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EXPLORING THE IMPACT OF LIGHT TECHNOLOGY ON THE PREHARVEST AND POSTHARVEST QUALITY OF FRESH PRODUCE: A REVIEW

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Abstract: Fresh produce is highly susceptible to physiological deterioration and decay due to mechanical damage, improper storage, environmental stress, and bacterial as well as fungal contamination, resulting in limited shelf life. Biofilm-forming bacteria can reside as micro-colonies on the exterior of vegetables and fruits, increasing their resistance to adverse conditions, including antibiotics and disinfectants. Due to growing health concerns, consumers are increasingly rejecting chemical preservation methods. Therefore, safer and more sustainable alternatives are urgently needed to ensure food safety and security. Light technology has emerged as a promising solution due to its effectiveness, residue-free nature, and ability to control decay while extending shelf life. Light-emitting Diode (LED) irradiation, in particular, can stimulate antioxidant and bioactive compound synthesis, enhance crop yields, preserve quality, inactivate pathogens, and retain nutritional value during both preharvest and postharvest stages. LED is a safe technology that uses minimal heat and improves food safety without using additives and chemical sanitisers that meet the United States Department of Agriculture and the US Food and Drug Administration requirements. This review examines light technology's effectiveness on the preharvest and postharvest quality of fresh produce in terms of marketability and food safety.

Keywords: LED lights, nutritional quality, preharvest quality, postharvest preservation.

Introduction

Fruits and vegetables are essential dietary sources vitamins and minerals, including vitamins B6 and C, and pro-vitamin A. Vitamin C, in particular, enhances the absorption of dietary iron (Abdullah *et al*., 2023). Compared with other food sources, they are also rich in potassium and low in sodium. In addition, they are rich in various bioactive compounds such as dietary fibres, tocopherols, glucosinolates, thiosulfinates, carotenoids, phytosterols, and phenolic compounds such as flavonoids and catechins (Karasawa & Mohan, 2018).

The Food and Agriculture Organisation of the United Nations (FAO) estimates that at least one-third of the globally produced food goes to waste every year (about 1.3 billion metric tonnes), with horticulture's waste commodities (vegetables and fruits) ranking first among all food waste types, reaching up to 60% (FAO, 2014). Losses and waste can occur throughout the supply chain, including harvesting, production, transportation, grading, processing, pre- and post-preparation, marketing, and storage (Al Shaibani *et al*., 2022).

The postharvest problem has become an important concern worldwide in economically developed and developing nations. The stage is a vital agricultural component that maximises the shelf life and preserves the standards of fresh horticultural commodities (Ahmed *et al*., 2016).

Postharvest activities ensure that the produce enters the market in the most optimum form (Valenzuela, 2023). Maintaining postharvest quality is crucial for minimising food loss and ensuring food security (Kaur *et al*., 2023). The effectiveness of various interventions such as the exogenous application of hydrogen-associated treatments, ozone technology, and the use of light-emitting diodes (LED), remains underexplored (Ahmed *et al*., 2022). Recently, Aslam *et al*. (2020) and Ali *et al*. (2024) provided an insight review of the recent advancements in hydrogen-associated treatment and ozone technology and their roles in managing fresh commodities' postharvest quality, respectively. However, a comprehensive evaluation of LED lighting technologies in this context was lacking.

There is growing interest in the use of LEDs as a modern technique applied for managing the postharvest quality in horticultural crops. Numerous studies have investigated the application LEDs for extending the shelf life of fruits and vegetables during the postharvest period (Nassarawa *et al*., 2021). LEDs emit radiation with narrow bandwidths, offering benefits such as low thermal effects and high irradiance, and can be integrated into electronic systems (Branas *et al*., 2013). Additionally, LED systems are cost-effective and contribute to reducing disease susceptibility, enhancing yield, and improving crop quality.

As a preservation tool, LEDs have shown potential in delaying senescence, stimulating ripening, and enhancing the nutritional and bioactive compound content of fresh produce (Bantis *et al*., 2018). Delayed senescence can increase the consumability duration of fresh produce before they are marketed. Ripening is one of the physical attributes that consumers look for before consuming fresh fruits and vegetables. With the LED light treatment, ripening is said to be at the best level. LED light irradiation in a certain period could enhance the ripening process as one of the postharvest quality attributes. LED technology has also been used to reduce microbial growth during storage and inactivate various pathogens, for instance, yeast, bacteria, fungi, and viruses (D'Souza *et al*., 2015).

This review aims to discuss how light technology affects the preharvest and postharvest quality of fresh produce, with particular focus on the use of LED irradiation.

Overview and Mechanism of LEDs

LED lights are among the latest advanced technologies designed to reduce the environmental impat of conventional bulbs. One of their key advantages is their lower carbon emissions compared with traditional bulbs. LED lights do not radiate heat faster. Studies have demonstrated that different LED light spectra can positively influence crop yield and quality during both preharvest and postharvest stages. Furthermore, LED lights contribute to mitigating global warming effects by emitting safer wavelengths than ultraviolet (UV) light and producing minimal heat, making them suitable for sustainable agricultural practices.

According to Pimputkar *et al*. (2009), LEDs are applied widely because of their high brightness, longer lifetime, environmental friendliness, and spectral manipulation. The benefits of using LEDs compared with other conventional artificial lighting are high conversion efficiency with low production of heat radiance and energy conservation. The properties of semiconductor materials in LEDs have influenced the wavelength of emitted light (Olle & Viršilė, 2013). LEDs are employed as a source of artificial lighting in closed-type plant production systems. Environmental conditions are controlled in permitting crops to become available all year round, except for severe weather events. Prior research has examined LED efficiency for postharvest treatments and investigated the nutritional quality found in fruits and vegetable crops after the treatment of LED lighting for a certain period.

According to Bourget (2008), LEDs release a narrow band wavelength from 250 nm for UV-C to 1,000 nm for infrared. LED is a semiconductor device that produces light via electroluminescence, a phenomenon where a material emits light while a current is flowing or an electric field is passing through it. The LED consists of a semiconductor with a p-n (positive-negative) junction, comprising p-type (positively doped), and n-type (negatively doped) semiconductors on the respective right and left sides. A depletion region is formed due to diffusion currents, acting as a barrier between the p-type and n-type regions, which prevents the movement of electrons from the n-type semiconductor and holes from the p-type semiconductor. Electrons and holes, the latter being the absence of particles, spontaneously recombine when a forward bias induces their interaction within the depletion region. This recombination process generates light in the form of photons through spontaneous emission.

One advantage of LEDs is their capacity to regulate Photosynthetic Photon Flux (PPF), which is the amount of light and intensity produced (Rasiukevičiūtė *et al*., 2022). There are numerous uses of LEDs in crop preservation, horticulture, and agriculture. Figure 1 shows the working principle of LEDs.

Effects of LED on Preharvest Quality of Fresh Produce

The use of LED lighting in preharvest stages has demonstrated significant potential to enhance plant growth, morphology, and nutritional quality. The combination of far-red light with red LEDs or white LEDs and fluorescent lamps has been shown to promote biomass accumulation and leaf length in leafy greens (Li & Kubota, 2009; Stutte *et al*., 2009). Under red light treatment with a 50 μmol $m^{-2}s^{-1}$ light intensity, broccoli, or *Brassica oleracea* var. *italica*, exhibited delayed senescence (Ma *et al*., 2014). With the storage, period of postharvest broccoli being longer under red LED treatment. However, Demotes-Mainard *et al*. (2016) discovered that the low red-to-far-red light (R:FR) ratio could reduce the chlorophyll level in a few crop species.

Son *et al*. (2012) reported that red LED lighting is the most effective as it has the potential to increase the mass per unit area of lettuce. Red light irradiation has a significant influence on plant development as it has a

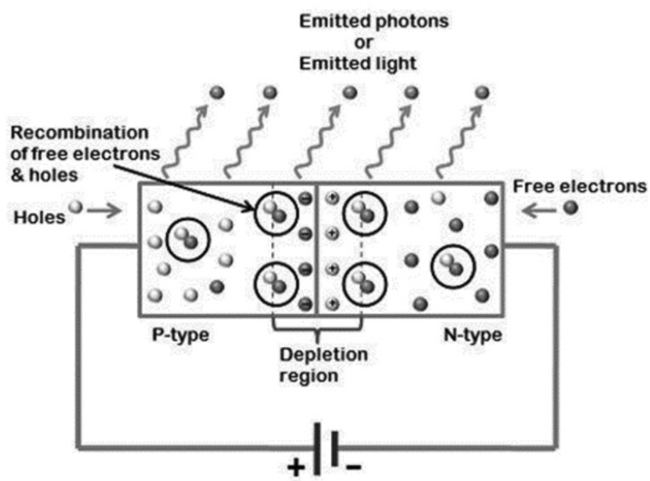

Figure 1: Working principle of light-emitting diodes
Source: Electrical4U (2020)

role in stimulating photoreceptors. Folta and Childers (2008) stated that red light causes phytochromes to change from dormant to active. Photoreceptors are specialised proteins in plant cells that sense light and play a crucial role in regulating various light-dependent processes such as photomorphogenesis, which affects plant growth and development. Red light triggers mesophyll cells' intercellular gaps to absorb CO_2 for the photosynthesis process, thereby enhancing plants' growth photosynthetic ability (Kim *et al*., 2005).

Phototropism, photomorphogenesis, stomatal opening, and photosynthesis are part of plant processes that require blue lighting. Phototropism, growth, circadian rhythms, opening of stomata, and chloroplasts' intracellular position to increase light absorption are examples of how plants respond to blue light. The impact of blue light source on the photosynthetic rate may have a relation with chloroplast protein. Muneer *et al*. (2014) stated that blue LEDs can induce plant growth because it can control chloroplast protein integrity and help to improve photosynthetic ability. Izzo *et al*. (2020) also reported that tomato plants were observed to produce more biomass under a blue and red light treatment. Proper control of light quality can lead to improvement in crop quality and yield. Liu *et al*. (2011) found that blue lighting is necessary for the proper structure of chloroplasts.

Combining red and blue LEDs has emerged as one of the most effective lighting strategies in controlled-environment agriculture (Yorio *et al*., 2001). Blue LEDs, with a wavelength range of about 440 nm to 476 nm, when used alone or combined with red LEDs have been shown to increase mass per unit of area in lettuce (Johkan *et al*., 2010). In lettuce, stem length is more effectively regulated under pure blue light. Cope and Bugbee (2013) reported that higher levels of blue light lead to a reduction in stem elongation.

Fan *et al*. (2013) found that blue and red LED lights produced varying light intensities within a uniform spectrum. They also observed that different light intensities influenced the growth and leaf development of young tomato plants. In a postharvest treatment of cherry tomatoes, exposure to blue and red LED lights for 10 days triggered a colour change from immature green to yellow and red.

Effect of LED on the Phytochemical Content of Fresh Produce

LED light increases the concentration of nutritional compounds in vegetables and fruits. Each fresh produce has distinct type of bioactive compounds and different LEDs play different roles in producing distinct secondary metabolites. This highlights the important role of LED lighting during the postharvest period in maintaining or enhancing nutritional content. These nutrients such as anthocyanins, flavonoids, carotenoids, and phenolic compounds are vital to human health due to their antioxidant properties.

Blue light irradiation has been shown to increase phenolic compounds in green vegetables (Johkan *et al*., 2010; Bian *et al*., 2016), raise vitamin C levels (H. Li *et al*., 2012), and leaf colouration (Xin *et al*., 2015). In tomatoes, which are rich in lycopene, exposure to red LED and darkness resulted in higher lycopene levels than those pre-treated with blue light (Dhakal & Baek, 2014). However, prolonged blue light exposure followed by storage in the dark also gradually raised lycopene content, suggesting that blue LEDs can extend shelf life and delay ripening by slowing red colour development.

Prior research has also shown that postharvest light treatment for fresh commodities can increase the antioxidant compounds in sweet cherries (Kokalj *et al*., 2019), Phlegrean mandarins (Costanzo *et al*., 2023), and baby mustard (Sun *et al*., 2021). In addition, green (510 nm) and a combination of red and white LEDs have been shown to enhance both antioxidant properties and anthocyanin accumulation (Lekkham *et al*., 2016). The observed improvements in antioxidant characteristics may be attributed to the induction of beta-carotene, glucosinolates, free radicals, scavenging activity, Reactive Oxygen Species (ROS)-scavenging enzymes, phenolic compounds, and vitamin C (Johkan *et al.,* 2010 and Kim *et al.,* 2013).

Total Anthocyanin Level

Anthocyanins are widespread in higher plants and are responsible for the red, purple, blue, and violet pigmentation in fruits, vegetables, and flowers. Studies have shown that LEDs can regulate anthocyanin synthesis in fruits such as immature strawberries (*Fragaria ananassa*) and Chinese bayberries (*Myrica rubra Sieb*) by modulating the expression of anthocyanin biosynthesis genes (Shi *et al*., 2014; Xu *et al*., 2014a; 2014b). An eight-day treatment of blue LED with a 40 µmol $m^{-2}s^{-1}$ intensity effectively improved the overall anthocyanin level in Chinese bayberries. The most effective biosynthesis regulation of anthocyanin in strawberries was under blue light. Xu *et al*. (2014a) reported that under blue light treatment, there was an increased total anthocyanin content in strawberries during the first four days of storage and nearly doubled after 12 days, compared with the control samples. This enhancement is linked to interactions among enzymes in the phenylpropanoid, shikimate, flavonoid, and pentose phosphate pathways.

Mixed artificial lighting, particularly blue-red LEDs also enhances anthocyanin accumulation due to a synergistic effect mediated by specific pigmentation-related genes. Heo *et al*. (2012) found that blue-red LED treatment at 90 µmol $m^{-2}s^{-1}$ doubled anthocyanin levels in lettuce compared with control samples. Additionally, blue light can help reduce nitrate accumulation in lettuce (Xin *et al*., 2015). Continuous exposure to blue-red LEDs for 48 hours is recommended for optimal results. Similarly, storing grapes under blue-red LED lighting for 10 days significantly increased anthocyanin levels (Rodyoung *et al*., 2016) (Table 1).

Table 1: Effects of LED treatment on the bioactive compounds of fruits and vegetables during postharvest storage
Source: Nassarawa *et al*., (2020)

Treated Fruits/ Vegetables	LED Type	Treatment	Results	References
Blueberries (*Vaccinium*)	Red LED treatment	2, 4, and 6 hours of LED treatment	Total phenolic content increased as storage time increased.	Spotts *et al*. (2017)
Blueberries (*Vaccinium*)	Red, blue, and green LEDs (630, 463, and 520 nm, respectively)	Treatment for 3 days under 20°C with a wavelength of 20 Wm^{-2}	Non-flavonoid content such as vitamin C, chlorogenic, and caffeic acid showed a slightly higher result in blueberries. Total phenolic content was also significantly higher in blueberries.	Kim *et al*. (2011)
Satsuma mandarins (*Citrus unshiu* Marc.)	Blue and red LED treatment	Treatment for 6 days at a photon release rate of 50 Wm^{-2}	The accumulation of β-cryptoxanthin was induced by red light but unaffected by blue light.	Ma *et al*. (2012)
Non-matured strawberries (*Fragaria ananassa)*	Blue LED treatment	Treatment for 12 days with 470 nm	Total phenolic content slightly increased at 5°C.	Kim *et al*. (2011)
Non-matured broccoli	Blue LED treatment	Treatment for 7 days with 20 Wm^{-2} under 2°C	Total phenolic content increased slightly at 2°C.	Zhan *et al*. (2012a; 2012b)

Blueberries (*Vaccinium*)	Blue, red, and green LED treatment (470, 525, and 630 nm, respectively)	Treatment for 10 days	The treatment slightly increased the anthocyanin level in blueberries.	Shi *et al*. (2014)
Grape berries (*Vitis labruscana Bailey* x 'Kyoho')	Blue LED light	Treatment for 9 days at a rate of 80 Wm^{-2} under a temperature range between 15°C and 25°C	The anthocyanin level significantly increased under the blue light treatment.	Azuma *et al*. (2019)
Sweet cherries (*Prunus avium* L.)	Combination of white, blue, and green LED lights (450, 473, and 532 nm, respectively), UV-B (310 nm)	Treatment for 10 days at rates of 23, 0.046, 3.6, and 0.02 Wm^{-2} under temperature range between 1°C and 0.5°C	The anthocyanin level increased.	Kokalj *et al*. (2019)
Habanero peppers (*Capsicum chinense*)	Treatment of blue LED light	Treatment for 30 days under 4°C–5°C	All bioactive compounds and antioxidant capacity increased.	Pérez-Ambrocio *et al*. (2018)
Strawberries (*Fragaria ananassa*)	Blue LED light treatment	Treatment for 12 days under 5°C	The levels of phenolic acid and vitamin C increased significantly. The antioxidant level and DPPH scavenging activity also increased.	Xu *et al*. (2014a; 2014b)
Immature green tomatoes	Blue LED light treatment	Treatment for 21 days under 25°C	The lycopene content in green tomatoes increased as storage time increased.	Dhakal and Baek (2014)
Lettuce (*Lactuca sativa* L. cv. 'Zishan')	Red and blue LEDs	Treatment for 20 days under 23°C	The anthocyanin level, total flavonoid content, total phenolic, and vitamin C increased after 20 days of treatment.	Shao *et al*. (2020)
'*Kyoho*' grapevine (*Vitis labrusca* x *Vitis vinifera*)	Red and blue LED lighting	Treatment for 10 days under 35°C	Anthocyanin accumulation increased.	Rodyoung *et al*. (2016)
Citrus fruits (*Citrus* sp.)	Red and blue LED lighting	Treatment for 6 days under 20°C	The antioxidant level, total phenolic content, and vitamin C value increased significantly after six days of treatment.	Xu *et al*. (2014a; 2014b)
Chinese bayberries (*Myrica rubra* Sieb. and Zucc.)	Blue LED lighting	Treatment with 40 $\mu mol\ m^{-2}s^{-1}$	The anthocyanin level increased under the treatment of blue LED with 40 $\mu mol\ m^{-2}s^{-1}$.	Shi *et al*. (2014)

Studies by Chua *et al*. (2021) and Ching *et al*. (2022) demonstrated that treating tomatoes and strawberries with 405.5 nm LED light significantly enhanced their antioxidant activities during storage. This effect is attributed to the complex interactions between light and plant physiology, particularly through the activation of plant photoreceptors by the 405.5 nm wavelength. When exposed to specific wavelengths of light, these receptors trigger a range of biochemical and physiological reactions that stimulate the synthesis of antioxidant compounds. Consequently, this light-mediated activation strengthens the plant's defence mechanisms, leading to an enhanced vital antioxidant, including phenolic compounds, flavonoids, and ascorbic acid, over the storage period.

Similarly, postharvest ultraviolet (UV) irradiation has been identified as an effective treatment for bell peppers, markedly increasing the biosynthesis of bioactive compounds, especially flavonoids and carotenes (Castillejo *et al*., 2022). This effect occurs through the activation of signalling pathways that upregulate metabolic processes responsible for the production of these compounds. Flavonoids and carotenes, known for their antioxidant properties, contribute to the plant's defence against environmental stressors while also enhancing the nutritional value and visual appeal of fresh produce. Plants perceive UV light as a stress signal, triggering protective responses that activate phytochemical pathways and increase the accumulation of antioxidant-rich secondary metabolites.

Total Carotenoid Content

Carotenoids are natural pigments found in the chloroplasts and chromoplasts of plants. They serve numerous vital roles, including stabilising lipid membranes, colour attractants, antioxidants and photo-protectors. They are also predecessors of abscisic acid (ABA) or plant hormones, in plants' non-photosynthetic organs (Ma *et al*., 2012; Maoka, 2020). As an essential carotenoid in citrus fruits and human plasma, β-Cryptoxanthin has a significant influence in reducing risks of infection and helping to treat certain diseases, especially cancer, due to its antioxidant properties (Ma *et al*., 2012; Burri *et al*., 2016).

The effect of LED light on carotenoid content has been studied in various fruits and vegetables. In Satsuma mandarin, red LED irradiation at an intensity of 50 μmol $m^{-2}s^{-1}$ over six days significantly increased β-cryptoxanthin levels while blue light had no effect. The escalations in the gene expression, which include CitLCYb1, CitLCYb2, CitHYb, CitPDS, CitPSY, CitZEP, and CitZDS were believed to be the cause of ß-cryptoxanthin accumulation (Ma *et al*., 2012) (Table 1).

Similarly, Wu *et al*. (2007) found that ß-carotene levels increased under red light treatment more effectively than blue light treatment in pea seedlings' leaves and stems. Xie *et al*. (2019) reported a higher lycopene concentration in tomatoes and induced gene expression related to the lycopene synthesis pathway due to supplemented blue-red LED treatments. According to Soytong *et al*. (2021), the carotenoid properties in tomatoes are key to their distinctive red colour and nutritional quality.

Total Phenolic Content

Phenolic compounds such as flavonoids are commonly found in a wide range of fruits and vegetables. Xu *et al*. (2014a; 2014b) reported that blue light treatment at a 470 nm wavelength resulted in significantly increased total phenolic content in fruits. In citrus fruits, flavonoids and limonoids are the primary health-promoting constituents and exhibit diverse biological activities (S. Liu *et al*., 2019).

Blue LED irradiation has been shown to improve total flavonoid content in various produce, including tea plants (Wang *et al*., 2020), Brussels sprouts (Hasperué *et al*., 2016b), and mangoes (González-Aguilar *et al*., 2007). Wang *et al*. (2020) suggested that blue light may induce a higher level of flavonoid production.

Antioxidant activities are known to increase in plants that thrive in challenging environments. In general, antioxidant activity tends to rise in plants exposed to stress and blue light during postharvest storage enhances antioxidant status in green vegetables. Seedlings grown under blue LED light show higher phenolic accumulation. S. Liu *et al*. (2019) also noted that blue LEDs promoted the biosynthesis of four flavonoid types.

In Newhall Navel oranges, flavonoids such as eriocitrin and neohesperidin were induced by red LED and UV-B irradiation. Different LED colours produce varying bioactive compound profiles in postharvest oranges. UV-A, UV-B, UV-C, red, and white LED lights have all been reported to enhance limonoid concentrations in fruits, including limonin, epilimnion, and 7α-limonyl acetate. However, these limonoids declined under blue light and darkness. Notably, epilimnion content increased under red light and UV-B while 7α-limonyl acetate rose with UV-A and UV-B exposure, even without additional light treatment. Blue-red LED treatment has also been shown to increase flavonoid content in microgreens (Lobiuc *et al*., 2017), While blue light induced the flavonoids accumulation in Saussurea's callus cultures (Guo *et al*., 2007). Red LEDs and UV-C proved to become more effective in boosting flavonoid levels during the postharvest period. In citrus fruits, the flavonoids and limonoids' metabolism are affected by both light irradiations, namely LED and UV light. Lee *et al.* (2014) found that white and green light (524 nm) enhanced the total phenolic content in cabbage.

Vitamin C

Red and blue LED lighting plays an important role in vitamin C metabolism in three different citrus species' juices: Lisbon lemons, Valencia oranges, and Satsuma mandarins (*Citrus unshiu Marc.*) (Zhang *et al*., 2015). Blue, red, green, or white LEDs have the potential to enhance cultivated vegetables' nutritional value. Different-coloured LED lights have distinct effects on specific bioactive components in fresh commodities. According to Table 1, both varieties of cabbage, *Brassica rapa* and *Brassica oleracea* (wild cabbage) treated with blue light under a 50–80 μmol $m^{-2}s^{-1}$ intensity showed increase in their composition of vitamin C (Lee *et al*., 2014). Green LED light also raised vitamin C concentration in wild cabbages, strawberries, and lettuce (Lee *et al*., 2014). Red lights has been reported to enhance vitamin C levels in sprouts and microgreens (Brazaitytė *et al*., 2013) while blue light could elevate amaranth microgreens' vitamin C content (Meas *et al*., 2020).

Effects of LED on the Physiochemical Properties of Fresh Produce

Kasim and Kasim (2017) reported that green, red, and white LED light treatments extended the shelf life of leafy lettuce. Hasperué *et al*. (2016b) found that a combination of white light and blue light effectively preserved the quality of Brussels sprouts during the postharvest period and transportation stage. The irradiation of red (Ma *et al*., 2014) and green LEDs (Jin *et al*., 2015) applied during the postharvest period helped delay the ageing and prolong the shelf life of broccoli.

A previous study confirmed that the quality of postharvest vegetables would be maintained with the application of LED lights (Pataro *et al*., 2015). The blue LEDs, in particular, were effective in minimising weight loss, delaying firmness reduction, and preserving the colour of strawberries (Hidayah, 2021).

Yellowing of leaves is a common postharvest issue in pak choi. Hasperué *et al*. (2016b) observed that LED light treatment delayed yellowing and reduced the respiration rate in Brussels sprouts. Similarly, blue light was most effective in delaying Browning Incidence (BI) in fresh-cut pineapples, preserving key postharvest quality traits regardless of exposure duration (Qi, 2019).

In broccoli, repeated exposure to blue-white LED treatment extended storage life and increased the accumulation of antioxidant compounds, confirming the benefit of continuous application (Hasperué *et al*., 2016a).

Total Soluble Solids

Total Soluble Solids (TSS) refer to the total amount of solids found in vegetables and fruits, including total soluble sugar, acids (malic and citric acids), and additional elements like minerals, vitamin C, phenols, and amino acids. A previous study found that after seven days of storage in the dark, the TSS content of tomatoes priorly treated with red and blue lights and darkness showed insignificant differences and remained constant after 14 days of storage. This suggests that the sweetness of the tomatoes was preserved during this period. However, a notable decline in TSS content was observed by day 21 (Dhakal & Baek, 2014).

In contrast, citrus fruits under the treatment of blue and red LEDs (470 nm and 660 nm, respectively) for six days at a temperature of 20°C experienced an increase in both TSS and vitamin C levels. Blue light treatment using a 470 nm wavelength also elevated TSS levels in postharvest peaches. Sun *et al.* (2014) reported that white LED treatment enhanced the TSS content of red Chinese sand pear fruit over a 10-day period at 32°C, in comparison to the untreated sample. Lin *et al.* (2013) also noted that the highest content of soluble sugars in lettuce was observed under a combination of red, blue, and white LED treatment, indicating that such treatments may be beneficial in enhancing sugar content.

Firmness

Dhakal and Baek (2014) reported that blue LED was more effective than red LED in delaying firmness loss in fruits, thereby extending their shelf life during the postharvest phase (Table 2). In immature tomatoes, firmness decreased as storage time increased; however, those exposed to blue light maintained higher firmness levels compared to samples treated with red light or kept in darkness. This finding was supported by the observation that blue-light-treated tomatoes had a firmer texture.

Table 2: Effects of LED on postharvest quality of fruits and vegetables crop
Source: Hasan *et al*. (2017)

Type of LED Light	Light Intensity	Crops	Effects on Postharvest Quality to Treated Crops	References
Red	Treatment with 50 $\mu mol\ m^{-2}s^{-1}$	Broccoli (*Brassica oleracea* var. *italica*)	Delayed senescence.	Ma *et al*. (2014)
Blue	Treatment with blue LED for 12 days	Strawberries (*Fragaria ananassa*)	Resulted in increased colour development after five days of blue light treatment. CRIG value also significantly increased with blue light treatment.	Xu *et al*. (2014a; 2014b)
	Treatment with 85 to 150 $\mu mol\ m^{-2}s^{-1}$	Tomatoes (*Solanum lycopersicum*)	Shelf life, γ-aminobutyric acid, and free amino acid.	Dhakal and Baek (2014)
	Treatment with more than 20 to 40 $\mu mol\ m^{-2}s^{-1}$	Strawberries (*Fragaria* x *ananassa*)	Ripening, where the results showed there was colour development after five days of treatment.	Xu *et al*. (2014a)

Blue	Treatment with 40 μmol $m^{-2}s^{-1}$ and under 470 nm	Peach (*Prunus persica*)	Ripening, where the results showed there was an increase in the production of ethylene, causing the occurrence of colour development. The value of Ttotal Soluble Solids (TSS) increased while acidity decreased after 15 days of storage.	Gong *et al*. (2015)
	Treatment with 40 μmol $m^{-2}s^{-1}$ and under 470 nm of 10°C	Chinese bayberries (*Myrica rubra* Sieb. and Zucc.)	The anthocyanin level slightly rose. The TSS level slightly increased after eight days of storage treatment.	Shi *et al*. (2014)
	Treatment with blue LED light under 445 nm with a temperature of 15°C to 25°C	Grape berries (*Vitis labruscana Bailey* cv. 'Campbell Early' and 'Kyoho')	After nine days of treatment, the firmness of grape berries was not significantly influenced by any other treatment. TSS showed a decrease after nine days of treatment.	Azuma *et al*. (2019)
Red and blue	Treatment of blue (655 nm) and red (456 nm) under 23°C for 20 days	Lettuce (*Lactuca sativa* L. cv. 'Zishan')	While ongoing treatment, lettuce showed an increased weight. However, after 10 days, the weight slightly decreased. Both treatments under red light and dark showed a significant increase in the TSS level compared to untreated samples.	Shao *et al*. (2015)
Red and blue	Treatment of blue (440 nm) and red (450 nm) under 25°C for 21 days	Immature green tomatoes	After blue, red light, and dark treatments, the colour development of tomatoes increased. The firmness level slightly decreased when the storage period increased. Tomatoes when treated with blue light resulted in a significantly increased firmness level compared to tomatoes under the treatment of red light and dark. The TSS level did not significantly differ when treated by any treatment after seven days.	Dhakal and Baek (2014)

Conversely, Azuma *et al*. (2019) found that even with other light treatments, the blue LED therapy had no discernible effect, where green tomatoes stored at 25°C under a red (450 nm) and blue (440 nm) LED combination for 21 days exhibited decreased firmness. These variations suggest that the physiochemical outcomes depend on the blue-to-red light ratio used in the treatment. However, C. Liu *et al*. (2022) reported that postharvest LED treatment positively contributed to maintaining the firmness of chilli peppers.

Colour

Cherry tomatoes exposed to blue and red LED treatments for ten days after harvest began to change colour from green to yellow and red. This result suggests that LED treatment can positively influence colour development in cherry tomatoes. As shown in Table 1, strawberries also exhibited colour changes after four days of storage under blue LED light (Xu *et al*., 2014a; 2014b). A blue LED treatment at a wavelength of 470 nm over 15 days increased ethylene production, which in turn accelerated the ripening process. Since ethylene plays a key role in fruit ripening, its peak production correlates with faster colour development in postharvest produce.

Blue light irradiation was also found to influence tomato ripening by initiating colour changes from green to red, although in some cases it delayed these changes (Dhakal & Baek, 2014). For fresh broccoli, a decline in postharvest quality was observed when stored under low-intensity white LED light (20–25 μmol $m^{-2}s^{-1}$), as chlorophyll degradation led to yellowing of the broccoli heads (Favre *et al*., 2018). Figure 2 shows the summary of the mechanism and effects of LED treatment on the preharvest quality of fresh produce while Figure 3 shows the summary of the mechanism and effects of LED treatment on the postharvest quality of fresh produce.

Other Light Technology Treatments on Fresh Produce

In addition to LED lighting, ultraviolet (UV) radiation has also been studied for its effectiveness in enhancing the postharvest

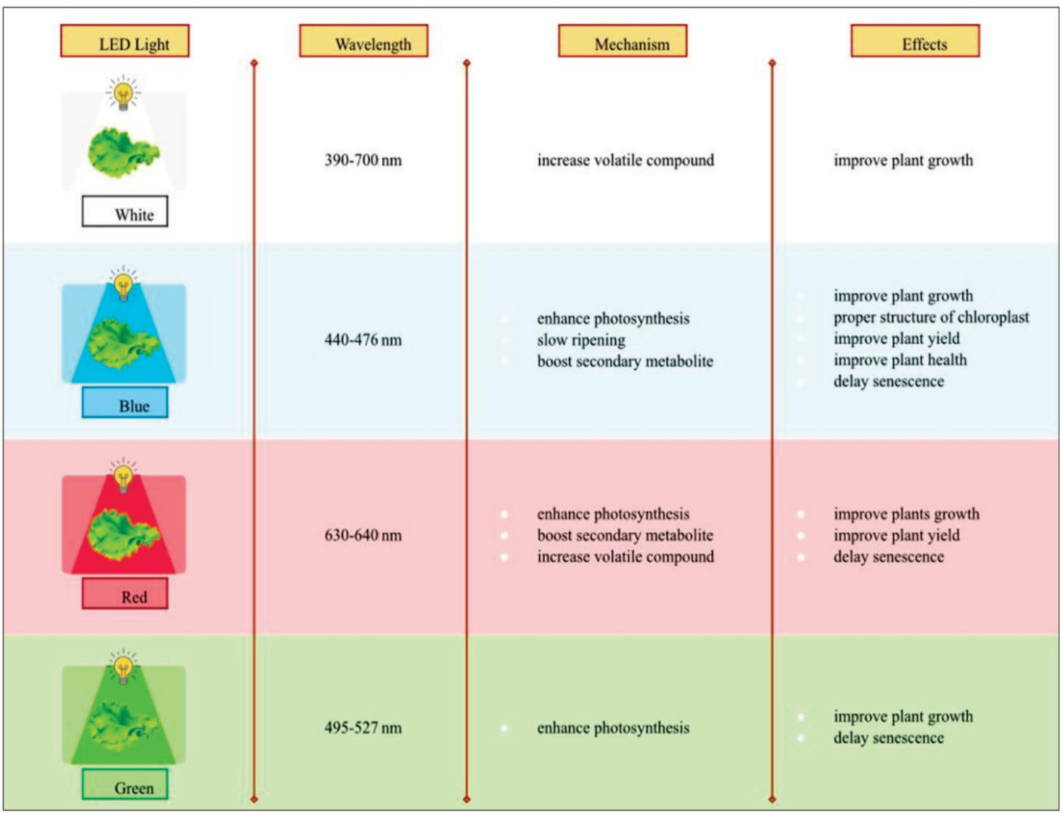

Figure 2: Summary of the mechanism and effects of LED treatment on the preharvest quality of fresh produce
Source: Author's collection

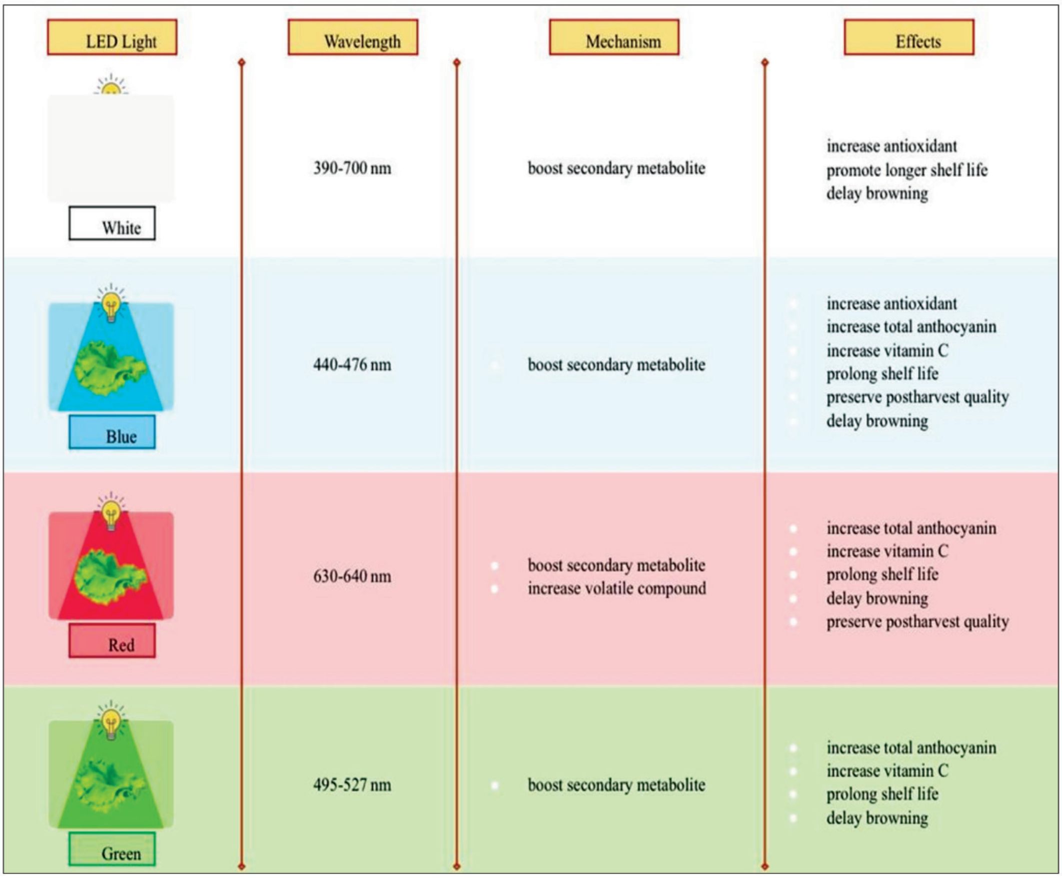

Figure 3: Summary of the mechanism and effects of LED treatment on the postharvest quality of fresh produce
Source: Author's collection

quality and nutritional value of fresh produce. UV light comprises three types: UV-A (315 nm–400 nm), UV-B (280 nm–315 nm), and UV-C (100 nm–280 nm) (Loconsole & Santamaria, 2021). As one of the key components in postharvest preservation, UV light offers advantages such as low cost and broad applicability across various crop types.

UV technology has been effective in extending the shelf life of fresh-cut produce such as pears, apples, pineapples, papayas, strawberries, and peaches (Turtoi, 2013; M. Li *et al*., 2019; Y. Li *et al*., 2022). These fruits are prone to rapid spoilage due to microbial contamination by bacteria, viruses, and pathogens. Examples of UV-A LED-treated produce include apples and pears (Lante *et al*., 2016) and watercress (Kanazawa *et al*., 2012).

UV treatment has also been reported to increase phytochemical levels, particularly flavonoids (Zhang *et al*., 2021). For instance, high levels of quercetin glycosides were observed in watercress and baby-leaf lettuce following UV-A and UV-B treatments, respectively (Kanazawa *et al*., 2012). Moreover, UV-A LED irradiation has demonstrated antimicrobial effects by inhibiting the growth of *Escherichia coli*.

By contrast, traditional lighting technologies such as incandescent, fluorescent, and high-pressure sodium lamps are less favourable for agricultural use due to their short lifespan, high energy consumption, and excessive heat output during prolonged use.

Conclusions and Future Direction

The use of LED lighting as a modern technology has proven effective in enhancing crop productivity and yield. Numerous studies have demonstrated the high efficiency of LED lights improving the nutritional value of fruits and vegetables such as tomatoes, broccoli, cabbages, leaf lettuce, strawberries, peaches, grapes, and citrus fruits. LED irradiation promotes the accumulation of several bioactive compounds, including anthocyanin, flavonoids, carotenoids, phenolic compounds, and vitamin C. In addition, LED treatment positively influences key physiochemical properties such as TSS, colour development, ripeness, and firmness.

Overall, studies have shown that LED treatment of white, blue, red, and green colour improves plant growth, postharvest quality, nutritional value, and the concentration of bioactive compounds in fresh produce both under field conditions and during postharvest processing.

In future, research in LEDs should investigate other vegetable and fruit crops and determine other beneficial properties such nutritional content, postharvest quality, as well as microbiological safety, of fresh produce. The combined effects of different LED colours and wavelengths on both preharvest and postharvest stages also warrant further investigation. Insights from such research can assist academics, local authorities, and industry stakeholders in developing innovative strategies to improve the storage and safety of fresh produce, contributing to food security and reducing food waste.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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