Greenhouse Plant Production Journal 1(4) (2024) 73 –92 gppj.araku.ac.ir

Greenhouse Plant Production Journal

Effect of different light spectra from light-emitting diodes (LEDs) on the postharvest quality of vegetables and fruits. A Review

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Review Article

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Citation: Azizi S., Esmaeili, S., Eskandarzadeh, P., Karimi, R., Lastochkina, O. and Aliniaeifard. S. 2024. Effect of different light spectra from light-emitting diodes (LEDs) on the postharvest quality of vegetables and fruits. A Review. Greenhouse Plant Production Journal, 1(4): 73-92.

https://10.61186/gppj.1.1.73

KEYWORDS

Antioxidant
Light quality
Senescence
Shelf-life
Storage

ABSTRACT

The postharvest quality of vegetables and fruits is significantly influenced by environmental factors, including light exposure. Light-emitting diodes (LEDs) offer a versatile tool for manipulating light spectra to enhance the preservation and quality of produce. This review examines the impact of different LED light spectra on the postharvest quality of vegetables and fruits. The research problem addressed is the optimization of LED lighting conditions to extend shelf life and maintain nutritional and aesthetic qualities of produce. The methodology involved a comprehensive analysis of existing literature on the effects of various LED light spectra, including red, blue, green, ultraviolet and combinations thereof, on postharvest attributes such as color, texture, and nutrient retention. Key findings indicate that specific LED spectra can delay senescence, reduce spoilage, and enhance antioxidant content in certain produce types. For instance, red light often promotes ethylene production, while blue light can suppress microbial growth. The main conclusions highlight the potential of tailored LED lighting strategies to improve postharvest management practices. These findings have significant implications for the development of more efficient storage and transportation systems, potentially reducing food waste and enhancing consumer satisfaction. Future research directions include exploring the molecular mechanisms underlying light-induced responses in produce and integrating LED technology into commercial postharvest handling systems. Overall, this review underscores the importance of light spectrum optimization in maintaining the quality and extending the shelf life of vegetables and fruits, contributing to a more sustainable food supply chain.

ARTICLE HISTORY

Received: 11 December 2024
Revised: 11 December 2024
Accepted: 31 December 2024

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Publisher: Arak University

1. Introduction

Postharvest quality preservation is critical to ensuring the availability of safe, nutritious, and marketable produce. Physiological deterioration, including water loss, chlorophyll degradation, texture softening, and nutrient depletion, significantly impacts the visual, sensory, and nutritional attributes of fruits and vegetables (Ziv and Fallik, 2021). Additionally, microbial decay caused by yeasts, molds, and pathogenic bacteria further exacerbates postharvest losses (Droby *et al*., 2016). Effective postharvest management strategies, such as controlled atmosphere storage, modified atmosphere packaging (MAP), and the application of chemical preservatives (e.g., 1-methylcyclopropene and chitosan coatings), have been widely employed to mitigate these issues (Amornputti *et al*., 2014). However, the increasing demand for chemical-free and sustainable preservation methods has driven research toward non-thermal and non-chemical alternatives, such as ultraviolet (UV) light and light-emitting diode (LED) technology (Khalighi *et al*., 2021).

Light-emitting diode (LED) technology has emerged as a promising tool for postharvest preservation due to its energy efficiency, customizable spectral output, and minimal heat generation. LEDs can emit specific wavelengths of light that correspond to the absorption spectra of plant photoreceptors, such as phytochromes, cryptochromes, and phototropins, enabling precise modulation of physiological processes (Aalifar *et al*., 2020a, 2020b; Aliniaeifard *et al*., 2020). Recent studies have demonstrated that LED lighting can enhance the postharvest quality of fruits and vegetables by regulating photosynthesis, delaying senescence, and increasing the accumulation of bioactive compounds such as phenolics, flavonoids, and antioxidants (Liu *et al*., 2015; Pintos *et al*., 2020). For instance, blue and red LED lights have been shown to improve the shelf life and nutritional quality of leafy greens, strawberries, and tomatoes by enhancing antioxidant activity and reducing microbial load (Dhakal and Baek, 2014a; Xu *et al*., 2014). Furthermore, the ability of LEDs to operate in continuous or pulsed modes makes them highly versatile for postharvest applications, including disinfection and quality enhancement (Prasad *et al*., 2020).

This review provides information on the application of LEDs for the postharvest preservation of fresh horticultural crops. It discusses how LEDs serve as a nonhazardous technique to enhance the ripening process and improve nutritional parameters, secondary metabolites, and overall fruit quality. Additionally, the review addresses how LEDs can delay senescence and promote quality improvements in fruits. The physiological responses of postharvest vegetables examined in this review include photosynthesis, senescence, antioxidant activity, membrane integrity, lycopene content, vitamin C levels, phenolic compounds, and chlorophyll metabolism. It also covers future prospects, practical applications, and limitations of using LED light in the postharvest treatment of vegetables, thus opening new avenues for research in this area.

2. LED Technology in Postharvest Applications

Light-emitting diodes (LEDs) have revolutionized postharvest technology by offering precise control over light spectra, which significantly influences the physiological and biochemical properties of stored produce. Unlike traditional lighting systems, LEDs can emit specific wavelengths of light, including ultraviolet (UV), blue (400–500 nm), green (500–600 nm), red (600–700 nm), and far-red (700–800 nm) spectra. Each of these wavelengths has distinct effects on fresh produce, from delaying senescence to enhancing nutritional quality (Sena *et al*., 2024).

Blue light is recognized for its antimicrobial properties, reducing microbial growth on fresh produce surfaces and extending shelf life. Red light, in contrast, can enhance anthocyanin accumulation, improving the color and antioxidant properties of fruits and vegetables. Far-red light influences phytochrome-mediated responses, affecting ripening and dormancy processes. Additionally, UV-A and UV-B light play roles in inducing secondary metabolite production, enhancing resistance to pathogens and improving the nutritional content of stored crops (Poonia *et al*., 2022).

LEDs offer several advantages over conventional lighting technologies such as fluorescent, incandescent, and high-pressure sodium (HPS) lamps. These advantages include energy efficiency, longevity, minimal heat emission, and the ability to emit specific wavelengths suitable for postharvest applications (Nassarawa *et al*., 2021).

The application of LED technology in postharvest storage has gained significant attention due to its ability to enhance shelf life, maintain quality, and reduce postharvest losses. Several studies have demonstrated the effectiveness of LED lighting in different storage conditions for various crops (Ngcobo *et al*., 2021).

Overall, LED technology offers a sustainable and effective approach to postharvest storage. Its ability to enhance produce quality, extend shelf life, and minimize losses makes it a promising tool for modern agricultural practices. LEDs influence physiological processes like photosynthesis and senescence, enhancing freshness and extending shelf life by stimulating antioxidant activity. The antimicrobial properties of blue light LEDs control microbial contamination, while red light enhances pigmentation (Figure 1). LED treatments enrich the nutritional profile of produce by promoting the accumulation of bioactive compounds and elevating vitamin C levels. Prospects include non-chemical alternatives to traditional preservation methods and optimizing light spectra for specific crops to achieve sustainable postharvest management (Figure 1).

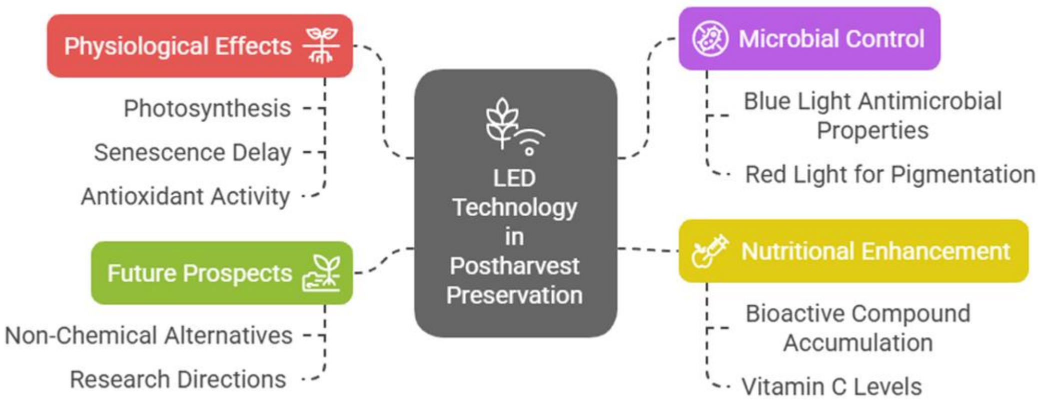

Figure 1. LED technology offers multifaceted applications and benefits in postharvest preservation, categorized into physiological effects, microbial control, nutritional enhancement, and future prospects.

3. Effects of Different LED Spectra on Fruit Quality

3.1. Red light

3.1.1. Impact on ripening

Among different light wavelengths, red light has been shown to play a significant role in modulating ripening by affecting ethylene biosynthesis, respiratory activity, and enzymatic processes. Research indicates that red light exposure can either accelerate or regulate ripening, depending on the fruit type and its physiological response to light (Qi *et al*., 2022). Ethylene is the primary plant hormone controlling ripening in climacteric fruits, including apples, pears, peaches, bananas, and plums (Nassarawa *et al*., 2021). Red light has been found to enhance ethylene production by stimulating the activity of 1-aminocyclopropane-1-carboxylic acid (ACC) synthase and ACC oxidase, key enzymes in the ethylene biosynthesis pathway (Houben and de Poel, 2019). Studies suggest that exposure to red light can accelerate the softening process and promote color changes in fruits such as peaches by increasing chlorophyll degradation and anthocyanin accumulation (Chi *et al*., 2023). In grapes and cherries, which are non-climacteric fruits, red light does not significantly affect ethylene levels but can influence phenolic metabolism and sugar accumulation, leading to enhanced pigmentation and improved sensory qualities (Kondo *et al*., 2014; Ngcobo *et al*., 2021). Red light exposure has been observed to influence fruit respiration rates, which are closely linked to ripening and senescence (Perera *et al*., 2022). In climacteric fruits, higher respiration rates under red light treatment can lead to faster sugar metabolism, resulting in increased sweetness and flavor development. For example, in bananas and pears, red light has been shown to enhance starch-to-sugar conversion, accelerating ripening and improving fruit palatability (Zhou *et al*., 2023). Conversely, in citrus fruits such as oranges and tangerines, red light may help maintain sugar-acid balance by modulating the activity of enzymes involved in citric acid metabolism (Figure 2). This effect contributes to prolonged freshness and improved taste during storage (Costanzo *et al*., 2023; Hu *et al*., 2019). For fruits requiring controlled ripening, such as apples, pears, and peaches, red light exposure can be utilized to synchronize ripening for market readiness (Peavey *et al*., 2024; Sun *et al*., 2014).

3.1.2. Effects on pigmentation and antioxidant content

Post-harvest quality preservation is crucial for maintaining the nutritional and commercial value of fruits. Recent research highlights the role of red light exposure in modulating key biochemical parameters, particularly pigments and antioxidants, which are essential for fruit longevity and consumer appeal. Red light influences chlorophyll degradation, anthocyanin accumulation, and carotenoid biosynthesis, impacting color and antioxidant potential (Lauria *et al*., 2023). Studies show that prolonged red light exposure enhances anthocyanin levels in cherries and grapes, improving their deep red coloration (Zhu *et al*., 2021). Similarly, moderate-intensity red light stimulates carotenoid synthesis in peaches and lemons, leading to improved yellow-orange hues and increased antioxidant activity (Zhang *et al*., 2011; Zhu *et al*., 2021). Antioxidants, including flavonoids and polyphenols, play a vital role in delaying senescence and oxidative stress (Table 1). Controlled red light treatments have been linked to elevated antioxidant enzyme activities in apples and grapes, reducing post-harvest deterioration. However, excessive intensity or prolonged exposure may induce photodamage, necessitating optimal light regulation (Yao *et al*., 2023).

3.2. Blue light

3.2.1. Influence on chlorophyll retention

Post-harvest preservation is a critical aspect of fruit storage and transportation, directly influencing marketability and consumer preference. Light exposure, particularly blue LED, has emerged as a non-chemical, energy-efficient method to modulate physiological changes in stored fruits. Among its various effects, blue LED light plays a significant role in delaying chlorophyll degradation, thereby maintaining the visual and nutritional quality of fruits such as pears, apples, peaches, bananas, and citrus fruits (Liu *et al.* 2022; Yuan *et al*., 2017). Chlorophyll degradation is a major post-harvest concern, as it leads to undesirable color changes, reducing consumer appeal. Blue LED light exposure has been shown to suppress chlorophyll catabolism in citrus fruits by downregulating key enzymes such as chlorophyllase, peroxidase, and pheophytinase (Table 1). Studies have demonstrated that low to moderate intensities of blue LED light can effectively delay yellowing in pears, bananas, and citrus fruits by inhibiting chlorophyll oxidation. This effect is particularly useful for fruits that undergo de-greening processes, such as grapefruit and oranges, where prolonged green retention can extend their shelf life (Liu *et al*., 2022; Mesa *et al*., 2024; Xu *et al*., 2014). The regulatory effect of blue LED light on chlorophyll metabolism is linked to its influence on photoreceptors such as cryptochromes, which modulate gene expression related to pigment retention. By reducing the enzymatic breakdown of chlorophyll, blue LED exposure can slow down senescence-related oxidative processes. Additionally, blue light has been observed to suppress the production of reactive oxygen species (ROS), mitigating oxidative stress that accelerates pigment degradation (Deng *et al*., 2017).

3.2.2. Effects on firmness and texture

Fruit softening is a major determinant of post-harvest quality, as it affects consumer preference, transportability, and resistance to microbial decay. Blue light has been found to modulate cell wall degradation by regulating the activity of pectinases, polygalacturonases, and cellulases enzymes responsible for breaking down pectin and cellulose, leading to fruit softening. Studies indicate that moderate-intensity blue light exposure can significantly delay firmness loss in apples, pears, and peaches by inhibiting these enzymatic activities (Chi *et al*., 2023; Tao *et al*., 2018). In citrus fruits such as oranges and tangerines, blue light treatment has been shown to preserve peel integrity, reducing shrinkage and wrinkling during storage (Figure 2). The firmness and texture of fruits are primarily governed by the structural integrity of their cell walls. Blue light has been observed to enhance lignin deposition and maintain higher levels of hemicellulose and pectin, thereby improving mechanical strength and reducing tissue breakdown. In climacteric fruits like bananas and plums, blue light exposure can slow the ripening process by modulating ethylene biosynthesis, indirectly affecting textural stability (Du *et al*., 2023; Gong *et al*., 2015).

3.3. Far-red light

3.3.1. Influence on ethylene production and on senescence

Recent studies suggest that far-red light (700–780 nm) exposure can modulate ethylene biosynthesis, thereby influencing fruit aging, ripening, and shelf life. Far-red light interacts with phytochrome photoreceptors, particularly phytochrome A and B, which influence ethylene synthesis (Song *et al*., 2023). Studies indicate that prolonged far-red light exposure can suppress ethylene production by downregulating key enzymes in the ethylene biosynthesis pathway, such as ACC synthase and ACC oxidase. This effect has been observed in climacteric fruits such as apples, where far-red light treatment has led to delayed ripening and extended storage life (Nassarawa *et al*., 2021). In contrast, in non-climacteric fruits such as citrus, cherries, and tangerines, far-red light appears to have a lesser impact on ethylene synthesis but may still influence secondary aging processes, including antioxidant activity and peel firmness (Molligan, 2023). In apples and pears, far-red light treatment helps maintain firmness by reducing pectin degradation and limiting the activity of polygalacturonases, which are responsible for cell wall breakdown (Lotfi, 2022). Additionally, in bananas and plums, far-red light has been found to slow the conversion of starch to sugars, prolonging the pre-ripening phase and extending shelf life (Bege *et al*., 2025; Muzzaffar and Sidiq, 2022). Researchers explored the impact of supplemental FR light on basil plants grown at different temperatures. Additional FR light enhanced the chilling tolerance of basil leaves stored at 4 °C and 12 °C, regardless of the cultivation temperature. The improved tolerance was associated with increased levels of soluble sugars and starch, suggesting these compounds play a role in mitigating chilling injury (Larsen *et al*., 2023). Moreover, far-red light may play a role in mitigating oxidative stress by modulating antioxidant enzyme activity. Reduced ethylene levels contribute to lower ROS accumulation, preserving fruit freshness and delaying discoloration (Figure 2) (Song *et al*., 2023).

3.4. UV light

3.4.1. Impact on ripening

Ultraviolet (UV) light-emitting diodes (LEDs) have gained significant attention in post-harvest fruit preservation due to their ability to influence microbial control, biochemical pathways, and ripening processes. In particular, UV-A (315-400 nm) and UV-C (200–280 nm) irradiation have been studied for their effects on fruits such as apples (*Malus domestica*), pears (*Pyrus communis*), and peaches (*Prunus persica*), with significant implications for maintaining post-harvest quality (Zhang and Jiang, 2019). Ripening in climacteric fruits like apples, pears, and peaches is largely governed by ethylene biosynthesis and enzymatic activities. Studies indicate that UV-C irradiation can delay ripening by downregulating ethylene biosynthetic enzymes such as 1-aminocyclopropane-1-carboxylate synthase (ACS) and oxidase (ACO). This inhibition reduces ethylene production, thereby slowing softening and color changes associated with ripening. Conversely, low doses of UV-A light can stimulate ethylene production and accelerate ripening by enhancing cellular respiration and metabolic activity (Yang *et al*., 2014; Zhang and Jiang, 2019). Apples and pears subjected to controlled UV-C exposure demonstrate reduced degradation of pectin and hemicellulose components, leading to prolonged storage life. Peaches, which are more sensitive to rapid softening, benefit from UV-C by maintaining cellular integrity longer compared to untreated samples (Zhang *et al*., 2013; Zhang and Jiang, 2019).

Table 1. Summary of the Effects of Different LED Light Spectra on Fruits Quality

Treated fruit	LED types	Treatments	Results	Reference	
Strawberries (*Fragaria ananassa*)	Blue LEDs	12 days of treatment at 5 °C	After 4 days of blue LED treatment, the color development in strawberries increased. However, the respiration rate decreased during the initial 2 days of storage, followed by a gradual increase in the control and blue light treatment at 5 °C	(Xu *et al*., 2014)	
Peaches (*Prunus persica*)	Blue LEDs	15 days of treatment at 10 °C	Blue LED treatment significantly increased ethylene production, and the maximum ethylene production was delayed from 6 to 9 days, Total soluble sugar (TSS) content increased, and acidity decreased in peaches after 15 days of storage at 10 °C	(Gong *et al*., 2015)	
Citrus fruits	Red and blue LEDs	6 days of treatment at 20 °C	After 6 days of red and blue LED treatment, the contents of antioxidants, phenolics, total soluble sugars, and ascorbic acid and enzymatic activities increased significantly at 20 °C	(Nassarawa *et al*., 2021)	
Blueberries	Red, blue, and green	3 days of treatment at 20 °C	After 3 days of LED treatment, the content of non-flavonoids, including ascorbic, chlorogenic, caffeic	(Kim *et al*., 2011)	

			acid, and rutin in blueberries, showed a maximum increasing trend overall. However, the content of phenolic compounds were significantly increased	
Banana	Blue	Daily exposure for 8 days at mature-green stage	Accelerated ripening, increased peel de-greening, enhanced flesh softening, elevated ethylene production, higher respiration rate, and increased ascorbic acid, total phenols, and total sugars	(Zhou *et al*., 2023)
Lemons (*Citrus limon*)	UV-B	22.0 kJ m^{-2}	After 2 days of UV-B treatment, the content of flavanones–dihydroflavonols, flavonols and anthocyanins were increased in 29, 214 and 218% than control	(Ruiz *et al*., 2016)
Grape	UV-B and UV-C	3.6 kJ m^{-2}	UV-C treatment maintained high soluble solids content (SSC) at 7 days; UV-B and UV-C treatment both increased total phenolic content, phenylalanine ammonia lyase (PAL) activity and antioxidant activity in the first 21 days at 4 °C.	(Sheng *et al*., 2018)
Apple	UV-B	219 kJ m^{-2}	High-dose UV-B treatment reduced weight loss and increased total phenolic content after 14 days at 20 °C	(Gogo *et al*., 2017)

4. Effects of Different LED Spectra on Vegetable Quality

The application of light-emitting diodes (LEDs) in postharvest storage has gained significant attention due to their potential to enhance vegetable quality (Bárcena *et al*., 2024). Different spectra of LED light can influence biochemical composition, shelf life, visual appeal, and resistance to pathogens (Salehinia *et al*., 2024). By tailoring the wavelength of LED light exposure, it is possible to modulate various physiological and biochemical responses in vegetables, optimizing their nutritional value and prolonging freshness (Kim and Eom, 2025). Understanding these spectral effects is essential for developing customized postharvest lighting protocols to meet specific quality requirements and consumer preferences (Nicole *et al*., 2017). This section discusses the effects of various LED spectra on vegetable quality and highlights their implications for enhancing postharvest management (Figure 2).

4.1. Red Light

Red light also plays a crucial role in promoting photosynthesis, enhancing vegetative growth, and increasing tomato yield. In controlled environments such as greenhouses, the combination of red and blue LED lighting has been shown to optimize plant development by regulating light-dependent physiological processes, ultimately resulting in improved crop performance and fruit quality (Arif et al., 2024). The use of red LED light (656 nm) has been shown to enhance the content of proline, soluble sugars, and antioxidant enzyme activity(Soufi et al. 2023a) .In controlled environments like greenhouses, combining red and blue LED light optimizes plant development, enhancing crop performance and fruit quality. Moreover, this combination boosts shoot fresh mass and yield in hydroponic systems, especially in NFT systems. Red light also improves nutrient uptake, reduces water and nutrient consumption, and lowers electricity costs compared to fluorescent lamps, making it an efficient choice for sustainable farming practices (Soufi *et al*,. 2023b).

4.1.1. Impact on Carotenoid Content

Red light (600-700 nm) plays a crucial role in enhancing carotenoid biosynthesis in vegetables, particularly in leafy greens and tomatoes (Panjai *et al*., 2021). Carotenoids such as lycopene and β-carotene are vital antioxidants that significantly enhance both the nutritional value and color development of various fruits and vegetables (Table 2). Lycopene, responsible for the red color in tomatoes, is recognized as a potent antioxidant, offering protection against oxidative stress (Srivastava, 2019). Studies have shown that exposure to red LED light can significantly increase carotenoid accumulation, improving both the health benefits and visual appeal of vegetables (Liu *et al*., 2009). Additionally, red light is known to stimulate phytoene synthase, a key enzyme in carotenoid biosynthesis, which leads to a higher concentration of these compounds (Welsch *et al*., 2000). The enhanced accumulation of carotenoids not only boosts the nutritional profile of vegetables but also provides increased resistance to oxidative stress, ultimately improving their postharvest stability (Li *et al*., 2012). Therefore, strategies that enhance carotenoid content can effectively improve both the nutritional quality and storage resilience of vegetables.

4.1.2. Effects on Shelf Life

Red light has also been reported to influence postharvest longevity by regulating ethylene production (Jiang *et al*., 2019). Red LED irradiation has been shown to maintain the postharvest quality of broccoli by enhancing antioxidant enzyme activity and reducing the expression of senescence-related genes. A study investigated the effects of red LED light exposure (50 $\mu mol\, m^{-2}\, s^{-1}$) on harvested broccoli stored at 20 °C for 5 days. The results indicated that red LED treatment helped preserve sensory quality by delaying yellowing and chlorophyll degradation. This preservation was associated with increased activities of antioxidant enzymes, including peroxidase (POD), catalase (CAT), and ascorbate peroxidase (APX) (Jiang *et al*., 2019). Additionally, red light enhances the synthesis of secondary metabolites that act as natural preservatives, minimizing spoilage and weight loss (Demir *et al*., 2023). Furthermore, exposure to red LED light has been shown to maintain the postharvest quality of leafy vegetables by delaying senescence and reducing chlorophyll degradation. Studies indicate that red light inhibits the expression of chlorophyll degradation and senescence-associated genes, leading to prolonged freshness (Song *et al*., 2020). Studies have demonstrated that red LED treatment can maintain higher levels of total soluble solids and decrease respiration rates, further supporting its role in enhancing vegetable shelf life (Nassarawa *et al*., 2021).

4.2. Blue Light

4.2.1. Influence on Glucosinolate Content in Brassicas

Blue light (400–500 nm) plays a significant role in the cultivation and postharvest quality of cruciferous vegetables such as broccoli, kale, and cabbage. Research indicates that blue light exposure can enhance the accumulation of beneficial compounds and influence growth characteristics in these vegetables (Flores *et al*., 2024). Postharvest exposure to blue LEDs has been demonstrated to upregulate genes involved in glucosinolate biosynthesis, thereby increasing their concentrations in stored vegetables (Zhuang *et al*., 2022). Additionally, the breakdown of glucosinolates into isothiocyanates under blue light exposure has been linked to enhanced flavor and increased resistance to microbial contamination (Dinkova-Kostova *et al*., 2017). The modulation of transcription factors such as MYB28 and MYB29 by blue light further strengthens the metabolic pathways responsible for glucosinolate accumulation, making this spectrum particularly valuable for improving the functional properties of cruciferous vegetables (Table 2) (Yin *et al*., 2017).

4.2.2. Effects on Vitamin C Retention

Another significant advantage of blue light is its role in preserving vitamin C content (Bournonville *et al*., 2023). Vitamin C (ascorbic acid) is indeed highly sensitive to oxidative degradation during storage. Factors such as temperature, oxygen exposure, light, and pH levels significantly influence its stability (Yin *et al*., 2022). Blue LED illumination has been found to mitigate oxidative stress and maintain higher vitamin C levels, particularly in leafy greens and peppers (Table 2). This contributes to improved nutritional quality and consumer acceptance (Kelly *et al*., 2022). The ability of blue light to regulate ascorbate peroxidase and other antioxidant enzymes helps in reducing vitamin C degradation caused by prolonged storage (Li *et al*., 2020). Additionally, blue LED treatment has been reported to delay polyphenol oxidase activity, which is crucial in preventing browning reactions in certain vegetables, thereby maintaining both nutritional and aesthetic qualities (Pihen *et al*., 2024).

4.3. Green Light

4.3.1. Impact on Chlorophyll Preservation

Green light (500–570 nm) has been less studied compared to red and blue light, but recent research suggests that it can play a role in maintaining chlorophyll levels in postharvest vegetables (Salehinia *et al*., 2024). By modulating chlorophyll degradation pathways, green light exposure helps retain the fresh, green appearance of leafy vegetables such as lettuce and spinach, preventing premature yellowing (Zhu *et al*., 2024). The suppression of chlorophyllase activity under green light treatment contributes to sustained photosynthetic pigment stability (Table 2). Moreover, green light is believed to enhance the activity of cytokinin, a plant hormone that delays senescence and maintains chlorophyll integrity, thus extending the marketability of vegetables (Kumari and Solankey, 2018).

4.3.2. Effects on Overall Visual Quality

Green LED illumination has been linked to enhanced visual appeal, particularly in maintaining uniform coloration and reducing the development of undesirable pigmentation (Zhang *et al*., 2018). While its direct biochemical impacts require further investigation, green light exposure appears to complement other wavelengths in preserving the aesthetic quality of vegetables. In addition, green light is known to influence anthocyanin distribution in certain vegetables, leading to more vibrant and attractive coloration (Palsha *et al*., 2024). By interacting with other wavelengths in mixed LED applications, green light can help balance the physiological responses of vegetables, optimizing both visual and textural properties (Figure 2) (Chen *et al*., 2016).

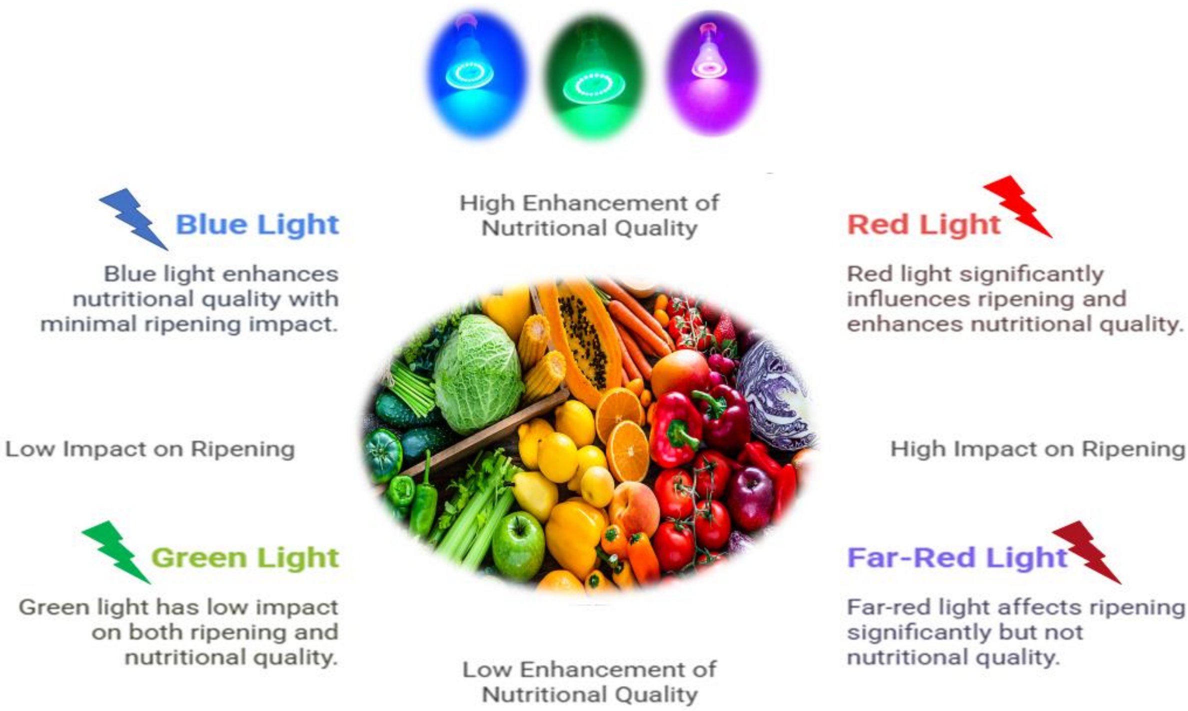

Figure 2. The effects of different light wavelengths—blue, red, green, and far-red—on the ripening process and nutritional quality of agricultural produce. Blue light is characterized by its ability to significantly enhance the nutritional quality of fruits and vegetables while having a minimal impact on the ripening process, making it a suitable choice for preserving freshness. Red light, on the other hand, plays a dual role by substantially influencing the ripening process and simultaneously improving nutritional quality. Green light shows minimal effects on both ripening and nutritional enhancement, indicating a limited role in postharvest management. Far-red light, however, has a strong influence on accelerating ripening but does not enhance the nutritional quality of the produce. This analysis underscores the potential of targeted light treatments in optimizing postharvest strategies for balancing shelf life, ripening control, and nutritional value in agricultural products.

4.4. UV Light

4.4.1. Influence on Pathogen Resistance

Ultraviolet (UV) light, particularly UV-B (280–315 nm) and UV-C (200–280 nm), has been widely studied for its antimicrobial effects (Bansaghi and Klein, 2024). UV exposure can induce the production of defense-related enzymes and antimicrobial peptides in vegetables, reducing microbial load and preventing fungal and bacterial infections. This contributes to prolonged shelf life and improved food safety (Menaka *et al*., 2024). The activation of plant defense mechanisms through UV light exposure, such as the accumulation of phytoalexins and increased production of reactive oxygen species, enhances resistance against spoilage organisms (Schumaker *et al*., 2024). Furthermore, UV-C treatment has been extensively utilized in postharvest management to reduce contamination by common pathogens like *Escherichia coli* and *Botrytis cinerea*, improving the microbial safety of fresh produce (Table 2) (Kodoth and Jones, 2015).

4.4.2. Effects on Phenolic Compound Accumulation

UV light also plays a crucial role in increasing the accumulation of phenolic compounds, which are known for their antioxidant, anti-inflammatory, and antimicrobial properties (Duval *et al*., 1999). Exposure to UV-B and UV-C radiation enhances phenolic synthesis in vegetables such as carrots, and peppers, leading to improved nutritional quality and stress tolerance (Castillejo *et al*., 2022; Formica-Oliveira *et al*., 2017). The upregulation of phenylpropanoid pathway enzymes, including phenylalanine ammonia-lyase (PAL), under UV light contributes to increased flavonoid and lignin production (Zhang *et al*., 2015). This not only enhances the bioactive properties of vegetables but also strengthens their structural integrity, making them more resistant to postharvest deterioration (Darré *et al*., 2022). The combined effects of UV-induced phenolic enrichment and pathogen resistance make this spectral treatment an effective tool for extending the storage life and health benefits of vegetables (Gastélum-Estrada *et al*., 2024).The table below summarizes the effects of various LED light spectra on different vegetables.

Table 2. Summary of the Effects of Different LED Light Spectra on Vegetable Quality

Crop	LED color	Effects on Plant	References
Green tomato *(Solanum lycopersicum* L.)	Red light (665 nm)	Reducing ripening time while enhancing nutritional quality (lycopene, β-carotene) and boosting antioxidant content (total flavonoids and phenolics)	(Panjai *et al*., 2017)
Broccoli heads (*Brassica oleracea* L. var. italica)	Red light (660 nm)	Delaying senescence by inhibiting ethylene production and slowing ascorbate processes	(Ma *et al*., 2014)
Red chard (*Beta vulgaris*)	Red light (660 nm)	Enhancing total phenol content and overall antioxidant capacity	(Pennisi *et al*., 2021)
Broccoli (*Brassica oleracea* L. var. italica)	Blue light (467 nm)	Preserving from postharvest senescence	(Loi *et al*., 2019)
Red chard (*Beta vulgaris*)	Blue light (465 nm)	Enhancing total phenol content and antioxidant capacity while reducing microbial counts	(Pennisi *et al*., 2021)
Wild rocket (*Diplotaxis tenuifolia*)	Blue light (465 nm)	Boosting total phenol content and antioxidant capacity	(Pennisi *et al*. 2021)
Broccoli (*Brassica oleracea* L. var. italica)	Green light (522 nm)	Preventing postharvest senescence by increasing ascorbic acid and chlorophyll content	(Loi *et al*., 2019)
lettuce	Green light (500 and 530 nm)	Increasing carotenoid, chlorophyll content and flavonoid	(Salehinia *et al*., 2024)
Red chard (Beta vulgaris)	Green light (517 nm)	Increasing carotenoids content	(Pennisi *et al*. 2021)
Wild rocket (Diplotaxis tenuifolia)	Green light (517 nm)	Maintaining chlorophyll content and visual quality while reducing microbial counts	(Pennisi *et al*. 2021)
Habanero pepper (*Capsicum chinense*)	Blue (465 nm) and UV-C LED light	Blue and UV-C LED light increased the content of all bioactive compounds and antioxidant capacity in habanero peppers stored at 4–5 °C for 30 days However, the enhancement of certain bioactive compounds, such as chlorophylls and total carotenoids, was noticeable only during the first day of storage	(Pérez-Ambrocio *et al*., 2018)
leaf vegetables (leek, spinach and cabbage)	UV-C	Multiple cycles of UV-C treatment maintained higher levels of soluble protein and ascorbic acid compared to a single treatment and delayed	(Liao *et al*., 2016)

		chlorophyll degradation for 5 days at 4 °C	
Ocimum basilicum	UV-C	Increasing total antioxidant capacity	(Solouki *et al*., 2023)
Tomato *(Solanum lycopersicum* L.)	Blue (400-500), Green (500-600), Red (600-700), Far-Red (700-790)	Increased yield by 60%, dry matter by 8-10%, and monosaccharides by 20%. Reduced stress from blue light. Improved appearance and nutritional value	(Dorokhov *et al.*, 2021)
Broccoli sprouts (*Brassica oleracea* var. italica)	Far-Red 730 nm	Promote the growth of hypocotyl and sprout length, enhance total antioxidant and scavenging activities, and reduce microbial growth.	(Castillejo *et al*,. 2021)

5. Challenges and Limitations

Post-harvest LED lighting can impact horticultural product quality, offering benefits but also potentially causing negative effects. While some studies report slight mass reduction due to increased moisture loss (D'Souza *et al*., 2017), potentially linked to specific wavelengths or prolonged exposure via stomatal opening, red and blue LED light generally improves nutritional quality and maintains product quality without significant mass loss (Maroga *et al*., 2019). However, high intensities, extended exposure, and continuous lighting can induce non-biological stress, leading to greater mass loss depending on the LED light spectrum (Pennisi *et al*., 2021). Therefore, careful selection of LED intensity, duration, and spectral combination is crucial for specific horticultural products.

Post-harvest light treatment in vegetables often leads to weight loss due to increased transpiration via open stomata (D'Souza *et al*., 2017; Pintos *et al*., 2020). For example, prolonged white LED light exposure increased weight loss in broccoli florets (Pintos *et al*., 2020), with higher light intensities (9.5 and 19.0 W m^{-2}) causing greater weight loss compared to dark storage. Consistent weight loss has also been observed in fresh-cut vegetables and red cabbage under continuous light, particularly with blue LED components, which promote stomatal opening and transpiration (Pennisi *et al*., 2021). Single-layered packaging further exacerbates moisture loss (Pennisi *et al*., 2021). While low-intensity LED lighting avoids non-biological stress, continuous use can still induce weight loss. However, cycled blue LED light (8 hours/day: 100 µmol $m^{-2}s^{-1}$) has been shown to maintain acceptable weight in sweet peppers for marketing (Maroga *et al*., 2019).

According to Lee *et al*. (2014), the duration of LED lighting can influence moisture loss in cabbage samples. Their findings suggested that LEDs either had no significant effect on moisture levels compared to dark conditions or showed varying impacts. Specifically, cabbages exposed to white, blue, and green LED light over 18 days (especially noticeable from days 9 to 18) exhibited lower moisture content compared to those treated with red LED light (664.907 nm) or control samples kept in darkness. Additionally, the firming and ripening of tomatoes after harvest are impacted by the spectral composition, duration, and intensity of LED treatments (Ngcobo *et al*., 2021; Panjai *et al*., 2019). Continuous exposure to blue LED lighting (85.70 µmol $m^{-2}s^{-1}$) was found to delay the ripening of green tomatoes (Dhakal and Baek, 2014a, 2014b), whereas continuous red LED lighting (113 µmol $m^{-2}s^{-1}$) accelerated their ripening (Panjai *et al*., 2017, 2019).

The impact of post-harvest red LED lighting on the firmness of tomatoes varies across different varieties and even within the same variety when exposed to different durations of lighting, despite having the same intensity (Ngcobo *et al*., 2021). For instance, continuous exposure to red LED lighting (113 µmol $m^{-2}s^{-1}$ for 24 hours) resulted in the quickest softening of green tomatoes. In contrast, a lighting cycle with the same intensity for just 30 minutes each day led to the highest pulp firmness during treatment (Panjai *et al*., 2019). Meanwhile, Ngcobo *et al*. (2021) applied red LED lighting at an intensity of 118 µmol $m^{-2}s^{-1}$ for 48 hours on cherry tomatoes, but this did not affect their firmness.

While most studies have concentrated on continuous LED lighting rather than cyclic lighting, it is crucial to carefully select the spectral composition, intensity, and duration of post-harvest LED lighting for specific vegetables. Additionally, very few studies have fully examined how these treatments affect consumer acceptance of food (D'Souza *et al*., 2015). Therefore, quality parameters such as color, taste, texture, and other sensory attributes should be evaluated using more quantitative and precise methods (D'Souza *et al*., 2015). This is important as these quality parameters can significantly influence consumer perceptions and purchasing decisions. For example, low moisture content can lead to wilting and reduced consumer acceptance (D'Souza *et al*., 2015). Conducting sensory evaluations with a trained panel can yield valuable insights into how LED treatments affect these quality parameters (D'Souza *et al*., 2015).

6. Future Prospects and Research Directions

From 2000 to 2024, there has been a growing interest in research related to fruits and vegetables exposed to LED lighting after harvesting. A review of the Science Direct database reveals an increase in the use of LEDs for storing fresh produce, indicating their effectiveness in post-harvest storage of horticultural products. The study of non-thermal methods to avoid chemical use has been explored. The application of LED technology in the post-harvest stage has significantly increased due to its advantages over traditional lighting methods (Taulavuori *et al*., 2017). LED technology has gained attention due to its advanced features compared to traditional lighting (Gatamaneni Loganathan *et al*., 2020). Additionally, LED technology has significant potential in processes such as aging, ripening, nutritional aspects, improving storage life, and preventing disease-causing microbes during the post-harvest period. Consequently, the LED system approach for post-harvest activities is continuously growing (Abewoy, 2018). However, most of the work in this area has been conducted in laboratories and needs implementation in real food supply chains. Such studies are crucial for utilizing the potential of this technology to increase storage life, provide high-quality and safe fresh produce in long-term storage, and facilitate long-distance transportation (Taulavuori *et al*., 2017).

LED technology offers promise for improving post-harvest management in both developing countries, where access to fresh produce is limited, and developed countries, where minimizing losses is key. Its application in retail, integrated with parameters like temperature, can improve efficiency (Dueck *et al*., 2015). Scaling up LED systems in the food industry is vital for realizing these benefits. However, risk assessment is crucial, as LED exposure can alter phytochemical profiles in produce, potentially leading to both beneficial and harmful effects. Specifically, light quality, especially in artificial environments, can influence nitrate production (Bian *et al*., 2015). Further research is needed to evaluate the impact of various LED wavelengths on consumer health and eye safety, particularly concerning blue light toxicity (Bian *et al*., 2015). Such studies are essential for responsible implementation of LED technology in post-harvest management of horticultural products. Economic viability is another challenge. While LEDs offer energy efficiency and durability, their integration into supply chains poses challenges. Compatibility with cold storage systems remains underexplored, and high initial costs require thorough cost-benefit analyses to ensure economic feasibility. Current studies focus predominantly on continuous lighting rather than cyclic methods, leaving gaps in understanding optimal configurations for various crops. Few studies address the broader impacts of LED treatments on consumer preferences or long-term storage conditions. Therefore, optimizing lighting parameters, developing appropriate packaging solutions, conducting economic assessments, and performing sensory evaluations are essential steps to mitigate these challenges and ensure the practical scalability of post-harvest LED lighting (Fylladitakis, 2023).

7. Conclusion

This review aimed to investigate the impact of different light spectra from LEDs on the postharvest quality of vegetables and fruits, addressing a critical need for innovative methods to enhance produce preservation and extend shelf life. The main findings indicate that specific LED light spectra can significantly influence postharvest attributes such as color, texture, and nutrient retention. For instance, red light often promotes ethylene production, which can affect ripening, while blue light has been shown to suppress microbial growth, thereby reducing spoilage. These findings contribute to existing knowledge by highlighting the potential of tailored LED lighting strategies in postharvest management. They provide new insights into how different light spectra can be optimized to delay senescence and enhance antioxidant content in various produce types. Theoretically, this research underscores the complex interactions between light and plant physiology, offering a deeper understanding of how light influences postharvest quality. Practically, the implications are substantial, as optimized LED lighting could be integrated into storage and transportation systems to reduce food waste and improve consumer satisfaction. However, this review also identifies limitations, including the need for more standardized experimental conditions across studies and further exploration of the molecular mechanisms underlying light-induced responses in produce. Future research should focus on these areas, as well as exploring the economic feasibility and scalability of implementing LED technology in commercial postharvest handling systems. In conclusion, this review reinforces the significance of LED light spectra in maintaining and enhancing the postharvest quality of vegetables and fruits. By providing a comprehensive overview of current knowledge and highlighting future research directions, this study contributes to the development of more sustainable and efficient food supply chains. Ultimately, the strategic use of LED lighting has the potential to transform postharvest practices; ensuring fresher, healthier produce reaches consumers worldwide.

Conflict of interest

The authors declare no conflict of interest

Acknowledgments

The support of the Iran National Science Foundation (project No. 4027100) is highly acknowledged.

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