	Lee et al. (2014)
	Peak at 610 nm	Red chard (*Beta vulgaris*)	Continuous illumination (35 ± 2.5 µmol m^{-2} s^{-1})	5^{0}C and 85% RH for 10 d	For increasing carotenoids content	Pennisi et al. (2021)
	Warm white light (peaks in 460 nm and 570 nm)	Lamb's lettuce (*Valerianella olitoria* L.)	Continuous illumination (one dose of 8 h[b] per day: 1.4 ± 0.4 µmol m^{-2} s^{-1})	6^{0}C	For promoting photosynthesis	Braidot et al. (2014)
	Warm white light (peaks in 460 nm and 570 nm)	Lamb's lettuce (*Valerianella olitoria* L.)	8 cycles of 1 h per day or 16 cycles of 0.5 h per day: 1.4 ± 0.4 µmol m^{-2} s^{-1})	6^{0}C	For maintaining the quality and inducing the production of pigments	Braidot et al. (2014)
		Okra (*Abelmoschus esculentus* L.)	For 8 h: 17.28 W m^{-2}	–	For increasing total phenolics content	Wilawan et al. (2019)
	448 nm and 549 nm	Pak choi (*Brassica campestris* L. ssp. *chinensis*)	Continuous illumination (10 µmol m^{-2} s^{-1})	20^{0}C and 90% RH for 7 d	For delaying senescence and maintaining the postharvest quality (suppressing the changes in sensory evaluation; maintaining higher vitamin C and chlorophyll content)	Zhou et al. (2020)
	–	Pak choi (*Brassica campestris* L. ssp. *chinensis*)	10 µmol m^{-2} s^{-1}	20^{0}C and 90% RH for 5 d	For maintaining the quality by regulating several metabolic processes [for elevating folate, glutathione, thiamine, total carotenoid, and riboflavin content; stimulating glucosinolate biosynthesis, porphyrin & chlorophyll metabolism	Zhou, Zuo, et al. (2019)
	Peak at 610 nm	Wild rocket (*Diplotaxis tenuifolia*)	Continuous illumination (35 ± 2.5 µmol m^{-2} s^{-1})	5^{0}C and 85% RH for 10 d	For preserving chlorophylls content and visual quality	Pennisi et al. (2021)
	–	Ripen tomato (*Solanum lycopersicum* L.)	1 h per day: 0, 92.60, 64.05, 84. 48 µmol m^{-2} s^{-1}	19^{0}C and 85% RH	For increasing lycopene content and organoleptic parameters	Nájera et al. (2018)
Blue phosphorous coated white light	350–850 nm	Green tomato (*Solanum lycopersicum*)	Continuous illumination (263 µmol m^{-2} s^{-1})	18^{0}C and 75% RH	For improving nutritional value (increasing L-ascorbate biosynthesis)	Ntagkas et al. (2016)
White and Blue (WB) light	–	Broccoli heads (*Brassica oleracea* var. *italica*)	Continuous illumination (20 µmol m^{-2} s^{-1})	5^{0}C or 22^{0}C and 68 ± 1% RH	For delaying senescence (highest levels of chlorophylls, increased total carotenoid content) and extending the shelf-life	Hasperué, Guardianelli, et al. (2016)
	Peak of blue and white LED as 458–467 nm and 450/525–558 nm	Brussels sprouts (*Brassica oleracea* var. *gemmifera*)	Continuous illumination (20 µmol m^{-2} s^{-1})	22^{0}C and 68% RH	For delaying senescence and maintaining or improving the postharvest quality (higher total flavonoids content)	Hasperué, Rodoni, et al. (2016)
Blue light	≈ 470 nm	Okra (*Abelmoschus esculentus* L.)	For 8 h: 17.28 W m^{-2}	–	For increasing total phenolics content	Wilawan et al. (2019)
	467 nm	Broccoli (*Brassica oleracea* L. var. *italica*)	21 µmol m^{-2} s^{-1}	4 ± 0.5^{0}C and 68 ± 2% RH	For preserving from postharvest senescence	Loi et al. (2019)
	Peak at 465 nm	Red chard (*Beta vulgaris*)	Continuous illumination (35 ± 2.5 µmol m^{-2} s^{-1})	5^{0}C and 85% RH for 10 d	For stimulating total phenols content and total antioxidant capacity; reducing microbial counts	Pennisi et al. (2021)
	Peak at 465 nm	Wild rocket (*Diplotaxis tenuifolia*)	Continuous illumination (35 ± 2.5 µmol m^{-2} s^{-1})	5^{0}C and 85% RH for 10 d	For stimulating total phenols content and total antioxidant capacity	Pennisi et al. (2021)
	460 nm	Amaranth (*Amaranthus dubius* L.)	12 h per day: 0, 10, 20, 30 µmol m^{-2} s^{-1} (best preservation with 30 µmol m^{-2} s^{-1})	4^{0}C and 90 ± 5% RH for 12 d	For increasing sensory acceptability; improving chlorophyll, ascorbic acid; inhibiting the growth of *Pseudomonas aeruginosa*; extending shelf-life by 2–3 d	Jin et al. (2021)
	455 nm	Iceberg lettuce	Continuous or photoperiod (12 h) illumination (5 µmol m^{-2} s^{-1})	12^{0}C and ≈ 90% RH	For extending shelf-life	Woltering and Seifu (2015)
	454 nm	Cherry tomatoes (*Solanum lycopersicum*	For 48 h:118 µmol m^{-2} s^{-1}	21 ± 1^{0}C for 21 d	For enhancing β-carotene and lycopene content more in samples treated at green-	Ngcobo et al. (2021)

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Table 1 (*continued*)

LED color	Wavelength (nm)	Leafy and non-leafy vegetable	Light intensity and treatment condition (PFD/ Irradiance)	Storage condition	Suitable application	References
		L.)- red and yellow cultivars			mature stage than turning stage; enhancing sugars	
	450 nm	Sweet peppers (*Capsicum annuum* L.)- red cultivar	8 h per day: 100 μmol m^{-2} s^{-1}	7^{0}C and 85% RH	For maintaining nutritional value (highest increase in lycopene content; maintaining phenolic compounds; minimum changes in ascorbic acid content, antioxidant activity, and color difference) and weight loss acceptable for marketing	Maroga et al. (2019)
	440–450 nm	Green tomato (*Solanum lycopersicum* L.)	Continuous illumination (85.72 μmol m^{-2} s^{-1})	25 ± 2^{0}C and 60–65% RH	For delaying softening and ripening; extending shelf-life	Dhakal and Baek (2014b)
	440–450 nm	Green tomato (*Solanum lycopersicum* L.)	Continuous illumination (85.70 μmol m^{-2} s^{-1})	25 ± 2^{0}C	For delaying ripening [increment of γ-aminobutyric acid (GABA) content]; extending shelf-life	Dhakal and Baek (2014a)
	436.438 nm	Cabbage (Dongdori)	Continuous illumination	4–5^{0}C	For improving nutritional quality (vitamin C and total polyphenolic content)	Lee et al. (2014)
Green light	524.344 nm	Cabbage (Dongdori)	Continuous illumination	4–5^{0}C	For maintaining visual quality and improving the nutritional quality (total chlorophyll content)	Lee et al. (2014)
	522 nm	Broccoli (*Brassica oleracea* L. var. *italica*)	24 μmol m^{-2} s^{-1}	4 ± 0.5^{0}C and 68 ± 2% RH	For preserving from postharvest senescence (increasing ascorbic acid and chlorophyll content)	Loi et al. (2019)
	520 nm	Broccoli heads (*Brassica oleracea* L. var. *italica*)	12 h per day: 12–13 μmol m^{-2} s^{-1}	25 ± 1^{0}C and ≈ 95% RH	For delaying senescence (maintaining visual quality); increasing total phenols and glucosinolates; extending shelf-life	P.Jin et al. (2015)
	Peak at 517 nm	Red chard (*Beta vulgaris*)	Continuous illumination (35 ± 2.5 μmol m^{-2} s^{-1})	5^{0}C and 85% RH for 10 d	For increasing carotenoids content	Pennisi et al. (2021)
	Peak at 517 nm	Wild rocket (*Diplotaxis tenuifolia*)	Continuous illumination (35 ± 2.5 μmol m^{-2} s^{-1})	5^{0}C and 85% RH for 10 d	For preserving chlorophylls content and visual quality; reducing microbial counts	Pennisi et al. (2021)
Yellow light	Peak at 600 nm	Red chard (*Beta vulgaris*)	Continuous illumination (35 ± 2.5 μmol m^{-2} s^{-1})	5^{0}C and 85% RH for 10 d	For reducing microbial counts	Pennisi et al. (2021)
	Peak at 600 nm	Wild rocket (*Diplotaxis tenuifolia*)	Continuous illumination (35 ± 2.5 μmol m^{-2} s^{-1})	5^{0}C and 85% RH for 10 d	For reducing microbial counts	Pennisi et al. (2021)
	590 nm	Bell pepper (*Capsicum annuum*)- red cultivar	Continuous illumination (1.81 W m^{-2})	10^{0}C	For improving nutritional value (higher antioxidant potential with higher mass fractions of β-carotene, α-tocopherol, γ-tocopherol, chlorophyll-a, and lutein)	Kokalj et al. (2016)
	590 nm	Red tomato (*Solanum lycopersicum* L.)	Continuous illumination (1.81 W m^{-2})	10^{0}C	For improving nutritional value (higher levels of total phenolic compounds)	Kokalj et al. (2016)
	587 nm	Broccoli (*Brassica oleracea* L. var. *italica*)	27 μmol m^{-2} s^{-1}	4 ± 0.5^{0}C and 68 ± 2% RH	For preserving from postharvest senescence (increasing ascorbic acid and phenolic compound content)	Loi et al. (2019)
Red light	Peak at 665 nm	Green tomato (*Solanum lycopersicum* L.)	Continuous illumination (113 μmol m^{-2} per day)	20/19^{0}C and 75/85% RH for 20 d	For shortening ripening time; increasing nutritional quality (lycopene, ß-carotene) and antioxidant content (total flavonoids and phenolics)	Panjai et al. (2017)
	Peak at 665 nm	Green tomato (*Solanumly copersicum* L.)	Continuous illumination (113 μmol m^{-2} s^{-1})	20/19^{0}C and 75/85% RH	For accelerating ripening; increasing β-carotene, lycopene, total phenolic content, total flavonoid concentration, and the antioxidant activity	Panjai et al. (2019)
	Peak at 665 nm	Green tomato (*Solanumly copersicum* L.)	30 min, 6 h and 12 h per day: 113 μmol m^{-2} s^{-1}	20/19^{0}C and 75/85% RH for 14 d	For resulting highest pulp firmness throughout the treatment period in samples illuminated for 30 min	Panjai et al. (2019)
	660 nm	Broccoli heads (*Brassica oleracea* L. var. *italica*)	Continuous illumination (50 μmol m^{-2} s^{-1})	20^{0}C and > 95% RH	For delaying senescence (suppressed the ethylene production & reduction of ascorbate processes)	Ma et al. (2014)
	660 nm	Broccoli sprouts (*Brassica oleracea* var. *italica*)	Continuous illumination (35 ± 2.5 μmol m^{-2} s^{-1})	5^{0}C and 85% RH for 15 d	For increasing sprout length	Castillejo et al. (2020)
	Peak at 660 nm	Red chard (*Beta vulgaris*)	Continuous illumination (35 ± 2.5 μmol m^{-2} s^{-1})	5^{0}C and 85% RH for 10 d	For stimulating total phenols content and total antioxidant capacity	Pennisi et al. (2021)
	660 nm	Butterhead lettuce				

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Table 1 (*continued*)

LED color	Wavelength (nm)	Leafy and non-leafy vegetable	Light intensity and treatment condition (PFD/ Irradiance)	Storage condition	Suitable application	References
			Continuous or photoperiod (12 h) illumination (5 μmol m^{-2} s^{-1})	12^{0}C and ≈ 90% RH	For extending shelf-life (increasing carbohydrate levels)	Woltering and Seifu (2015)
	660 nm	Sweet peppers (*Capsicum annuum* L.)-green and yellow cultivars	8 h per day: 150 μmol m^{-2} s^{-1}	7^{0}C and 85% RH	For maintaining nutritional value (highest concentrations of β-carotene, lycopene, and chlorophyll; maintained phenolic compounds; minimum changes in ascorbic acid content) and extending shelf-life	Maroga et al. (2019)
	660 nm	Sweet peppers (*Capsicum annuum* L.)-red cultivar	8 h per day: 150 μmol m^{-2} s^{-1}	7^{0}C and 85% RH	For maintaining nutritional value (highest concentrations of β-carotene, lycopene, and chlorophyll)	Maroga et al. (2019)
	Peak at 660 nm	Wild rocket (*Diplotaxis tenuifolia*)	Continuous illumination (35 ± 2.5 μmol m^{-2} s^{-1})	5^{0}C and 85% RH for 10 d	For stimulating total phenols content and total antioxidant capacity	Pennisi et al. (2021)
	638 nm	Cherry tomatoes (*Solanum lycopersicum* L.)-red and yellow cultivars	For 48 h:118 μmol m^{-2} s^{-1}	21 ± 1^{0}C for 21 d	For enhancing β-carotene and lycopene content more in samples treated at green-mature stage than turning stage; enhancing sugars	Ngcobo et al. (2021)
	625 nm	Broccoli (*Brassica oleracea* L. var. *italica*)	66 μmol m^{-2} s^{-1}	4 ± 0.5^{0}C and 68 ± 2% RH	For preserving from postharvest senescence (increasing ascorbic acid and phenolic compound content)	Loi et al. (2019)
	–	Broccoli heads (*Brassica oleracea* var. *italica*)	Continuous illumination (50 μmol m^{-2} s^{-1})	20 ± 1^{0}C and 90% RH for 5 d	For delaying senescence and maintaining the storage quality (effectively maintaining sensory quality, color, and freshness; effectively reducing membrane damage and maintaining membrane integrity)	Jiang et al. (2019)
	–	Pak choi (*Brassica rapa* ssp. *chinensis*)	Continuous illumination (65 μM m^{-2} s^{-1})	20^{0}C for 5 d	For inhibiting the chlorophyll degradation; decreasing the loss of photochemical efficiency (Fv/Fm ratio), vitamin C, and total soluble protein contents	Song et al. (2020)
	–	Pak choi (*Brassica rapa* ssp. *chinensis*)	Continuous illumination (35 μM m^{-2} s^{-1})	20^{0}C for 5 d	For inhibiting chlorophyll degradation; inhibiting photochemical efficiency (Fv/Fm ratio) and total protein content decline	Song et al. (2020)
	–	Pak choi (*Brassica rapa* ssp. *chinensis*)	4 and 8 h per day: 35 μM m^{-2} s^{-1}	20^{0}C for 5 d	For inhibiting chlorophyll degradation; inhibiting the decrease of photochemical efficiency (Fv/Fm ratio), relative protein content, or vitamin C content (by 8 h); delaying the senescence (by 8 h)	Song et al. (2020)
	–	Pak choi (*Brassica rapa* ssp. *chinensis*)	Continuous illumination (70 μM m^{-2} s^{-1})	20^{0}C for 5 d	For strongly inhibiting the vitamin C depletion (especially at 3 d of storage)	Song et al. (2020)
	–	Pak choi (*Brassica rapa* ssp. *chinensis*)	Continuous illumination (10 μM m^{-2} s^{-1})	20^{0}C for 5 d	For inhibiting leaf senescence and the decline of chlorophyll content, photochemical efficiency (Fv/Fm ratio), total soluble protein content, and vitamin C content	Song et al. (2020)
Red-Blue (RB)	Red (660 nm) & Blue (455 nm) (50% Red + 50% Blue)	Butterhead lettuce	Continuous illumination (5 μmol m^{-2} s^{-1})	12^{0}C and ≈ 90% RH	For extending shelf-life (increasing carbohydrate levels)	Woltering and Seifu (2015)
	–	Pak choi (*Brassica rapa* ssp. *chinensis*)	Continuous illumination (45 μM m^{-2} s^{-1})	20^{0}C for 3 d	For inhibiting chlorophyll degradation; decreasing the loss of photochemical efficiency (Fv/Fm ratio), total soluble protein and vitamin C contents	Song et al. (2020)
Red-violet	Composite of 660 & 405 nm	Pak choi (*Brassica rapa* L. *chinensis*)	12 h per day: 15 μmol m^{-2} s^{-1}	4^{0}C and 90 ± 5% RH	For increasing chlorophyll, soluble solids, ascorbic acid content, and antioxidant enzymes activity; extending shelf-life; inhibiting specific spoilage organism reproduction	Zhang and Xie (2021)
Far-Red	730 nm	Broccoli sprouts (*Brassica oleracea* var. *italica*)	Continuous illumination (35 ± 2.5 μmol m^{-2} s^{-1})	5^{0}C and 85% RH for 15 d	For increasing hypocotyl and sprout length; improving total antioxidant and scavenging activities; decreasing the microbial growth	Castillejo et al. (2020)

[a] RH: Relative Humidity
[b] h: Hour

blue LED treatment improving the chlorophyll content in fresh-cut amaranth. However, Song et al. (2020) observed a much weaker inhibitory effect on senescence when illuminated pack choi with blue light compared to the red light, both at intensities of 50 and 65 μmol m^{-2} s^{-1}, close to the light compensation point. However, red-violet (660 and 405 nm; 15 μmol m^{-2} s^{-1}) LED illumination increased chlorophyll content in postharvest pak choi samples (Zhang and Xie, 2021). Based on the available findings, the intensity range of 10–35 μmol m^{-2} s^{-1} effectively preserved the chlorophyll content of postharvest vegetables using white, WB, green, and blue LEDs (P. Jin et al., 2015; Hasperué, Guardianelli, et al., 2016; Jiang et al., 2019; Loi et al., 2019; Song et al., 2020; S. Jin et al., 2021; Pennisi et al., 2021; Zhang and Xie, 2021). Nevertheless, of red LED, the intensity effective for inhibiting chlorophyll degradation ranges within 10–65 μmol m^{-2} s^{-1}, which is somewhat higher than in the other LEDs.

2.3. *Impact on sprout growth and senescence*

Plants perceive the different wavelengths of light via distinct photoreceptors (Jones, 2018). Plant photoreceptors comprise phytochromes [as the red light receptors absorbing red (600–700 nm)/far-red (700–750 nm) light] (Chen and Chory, 2011; Costa et al., 2013; Christie et al., 2015), cryptochromes, and phototropins [as the UV-A/blue light receptors absorbing UV-A (315–400 nm)/blue (420–500 nm) light] (Takemiya et al., 2005; Muneer et al., 2014). In the study of Castillejo et al. (2020), a positive physiological effect was observed in minimally processed broccoli sprouts (*Brassica oleracea* var. *italica*) treated with red and far-red LEDs. Park and Runkle (2017) also reported the influence of far-red illumination in promoting the growth of seedlings by the increment of plant expansion. Thus, the inclusion of far-red radiation during seedling growth of geranium (*Pelargonium* ×*hortorum*) increased the plant growth directly through whole-plant net assimilation and indirectly through leaf expansion (Park and Runkle, 2017). Therefore, Castillejo et al. (2020) pointed out that far-red illumination on plants may encourage plant elongation and affect the physiological mechanisms as far-red wavelengths can regulate phytochrome-mediated morphological and developmental plant responses. As aforementioned, phototropins are receptors activated by blue light (Christie, 2007; Christie et al., 2015; Hart et al., 2019) and are involved in the inhibition of hypocotyl elongation and regulation of plant growth and directional light orientation as well (Folta and Spalding, 2001; Castillejo et al., 2020). Therefore, it explains the reason for the lower growth of blue light illuminated minimally processed broccoli sprouts compared to both red and far-red light treatments obtained in the study of Castillejo et al. (2020), and the blue light illumination can reduce the plant size even more than the darkness and fluorescence treatments (Castillejo et al., 2020).

Even though the far-red caused a positive effect on broccoli sprouts (Castillejo et al., 2020), the illumination of harvested green vegetables with far-red may affect senescence. Based on the opposite effects obtained with red and far-red light irradiation on pak choi leaves senescence, Song et al. (2020) pointed out the involvement of the phytochrome signaling pathway in the regulation of postharvest leaf senescence. In their study, the senescence was inhibited by red light, whereas it was enhanced by the far-red light treatment (Song et al., 2020), suggesting that the senescence might get suppressed by red light through the phytochrome light-sensing pathway, and far-red light would reverse the effect of red light by inactivating the phytohormone photoreceptor pathway. Song et al. (2020) also reported that the inhibitory effect of red light on senescence is affected by the duration of irradiation. Besides, Sakuraba et al. (2014) reported that intermittent red light treatment could inhibit the senescence of leaves through phytochrome signaling in *Arabidopsis*. The red light illumination activates phytochromes and promotes interaction between phytochrome interacting factors (PIFs) and phytochromes (Song et al., 2020). Thus, it triggers the degradation of PIFs and releases the suppressive effect of PIFs on light-responsive genes (Castillon et al., 2007; Song et al., 2020). Several PIFs could promote the leaf senescence in *Arabidopsis* by inhibiting chloroplast activity and at the same time enhancing chlorophyll catabolic genes' expression and ethylene production/signaling (Song et al., 2014, 2020). Pak choi is a closely related species of *Arabidopsis* in Cruciferae. Thus, considering these findings, it can be assumed that there is a similar functional phytochrome signaling system in pak choi (Song et al., 2020).

2.4. *Impact on antioxidant enzyme activity and membrane integrity*

The oxidative damage to cellular membrane components disrupts the integrity of the membrane (Zhou, Gu, et al., 2019). Furthermore, when plants are exposed to abiotic stress conditions, it increases the generation of ROS and causes indirect or direct oxidative damage to membrane lipids and other cellular components, resulting in the formation of malondialdehyde (MDA) like toxic products (Q. Wang et al., 2016; Jiang et al., 2019; Zhou et al., 2020). As MDA levels indicate lipid peroxidation (Zhou, Gu, et al., 2019; Zhou et al., 2020), the MDA content can be considered an indicator of the degree of oxidative stress and membrane structural integrity in plants (Imahori et al., 2008; Q. Wang et al., 2016; Jiang et al., 2019). The continuous white (Zhou et al., 2020) and red (Jiang et al., 2019) LED illumination effectively decreased the MDA content in harvested pak choi and broccoli, respectively. Zhou et al. (2020) observed a lower MDA level in white LED (10 μmol m^{-2} s^{-1}) treated pak choi samples on 3 and 7 d in storage. At the end of 5 d, the control samples had 1.24 times MDA content than in red LED (50 μmol m^{-2} s^{-1}) treated broccoli samples (Jiang et al., 2019). Jiang et al. (2019) observed the resulted MDA content to be positively correlated with weight loss. The weight loss (%) on 5 d was between 0.02 and 0.03 in red LED treated broccoli samples, whereas > 0.03 in control samples (Jiang et al., 2019).

The antioxidant defense system in plants contributes to repairing oxidative damage and inhibiting the accumulation of ROS (Imahori et al., 2016; Jiang et al., 2019); because antioxidant enzymes can detoxify ROS (Zhou, Gu, et al., 2019). Catalase (CAT), peroxidase (POD), and ascorbate peroxidase (APX) are the major antioxidant enzymes that catalyze the decomposition of H_2O_2 and eliminate excess H_2O_2 in fruit and vegetables (Shi et al., 2018; Jiang et al., 2019; Zhou, Gu, et al., 2019; Zhou et al., 2020). The ROS content will increase during storage with the aging of leaves, and plants will produce more antioxidant enzymes to reduce leaf damage (Zhang and Xie, 2021). The senescence regulation in vegetables and fruit is based on the changes in ROS synthesis and removal ratio by antioxidant systems (Loi et al., 2019). Zhou et al. (2020) reported that the enzyme activity and the relative gene expression of POD, CAT, APX antioxidant enzymes were higher in the continuous white LED light treated pak choi samples than in the control samples over the 7 d of storage. Here, the relative gene expression of POD (at 1 and 3 d), CAT (at 1, 3, and 7 d), and APX (for 7 d except at 5 d) was higher in white LED treated samples than in the control samples (Zhou et al., 2020). According to Jiang et al. (2019), continuous illumination of red LED light (50 μmol m^{-2} s^{-1}) also stimulated antioxidant enzyme activity in broccoli, effectively reduced the membrane damage, and maintained the membrane integrity. For example, CAT activity decreased in untreated and treated broccoli samples, with a minimum value at 3 d and a spike at 4 d (Jiang et al., 2019). However, treatment differences were there from 1 d, where CAT activity was higher in red LED treated broccoli samples than in control (Jiang et al., 2019). APX activity also declined regardless of the treatment during storage but was higher at each time point in red LED treated broccoli samples, except at 3 d, where it was lower than in control (Jiang et al., 2019).

Further, the stimulated antioxidant enzyme activity observed in broccoli samples treated with red LED probably caused in maintaining the metabolic balance of ROS (Jiang et al., 2019). A higher POD and superoxide dismutase (SOD) activity were maintained by red-violet LED (660 and 405 nm; 15 μmol m^{-2} s^{-1}) light in fresh-cut pak choi during 12 d of storage as well (Zhang and Xie, 2021). Moreover, Jin et al. (2021) observed a rise in POD, APX, glutathione reductase (GR), and SOD activities in fresh-cut amaranth by blue (460 nm; especially 30 µmol m^{-2} s^{-1}) LED illumination. The activities of POD and SOD in fresh-cut amaranth samples treated with blue LED light reached the peak on 6 d, increased by 58% and 27%, respectively, compared to the control group (S. Jin et al., 2021). Therefore, based on the gathered information (Table 1), the lighting from red and blue LEDs was effective for various vegetables in increasing antioxidant activity (Panjai et al., 2017, 2019; Jiang et al., 2019; Maroga et al., 2019; S. Jin et al., 2021; Pennisi et al., 2021).

2.5. *Impact on lycopene, vitamin C, and phenolic compounds*

The wavelength selection for postharvest LED lighting appears to vary depending on several factors. It includes the vegetable species, cultivar, level of maturity of the harvested vegetables, and the type of nutrient or the desirable postharvest quality attribute expected to preserve. Within the available studies (Table 1), LED spectral composition for harvested vegetables can be identified for a particular nutritional attribute intended to preserve. The suitable postharvest LED lighting for improving lycopene content can be identified as white LED for red tomato; blue and red LED for cherry tomatoes (red and yellow cultivars at the mature green stage); red LED for green tomatoes and fresh-cut sweet pepper (green, yellow, red cultivar); and blue LED for fresh-cut sweet pepper (red cultivar). Moreover, postharvest illumination from LEDs is effective in either preserving or improving the vitamin C content in leafy and non-leafy vegetables, particularly white LED for green tomato; white and blue LED for cabbage; blue LED for amaranth and fresh-cut sweet pepper (red cultivar); red LED for fresh-cut sweet pepper (green and yellow cultivar); white, red, red-blue, and red-violet LED for pak choi; and red, green & yellow LED for broccoli. Further, the LEDs are helpful in postharvest illumination for preserving phenolic compounds in harvested produce, especially white LED for cabbage; white and blue LED for okra; blue LED for fresh-cut sweet pepper (red cultivar), red-chard, wild rocket; red LED for green tomato, fresh-cut sweet pepper (green and yellow cultivar), red-chard, and wild rocket; yellow LED for red tomato; and red, green and yellow LED for broccoli. Therefore according to the available research data, red, blue, and white LEDs were effective for preserving lycopene, vitamin C, and phenolic content in most studied vegetables. The general light intensity range for both red and blue LEDs in postharvest illumination to increase lycopene content in tomatoes and sweet peppers were 113–118 and 100–150 µmol m^{-2} s^{-1}, respectively (Panjai et al., 2017, 2019; Maroga et al., 2019; Ngcobo et al., 2021). These respective LED intensities were also able to maintain phenolic compounds content in tomatoes and sweet peppers (Panjai et al., 2017, 2019; Maroga et al., 2019). Here also, the red LED light intensity range effective to decrease the loss of vitamin C in leafy vegetables was somewhat lengthy as 10–70 µmol m^{-2} s^{-1} than the other LEDs (Lee et al., 2014; Ma et al., 2014; Loi et al., 2019; Maroga et al., 2019; Song et al., 2020; S. Jin et al., 2021).

2.6. *Impact on microbial safety*

The acceptable qualities of food (visual, flavor, nutritional, and textural), the absence of foodborne pathogens, and the delay of spoilage by microorganisms are coupled with the good postharvest qualities (D'Souza et al., 2015). LEDs can also be used in non-thermal means to inactivate foodborne pathogens (D'Souza et al., 2015). LEDs of visible wavelengths have been studied as an alternative to ultraviolet light. The bacteria are shown to be inactivated photodynamically by visible light illumination. This inactivation occurs, especially in the 400–420 nm wavelength range (Maclean et al., 2009; Endarko et al., 2012; M.-J. Kim et al., 2016). The photodynamic inactivation by visible blue light needs photosensitizers such as porphyrin compounds, oxygen, and light (in a range of 400–430 nm) (Lukšienė and Zukauskas, 2009; Dai et al., 2012; Endarko et al., 2012; M.-J. Kim et al., 2015). When porphyrin compounds absorb visible light of 400–420 nm in the presence of oxygen, it produces ROS (Lukšienė and Zukauskas, 2009; M.-J. Kim et al., 2016). ROS may damage membrane lipids, proteins, enzymes, or DNA and thus induce bacterial death (Lukšienė and Zukauskas, 2009; Ghate et al., 2013; M.-J. Kim et al., 2016). As proposed by Kim et al. (2016), LED lighting with 405 ± 5 nm wavelengths under refrigerated conditions may effectively control foodborne pathogens. It is generally known that bacteria can be inactivated more effectively at low temperatures. Hence, LEDs can be used with a combination of cold storage conditions (Ghate et al., 2013; D'Souza et al., 2015). According to Table 1, the storage temperature used for postharvest illumination of most leafy vegetables was about 4–5 ^{0}C (Lee et al., 2014; Loi et al., 2019; Castillejo et al., 2020; S. Jin et al., 2021; Pennisi et al., 2021). However, high-temperature storage conditions were used for some vegetables such as pak choi (20 ^{0}C) (Zhou, Zuo, et al., 2019; Song et al., 2020; Zhou et al., 2020), brussels sprouts (22 ^{0}C) (Hasperué, Rodoni, et al., 2016), cherry tomato (20–22 ^{0}C) (Ngcobo et al., 2021), green tomato (18–27 ^{0}C) (Dhakal and Baek, 2014b; Ntagkas et al., 2016; Panjai et al., 2017, 2019), and some studies in broccoli (19–26 ^{0}C) (Ma et al., 2014; P. Jin et al., 2015; Jiang et al., 2019).

Wavelengths at 425 and 525 nm are reported to have bactericidal effects (S. Kim et al., 2013). For example, *Staphylococcus aureus* could be killed at 525 nm (S. Kim et al., 2013). Blue LED light was suggested as effective in controlling food-relevant fungi (Schmidt-Heydt et al., 2011), *Listeria monocytogenes* (Ondrusch and Kreft, 2011), and other harmful pathogens derived from fruit contamination (Lafuente and Alférez, 2015). Studies focused on the microbial safety of postharvest illuminated vegetables are somewhat lacking. Postharvest blue LED illumination from wavelength 460 nm effectively inhibited the growth and colony reproduction of dominant spoilage bacteria *Pseudomonas aeruginosa* on fresh-cut amaranth (S. Jin et al., 2021), whereas 465 nm reduced the microbial counts on red-chard (Pennisi et al., 2021). Nevertheless, according to the study of Castillejo et al. (2020), the results they obtained by them were not consistent enough to recognize the antimicrobial effect of blue LED illumination on broccoli sprouts. In addition to the blue LED, postharvest illumination by red-violet, far-red, green, and yellow LEDs also obtained positive results on the microbial status of some vegetables. Specific spoilage organism reproduction in fresh-cut pak choi was inhibited by LED illumination by red-violet (660 and 405 nm) (Zhang and Xie, 2021). Far-red (peak at 730 nm) LED lighting during postharvest storage of minimally processed broccoli sprouts decreased the microbial growth of psychrophilic, enterobacteria, molds, and yeasts compared to the darkness and fluorescent lighting treatments (Castillejo et al., 2020). The microbial counts were reduced in wild rocket vegetables by postharvest green (517 nm; 35 µmol m^{-2} s^{-1}) LED treatment, while in postharvest red-chard and wild rocket vegetables by yellow (600 nm; 35 µmol m^{-2} s^{-1}) LED light (Pennisi et al., 2021).

3. Impact on modified atmosphere

Modified atmosphere packaging (MAP) is commonly used to delay the fruit ripening process and associated physiological and biochemical changes by altering CO_2 and O_2 levels around the commodity (Ngcobo, 2017). When fruit respires, it causes to reduce the O_2 levels in packages while increasing the CO_2 simultaneously (passive MAP) or by removing and adding gases (active MAP) to manipulate CO_2 and O_2 levels (Ngcobo, 2017). Elevated CO_2 and reduced O_2 levels cause to reduce respiration, decrease ethylene production, delay ripening and slow down associated compositional changes, while retarding the textural softening, and thus extend the shelf life (Ngcobo, 2017). However, only a few studies have examined the effect of postharvest illumination on modified atmospheric packaging-conditions that developed during the storage period (Gil and Garrido, 2020). Among those, the studies that used LED lighting during the storage of packaged intact and fresh-cut vegetables are scarcely available. Most of the available studies have used packaging not to evaluate the impact of illumination on the variation of in-package MA condition but only as a pre-or post-treatment to postharvest LED illumination. These treatments include placing vegetables in trays (thermally sealing the top with films like biaxially oriented polypropylene, polyvinyl chloride) and packages. The other studies have directly exposed the harvested vegetables to LED illumination.

As in other lighting sources, LED lighting may also lead to differences in the headspace composition of packages depending on whether the tissue is green or white. When the packaged green vegetables are exposed to light during storage, it affects the in-package atmospheric condition (Gil and Garrido, 2020). Under the light, it facilitates to continue the photosynthetic activity and causes to deplete of CO_2 and the release of O_2 (Garrido et al., 2016). For instance, Braidot et al. (2014) observed that Lamb's lettuce (*Valerianella olitoria* [L.] Pollich) fresh-packaged in transparent antifog polypropylene bags and stored in a refrigerator drawer under continuous low light irradiation dose (1 cycle of 8 h per day) of warm white LED light (1.4 ± 0.4 E m^{-2} s^{-1}) resulted in variation in CO_2 absorption and O_2 production. As evidenced in O_2 production and CO_2 consumption, longer illumination (8 h) could fully activate photosynthesis (Braidot et al., 2014). In comparison, short-time cycle illumination (8 daily cycles of 1 h) was long enough to promote just a minimal photosynthetic process (Braidot et al., 2014). Moreover, under the postharvest lighting, the carbohydrates assimilated via photosynthesis compensate for the carbohydrate loss through respiration (Gil and Garrido, 2020). When the package permeability is low, the increased oxygen release can lead to browning and color degradation in vegetables (Braidot et al., 2014). Thus, this altered atmosphere of packaged green vegetables affects the commodity's metabolic pathways, quality characteristics, and shelf-life (Gil and Garrido, 2020). However, it is not addressed that the observed quality changes of packaged products stored under light are due to direct consequences of light exposure or the indirect effect of the generated in-package gas composition (Garrido et al., 2016). Therefore, when selecting the most suitable film for packaging, consideration should also be given to light exposure during storage, as photosynthesis can compensate for respiratory activity (Gil and Garrido, 2020).

4. Limitations of postharvest LED lighting

Apart from the benefits of postharvest LED lighting, its negative impact on harvested produce was minimally addressed. The mass reduction due to moisture loss is a recurring issue in light-treated vegetables (D'Souza et al., 2017). The postharvest illumination treatment induces stomata opening and thus can favor water loss in treated vegetable samples (Pintos et al., 2020). According to the findings of Pintos et al. (2020), longer daily exposure to white LED light resulted in greater weight loss in broccoli florets. Moreover, broccoli samples treated with mid (9.5 W m^{-2}) and high (19.0 W m^{-2}) intensities with continuous white LED illumination showed higher weight loss after the 11 d of storage than the control samples stored in the dark. Pennisi et al. (2021) also observed that the weight loss was consistently greater in continuously light-treated (35 μmol m^{-2} s^{-1}) fresh-cut red chard and rocket leaves and more evident in LED treatments including a blue fraction within their spectrum. Therefore, even during the storage, the blue spectral fraction permits conserved stomatal opening and thus causing increased transpiration fluxes that ultimately lead to greater fresh biomass losses (Pennisi et al., 2021). Moreover, single leaf layers for uniformity in lighting may have primarily resulted in elevated transpiration (Pennisi et al., 2021). Therefore, though low-intensity LED illumination causes no abiotic stress, unlike high-light conditions and thus used in most studies, its continuous usage can lead to higher weight losses in vegetables. However, a study disclosed that the weight loss of sweet peppers (red cultivar) could be maintained at an acceptable level for marketing by using a blue LED photoperiod (8 h per day: 100 μmol m^{-2} s^{-1}) lighting (Maroga et al., 2019). Nevertheless, based on the lighting duration, Lee et al. (2014) observed either no effect or some effect of LED lighting on moisture loss of cabbage samples compared to the dark condition. According to their study, the cabbage exposed to white, blue (436.438 nm), and green (524.344 nm) LEDs over 18 d (especially during 9–18 d) had a lower moisture content than the samples treated with red (664.907 nm) LED light or control samples stored in the dark.

Firmness and ripening of tomatoes subjected to postharvest LED illumination differ depending on the spectral composition, treatment duration, and intensity (Dhakal and Baek, 2014a, 2014b; Panjai et al., 2017, 2019; Ngcobo et al., 2021). Continuous illumination from blue LED (85.70 μmol m^{-2} s^{-1}) delayed ripening in green tomatoes (Dhakal and Baek, 2014a, 2014b), whereas continuous red LED lighting (113 μmol m^{-2} s^{-1}) accelerated the ripening in green tomatoes (Panjai et al., 2017, 2019). The effect of postharvest red LED illumination on firmness in tomatoes tends to vary among varieties and even when the same variety was treated with the same intensity but with different durations (Panjai et al., 2019; Ngcobo et al., 2021). For instance, continuous postharvest red LED illumination (113 μmol m^{-2} s^{-1} for 24 h) on green tomatoes resulted in the fastest softening. In contrast, the same intensity with a photoperiod of 30 min per day resulted in the highest pulp firmness throughout the treatment (Panjai et al., 2019). Though Ngcobo et al. (2021) used red LED illumination with 118 μmol m^{-2} s^{-1} for 48 h on cherry tomatoes, it did not affect firmness. Altogether, even though more studies on postharvest illumination have focused on continuous LED treatment over photoperiod/cycle illumination, care should be taken when selecting the spectral composition, intensity, and duration of postharvest LED illumination for a particular vegetable.

In addition to the quality evaluation of foods based on the LED light treatment, only a few studies have thoroughly evaluated the impact of these treatments on the consumer acceptability of foods (D'Souza et al., 2015). Therefore, food quality parameters, such as color, flavor, texture, and other organoleptic qualities, need to be evaluated more in-depth with quantitative and instrumental analysis (D'Souza et al., 2015); because such quality parameters can affect the consumer perception in accepting and buying foods in the market. For instance, the low moisture content will result in wilted leaves and low consumer acceptance (D'Souza et al., 2015). Therefore, conducting sensory evaluations for foods with a trained panel would help to give valuable insight into the impact of LED treatment on the quality parameters mentioned above (D'Souza et al., 2015).

5. Practical application of postharvest LED lighting

In the postharvest management of developing countries, critical issues are involved in delivering safe and quality fresh commodities to consumers (Nassarawa et al., 2021). Therefore with further research and advancements, postharvest LED lighting application could be a promising approach to extend shelf life and supply safe and quality fresh produce over long-distance transportation and long-term storage (Nassarawa et al., 2021). Moreover, postharvest LED illumination can aid in ensuring wholesomeness as well as reducing losses of vegetables and fruit in developed countries (Nassarawa et al., 2021). Though the approach of LED systems in postharvest activities is in a continuous growth phase, most works in this area are laboratory-based (Nassarawa et al., 2021); generally, the fresh vegetables are stored/ transported in the dark, in pallets, or in baskets that are stacked one over another. Thus the arrangement itself acts as a barrier to light transmission. Postharvest lighting will be more effective when the vegetables are treated with uniform lighting (ex: by spreading on racks/baskets). Moreover, the LED installation cost is high as well. Therefore most commercial-scale vegetable producers are interested only in pre-harvest illumination.

Nevertheless, LEDs use 80% less energy than incandescent lamps (Ganandran et al., 2014). Even though the initial installation cost is higher for LED lighting systems (Ganandran et al., 2014) than for conventional lighting, it would result in more savings as the operational cost is low. Moreover, selecting the most suitable market, transportation modes, and vegetables in which the postharvest loss is high and easy to arrange in plastic baskets could be necessary for the practical application of postharvest LED illumination during transportation and storage. Here, leafy vegetables can be arranged vertically in baskets as the physical injury is minimal or spread as a thin layer to expose to uniform lighting. When supermarkets receive fresh goods, these vegetables can be stored on display racks equipped with LED lighting as in transportation. However, white lighting will be the most suitable lighting for fresh produce in convenience stores as other lightings on vegetables can mislead consumers on buying. As anticipated, supermarkets nowadays tend to use postharvest illumination on leafy vegetable displays by combining white light with low-temperature high humidity conditions. Further, postharvest illumination can also be combined with other preservation techniques such as packaging or coating to reduce transpirational weight loss. However, these suggestions need to be implemented with a proper plan with more research studies and innovative strategies.

6. Future aspects/recommendations

Postharvest LED lighting on some other leafy [ex: sessile joyweed (*Alternanthera sessilis*), water morning glory (*Ipomoea aquatica*), pennywort (*Centella asiatica*), and marsh barbel (*Hygrophila schulli*)], and green vegetables is an open up avenue for future research studies. There is a lack of studies on postharvest illumination from WB, green, yellow, RB, and far-red LEDs. More research is needed to exploit the accumulation of sugars depending on postharvest LED light treatment (ex: with the use of different wavelengths, intensity, and duration) and the vegetable species. Attention should be given to microbial safety of vegetables treated with postharvest illumination from different LEDs (ex: red-violet, far-red, green, yellow, and blue). Postharvest LED lighting on the same vegetable and cultivar should be studied further with different intensity and duration treatments for a deep understanding of their effect on nutritional (vitamin C, carotenoids, phenolics, chlorophylls, antioxidants), physical, and microbial quality. However, more research is required on the effect of postharvest LED illumination on vegetables packaged in MAP conditions. The sensory acceptability of vegetables treated with postharvest LED illumination should be studied further. The future of postharvest LED illumination must drive towards the implementation in commercial scale vegetable production such as during storage and transportation.

7. Conclusion

In recent years, postharvest LED illumination has acquired more research interest to preserve the quality and extend the shelf life of fresh vegetables. LED illumination from different LEDs preserved or improved the nutritional value (ex: chlorophyll, lycopene, vitamin C, and phenolic compounds) and stimulated antioxidant enzyme activity in some vegetables while effectively reducing the membrane damage and maintaining membrane integrity. According to the available research data, red, blue, and white LEDs are considerably effective for various vegetables. Though more studies on postharvest illumination have focused on continuous LED treatment over photoperiod/cycle illumination, factors such as vegetable condition (species, cultivar, and harvesting stage), postharvest LED illumination condition (spectral composition, duration, and intensity), storage condition (packaging, temperature, and relative humidity), and the type of nutrient or the desirable postharvest quality attribute expected to be preserved in the light treated vegetables are necessary to consider for the success of the postharvest LED application. Postharvest blue LED illumination from 460 & 465 nm positively impacted the microbial quality of vegetables. However, more research is needed to be carried out to establish clear-cut information.

CRediT authorship contribution statement

Wadduwa Pathirage Thilini Deepashika Perera: Conceptualization, Validation, Writing – original draft, Writing – review & editing. Senevirathne Navaratne**:** Funding acquisition, Project administration, Supervision, Writing – review & editing. **Indira Wickramasinghe:** Funding acquisition, Project administration, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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