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COMPREHENSIVE REVIEW

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Review on effect of postharvest illumination by fluorescent and ultraviolet light waves on the quality of vegetables

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Abstract

Postharvest illumination is an emerging nonthermal preservation technique used to preserve the quality of vegetables. This review aimed to provide an insight into the effect, importance, and limitations of postharvest illumination by fluorescent and ultraviolet (UV) light on the physical and nutraceutical properties of vegetables. It presents the current information on the postharvest application of these two lightings based on the vegetable species. According to the existing studies, both photoperiod and continuous (low-intensity) fluorescent lighting treatments were beneficial more toward preserving the quality (delaying senescence and deterioration) of postharvest vegetables, mainly leafy vegetables. However, inconsistent results are also possible with the light quality (intensity and duration) on the postharvest fluorescent lighting treatment. According to gathered information, both UV-B and UV-C postharvest irradiation has been beneficial in delaying senescence and chlorophyll degradation and inducing bioactive compounds accumulation in some vegetable species. UV-C application is appeared to have a relatively steady effect on the postharvest storage of vegetables. But UV-B irradiation effect on the postharvest quality of vegetables was appeared to be dose dependent and not stable. In conclusion, it is important to consider vegetable (species, cultivar, harvesting age, and intact or fresh-cut), previous treatments/conditions, optimum postharvest lighting condition (illumination source, dose, intensity, and duration), and the storage condition (temperature and relative humidity) for a successful implementation of postharvest illumination. More research is required to explore the postharvest application of fluorescent and UV (UV-A, UV-B, UV-C) irradiation on vegetables.

Practical Applications

Multiple research approaches have been taken to preserve the postharvest quality of vegetables while minimizing chemical preservation techniques. Postharvest illumination is a nonchemical preservation technique that has attained more interest due to the advantages it holds, such as being highly efficient and residue-free. Fluorescent and UV lighting on harvested leafy and non-leafy vegetables are beneficial in delaying senescence and chlorophyll degradation, preserving nutritional quality, and extending the shelf life. With the accessibility of more research data and innovative strategies, the future of postharvest illumination of fluorescent and UV maybe steer toward implementation on commercial scale vegetable production (e.g., during storage and/or transportation).

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1 | INTRODUCTION

Vegetables are composed of phytochemicals (flavonoids, phenolic compounds, bioactive peptides, etc.); dietary fiber; vitamins (C, E, A, B1, B6, B9); and minerals and are thus considered essential for well-balanced diets (Dias, 2012; Ülger, Songur, Çırak, & Çakıroğlu, 2018). These non-nutrient and nutrient molecules are associated with reduced risk of chronic diseases such as obesity, diabetes, cardiovascular diseases, and certain cancers (Dias, 2012; Liu, Cai, Lu, Han, & Ying, 2012; Ülger et al., 2018). These protective effects are regarded to be mainly associated with the various antioxidants available in them (Liu et al., 2012). Consumers and researchers have therefore paid more attention to the health and nutritional aspects of horticultural products (Liu et al., 2012; Venditti & D'Hallewin, 2014). Studies have been conducted focusing on increasing the functional and nutritional properties of horticultural crops (Venditti & D'Hallewin, 2014). However, the preservation technique has become the research focus due to the susceptible diseases and speedy senescence of postharvest vegetables and fruits (Mari, Bautista-Baños, & Sivakumar, 2016; Usall, Ippolito, Sisquella, & Neri, 2016; Zhang & Jiang, 2019). In the last decade, research interest has increased to evaluate the postharvest physical techniques on vegetable quality while overcoming chemical control methods (Darré et al., 2017; Nigro & Ippolito, 2016; Vicente et al., 2005). As a viable alternative toward thermal processing, non-thermal technologies are being applied for processing foods (Oms-Oliu, Martín-Belloso, & Soliva-Fortuny, 2010). Light irradiation has attained more interest due to the advantages it holds, such as being highly efficient and residue-free, able to control decay and extending the shelf life (Liu, Hu, Jiang, & Xi, 2019). Light regulates many pathways of plants including from seed germination to flowering and fruit development (Jiao, Lau, & Deng, 2007; Loi et al., 2019). Moreover, the modular structure of plants facilitates detached plant organs (harvested vegetables and fruits) to maintain active responsiveness to environmental stimuli such as daily cycles of darkness and light (Goodspeed et al., 2013; Liu et al., 2015). Thus, postharvest lighting can still affect the commodities as the harvested produces consist of residual biological activity sensitive for light. Therefore, researchers have focused on the influence of postharvest illumination on the quality of different vegetables (Martínez-Sánchez, Tudela, Luna, Allende, & Gil, 2011).

Several lighting sources, which produce white and ultraviolet (UV) (Tamuri et al., 2014) light, have commonly been used in food production and preservation. Those are; high-intensity discharge lighting (metal halide, high-pressure sodium, and xenon lamps) and fluorescent and incandescent lamps (D'Souza, Yuk, Khoo, & Zhou, 2015; Yeh & Chung, 2009). A fluorescent lamp delivers visible light with the use of fluorescence (Electrical4U, 2020). The UV radiation generates in these lamps causes the phosphor coating in the inner wall of lamps to radiate visible light (Electrical4U, 2020). Hence, fluorescent lamps are one of the artificial sources that can generate UV light (Tamuri et al., 2014). The effect of postharvest illumination by fluorescent light at various intensities and photoperiods has been studied on the quality and physiology of fresh vegetables (Büchert, Lobato, Villarreal, Civello, & Martínez, 2010; Costa, Montano, Carrión, Rolny, & Guiamet, 2013; Ferrante, Incrocci, Maggini, Serra, & Tognoni, 2004; Glowacz, Mogren, Reade, Cobb, & Monaghan, 2014; Lester, Makus, & Hodges, 2010; Liu et al., 2015; Martínez-Sánchez et al., 2011; Noichinda, Bodhipadma, Mahamontri, Narongruk, & Ketsa, 2007; Olarte, Sanz, Echávarri, & Ayala, 2009; Toledo, Ueda, Imahori, & Ayaki, 2003; Witkowska, 2013; Zhan et al., 2013; Zhan, Li, Hu, Pang, & Fan, 2012). Besides, among the emerging approaches, UV hormesis has got the attention as it can both control the development of disease and delay senescence in green vegetables such as broccoli (Aiamla-Or, Kaewsuksaeng, Shigyo, & Yamauchi, 2010; Charles, Goulet, & Arul, 2008; Costa, Vicente, Civello, Chaves, & Martínez, 2006).

Though there are research studies on postharvest fluorescent or UV lighting, fewer reviews are available on their effect on fruits and vegetables. Moreover, a summary concerning the effect of postharvest application of fluorescent and UV lighting separately and solely about the quality of vegetables is not available. Therefore, this review aims to elucidate the current knowledge on postharvest illumination by fluorescent and UV (UV-A, UV-B, and UV-C) light separately based on the vegetable species. Here, this review summarizes the effect, importance, and limitations of postharvest illumination from these two lightings on the physical and nutraceutical properties of intact and fresh-cut vegetables. It also presents future aspects of fluorescent and UV lighting on postharvest vegetables.

2 | POSTHARVEST SENESCENCE AND POSTHARVEST ILLUMINATION

Senescence helps to ensure the survival of plants (D'Souza et al., 2015). Though it is beneficial for growing plants, it causes to quality deterioration of harvested plants (D'Souza et al., 2015) and commodities. Senescence of fruits and vegetables is an irreversible process that involves a series of biochemical, physiological (Glowacz et al., 2014), and metabolic changes, accompanied by a decline in nutrition and flavor, color, and shelf life (Xu et al., 2019). The loss of green color or appearing yellowing in the tissues (Ferrante et al., 2004; Hasperué, Guardianelli, Rodoni, Chaves, & Martínez, 2016), an increase in reactive oxygen species, and tissue breakdown include in these processes (Glowacz et al., 2014). The green color is a critically important attribute in most leafy vegetables (Glowacz et al., 2014). The loss of the green color is perceived by consumers as a symptom of senescence (Ferrante et al., 2004; Koukounaras, Siomos, & Sfakiotakis, 2009) and will result in reducing marketability (Glowacz et al., 2014). The yellowing due to senescence leads to the loss of the nutritional value of green vegetables as well (Hasperué, Guardianelli, et al., 2016). Hence, among the symptoms of senescence, yellowing is the most evident major problem during postharvest storage of green vegetables (Bantis et al., 2018; Hasperué, Guardianelli, et al., 2016). Delaying the senescence symptoms is one of the main goals of the postharvest technology of green vegetables (Costa et al., 2013; Page, Griffiths, & Buchanan-Wollaston, 2001).

Various exogenous and endogenous factors are involved in senescence regulation (Bárcena et al., 2020). Detachment and storing in dark or very low light conditions induce senescence in postharvest green leaves (Costa et al., 2013). This phenomenon occurs probably due to the lack of photosynthesis and the ensuing water and nutrient deficiencies (Costa et al., 2013; Ella, Zion, Nehemia, & Amnon, 2003). Sugar starvation induces cellular changes during senescence (Hasperué, Rodoni, Guardianelli, Chaves, & Martínez, 2016). Dieuaide, Brouquisse, Pradet, and Raymond (1992) have explained a mechanism regulating metabolic processes during senescence and sugar starvation. In the darkness, carbohydrate reserves decrease quickly to low levels (Dieuaide et al., 1992). The intracellular carbohydrate depletion (carbohydrate starvation) causes a decrease in respiration rate (Dieuaide et al., 1992). Hence, cellular components are degraded to sustain respiration (Dieuaide et al., 1992). Therefore, when carbohydrates become limited, the contribution of proteins and lipids to respiration increases in senescing tissues and also during the normal life of plants (Dieuaide et al., 1992). As evidence, Dieuaide et al. (1992) have found that β-oxidation activity in the plant tissues (e.g., maize root tips) was increased during the sugar starvation. This increment of β-oxidation activity is possibly an essential part of the response to a condition in which proteins and lipids replace carbohydrates as major respiratory substrates (Dieuaide et al., 1992).

Researchers have reported that light treatment causes delaying senescence in detached stems, leaves, and flowers (D'Souza, Yuk, Khoo, & Zhou, 2017). The light compensation point could be considered as a benchmark for selecting the suitable light intensity (D'Souza et al., 2015, 2017). It is because the light compensation point is known as the amount of light that results in equal rates of photosynthesis and respiration (D'Souza et al., 2015, 2017). However, the photon flux beneath the light compensation point causes a net loss of sugars (D'Souza et al., 2015). Thus, senescence might get accelerated (D'Souza et al., 2015; Noodén & Schneider, 2004). Fluorescent and UV lighting are being studied in postharvest illumination.

3 | FLUORESCENT/LIGHT APPLICATION

The use of fresh-cut minimally processed or ready-to-eat leafy or non-leafy vegetables is being increased nowadays (Ferrante et al., 2004; Maroga, Soundy, & Sivakumar, 2019). The cutting process reduces the shelf life and limits marketability as it keeps the plant tissue metabolically active and highly perishable (Manolopoulou, Lambrinos, & Xanthopoulos, 2012; Maroga et al., 2019). Browning occurs in cut surfaces due to the oxidative reactions of phenolic compounds by polyphenol oxidase, and it gives an unattractive appearance for fresh-cut products (Ferrante et al., 2004). Therefore, the storage life of fresh-cut vegetables ranges usually from 7 to 14 days (Ferrante et al., 2004; García-Gimeno & Zurera-Cosano, 1997). The visual quality of fresh-cut vegetables includes color, size of cuts, and absence of defects, damages, or microbial contaminations (Ferrante et al., 2004). Thus, new technologies, including postharvest lighting, have been emerging to preserve the quality of these fresh-cut products during transportation and storage (Ferrante et al., 2004). Unlike the other lighting systems, fluorescent lights have been mainly used in the early years of studying postharvest illumination on vegetables.

The plant circadian clock is reported to regulate the levels of chlorophyll (Hasperué, Chaves, & Martínez, 2011), glucosinolates (Goodspeed et al., 2013), ascorbic acid (AsA) (Kiyota, Numayama, & Goto, 2006), and carbohydrates (Sicher, Kremer, & Harris, 1984) like aspects of plant biology which may have a human health impact (Liu et al., 2015). The clocks of tissues in harvested vegetables and fruits can be entrained with 12hr dark/12 hr light cycles producing rhythmic behaviors not found in tissues stored under constant darkness or constant light (Goodspeed et al., 2013; Liu et al., 2015). Therefore, rather than constant light conditions, senescence can be delayed through the utilization of light:dark cycles (Jones, 2018). In other words, maintaining daily light:dark cycles during postharvest life could improve the appearance as well as the nutritional value of crops through maintenance of phytochemicals and chlorophyll content after the harvest (Liu et al., 2015). But only a few studies have been conducted to identify whether 24 hr light/dark cycles during the postharvest storage preserve the quality (nutritional, visual, and textural) of vegetables (Ferrante et al., 2004; Liu et al., 2015; Martínez-Sánchez et al., 2011). And more studies have been conducted with continuous postharvest fluorescent/light treatment.

The negative or positive effect of light during postharvest senescence is dependent on the quality and intensity of the illumination used (Bárcena et al., 2020). On that account, extremely low light intensities such as below 5–8 μmol m^{-2} s^{-1} lead to the enhancement of senescence (darkness induced senescence) (Bárcena et al., 2020). Also, high light intensities encourage senescence-like symptoms because of the photooxidative damage resulting in chlorophyll breakdown (Bárcena et al., 2020; Muñoz & Munné-Bosch, 2018).

3.1 | Positive effect of postharvest illumination

The positive impact of postharvest fluorescent/lighting treatment on the quality of leafy and non-leafy vegetables has been elaborated in Table 1, of which available information has been grouped according to the plant species. Costa et al. (2013) have studied the low-intensity (30–37 μmol m^{-2} s^{-1}) white light pulses (daily exposure to fluorescent lighting for 2 hr) on postharvest senescence of fresh basil (*Ocimum basilicum* L.) leaves. Therein, the plant samples stored in darkness reported an accumulation of ammonium, a decrease in chlorophyll and protein levels, and the development of visual deterioration symptoms on leaves (Costa et al., 2013). But, they have found out that the light pulse treatment was effective for delaying postharvest senescence of basil leaves at 20°C storage (Costa et al., 2013). This delay of postharvest senescence was suspected to be mediated by phytochromes (Costa et al., 2013). The light pulses (2 hr per day) of low-intensity 20–25 μmol m^{-2} s^{-1} white fluorescent light (at 20°C) could also delay chlorophyll degradation and yellowing of broccoli (*Brassica oleracea* L. var. *italica* Plenck cv. Legacy) heads (Bárcena et al., 2020). However,

TABLE 1 Positive impact of postharvest fluorescent/lighting on leafy and non-leafy vegetables

Leafy and non-leafy vegetable/plant species	Cultivar/variety	Fluorescent/light (color temperature: K/W)	Light intensity (PAR/photon flux density/illuminance)	Treatment condition	Storage condition	Suitable application	References
Brassica oleracea L.	Broccoli heads (*Brassica oleracea* var. *iron*)	White light-fluorescent tubes (40 W)	12, 25, and 50 μmol m^{-2} s^{-1}	Continuous illumination	At 22°C in a well-ventilated chamber	For delaying senescence; delaying the loss of green color at all intensities compared to darkness; delaying chlorophyll degradation (at 12 μmol m^{-2} s^{-1}) compared to dark-treated samples; lowering the decrease of total and reducing sugar and starch levels in light-treated samples than dark-treated samples	Büchert et al. (2010)
	Broccoli (fresh-cut: *Brassica oleracea* L. var. *italica* Plenck)	Light fluorescent lights	24 μmol m^{-2} s^{-1}	Continuous illumination	At 4 and 7°C in plastic trays wrapped with polypropylene film for 10 days	For delaying sensory quality deterioration and prolonging shelf life (at 4 and 7°C); significantly preserving nutritional quality (at 7°C) associated with pigments (higher levels of chlorophyll-a and b and total chlorophyll), antioxidant capacity values, total phenols, and ascorbic acid contents throughout 10 days shelf life	Zhan, Hu, Li, and Pang (2012)
	Broccoli heads (*Brassica oleracea* L. var. *italica* Plenck cv. Legacy)	White light fluorescent lamps	20–25 μmol m^{-2} s^{-1} (low-intensity)	Light pulses (2 hr of daily irradiation)	At 20°C store in darkness after irradiation for 4 days	Maintaining the integrity of chloroplast; delaying chloroplast changes, including chlorophyll degradation, yellowing, senescence-associated gene BoSAG12 induction, senescence-associated vacuoles appearance, and protein degradation	Bárcena et al. (2020)
	Broccoli heads (*Brassica oleracea* L. var. *italica* cv. Legacy)	White light fluorescent tubes (40 W)	12 μmol m^{-2} s^{-1}	Continuous illumination	At 20°C for 5 days	Higher expression in most of the genes associated with glucosinolate metabolism (after 5 days) compared to control; keeping higher content of glucosinolate while maintaining visual quality at the same time	Casajús et al. (2021)
	Chinese kale (*Brassica oleracea* var. *alboglabra*)	Light-fluorescent tubes	21.8 μmol m^{-2} s^{-1} (low-intensity)	Continuous illumination	At 1°C and 95 ± 1% RH in perforated polyethylene bags for 10 days	For preventing the decrease in vitamin C content while increasing the monosaccharides (glucose and fructose) content and starch in leaves during storage	Noichinda et al. (2007)
	Kale (*Brassica oleracea* cv. Acephala group)	Light	120 ± 10 μE m^{-2} s^{-1}	Photoperiod illumination (12 hr dark and	At 22°C for 15 days	For improving the appearance; generally enhancing green coloration, tissue integrity, and chlorophyll content compared to continuous light or	Liu et al. (2015)

TABLE 1 (Continued)

Leafy and non-leafy vegetable/ plant species	Cultivar/variety	Fluorescent/light (color temperature: K/W)	Light intensity (PAR/photon flux density/illuminance)	Treatment condition	Storage condition	Suitable application	References
				12 hr light exposure)		darkness during the storage; making phytonutrient glucosinolates levels retained at higher levels over storage time	
	Cabbage	Light	120 ± 10 μE m^{-2} s^{-1}	Photoperiod illumination (12 hr dark and 12 hr light exposure)	At 22°C for 21 days	For improving the appearance; generally enhancing green coloration, tissue integrity, and chlorophyll content compared to continuous light or darkness during the storage; making phytonutrient glucosinolates levels retained at higher levels over storage time	Liu et al. (2015)
	Cabbage cultivars: Safekeeper and Houston Evergreen	Cool white light fluorescent lamps (40 W)	10,000–20,000 lx	Continuous illumination	At 1°C, l0 °C and 18 ± 0.5°C and 96 ± 2% RH for 14 days	For preventing yellowing by increasing chlorophyll content substantially at elevated temperatures (l0 °C and 18°C)	Perrin (1982)
Hydrilla verticillata [L.f.] Royle	*Hydrilla*	Cool-white light fluorescent lamps	20 μmol m^{-2} s^{-1}	Continuous illumination	At 25 ± 2°C (samples floated on distilled water in petri dishes, containing sodium penicillate and streptomycin sulfate) for 6 days	For retarding protein loss during the senescence (raising soluble protein levels and lowering the rise in protease activity) in light-treated samples than the darkness	Kar and Choudhuri (1986)
Lactuca sativa L.	Green leaf lettuce	Light	120 ± 10 μE m^{-2} s^{-1}	Photoperiod illumination (12 hr light and 12 hr dark exposure)	At 22°C for 9 days	For improving the appearance; generally enhancing green coloration, tissue integrity, and chlorophyll content compared to continuous light or darkness during the storage	Liu et al. (2015)
	Fresh-cut: Green butterhead genotype cv. Troubadour 1, cv. Troubadour 2, cv. Troubadour 3, and red butterhead genotype cv. Teodore	White light-fluorescent tubes (36 W)	8 μmol m^{-2} s^{-1} and 30 μmol m^{-2} s^{-1} (low-intensity)	Continuous illumination	At 12°C and 90% RH in white plastic boxes lined with wetted filter paper and equipped with a perforated transparent plastic lid	For effectively increasing the shelf life; improving visual and nutritional quality; preserving ascorbic acid levels; occurring carbohydrate accumulation; delaying rise in electrolyte leakage	Witkowska (2013)
	Romaine lettuce (fresh-cut)	Light -fluorescent lights (58 W)	6 ± 1 μmol m^{-2} s^{-1}	Continuous and photoperiod illumination (12 hr light and 12 hr dark exposure per day)	At 4°C in modified atmospheric package (active) for 3 days and then transferred at 7°C for the rest of the storage	For reducing electrolyte leakage (after 10 days)	Martínez-Sánchez et al. (2011)

(Continues)

TABLE 1 (Continued)

Leafy and non-leafy vegetable/plant species	Cultivar/variety	Fluorescent/light (color temperature: K/W)	Light intensity (PAR/photon flux density/illuminance)	Treatment condition	Storage condition	Suitable application	References
	Romaine lettuce (fresh-cut)	Light-fluorescent lights	2,500 ± 2 lx (high-intensity)	Continuous illumination	At 4°C in heat-sealed polypropylene film for 7 days	For inhibiting tissue browning; maintaining quality	Zhan, Li, et al. (2012)
Ocimum basilicum L.	Basil	Cool daylight-fluorescent lamps (6,200 K, 36 W)	30–37 μmol m^{-2} s^{-1} (low-intensity)	Photoperiod illumination (daily exposure to lighting for 2 hr)	At 20°C in trays covered with polyvinyl chloride film for 5 days	For delaying postharvest senescence	Costa et al. (2013)
Spinacia oleracea L.	Spinach	Light	120 ± 10 μE m^{-2} s^{-1}	Photoperiod illumination (12 hr light and 12 hr dark exposure)	At 22°C for 9 days	For improving the appearance; generally enhancing green coloration, tissue integrity, and chlorophyll content compared to continuous light or darkness during the storage	Liu et al. (2015)
	Spinach (*Spinacia oleracea* L.) cv. Lazio (flat-leaf) and cv. Samish (semisavoy or crinkle-leaf)	Light fluorescent lamps (single-element 32 W)	26.9 μmol m^{-2} s^{-1}	Continuous illumination	At 4°C in clear-plastic containers for up to 9 days	For maintaining/enhancing essential human-health vitamins C (total vitamin C and free ascorbic acid), B_9, K_1, and E and the carotenoids lutein, violaxanthin, zeaxanthin, and β-carotene over storage	Lester et al. (2010)
	Spinach (*Spinacia oleracea* L. cv. Atlas)	White light fluorescent light	20–25 μmol m^{-2} s^{-1} (low-intensity)	Continuous illumination	At 8°C in trays covered with polypropylene plastic for 24 days	For increasing total soluble carbohydrates and glucose contents; possibly enhancing ascorbic acid synthesis in leaves	Toledo et al. (2003)
	Baby leaf spinach (*Spinacia oleracea* L. cv. Toucan)-flat-leaf variety	Light	30–35 μmol m^{-2} s^{-1} (low-intensity)	Continuous illumination	At 1 ± 1°C in commercial storage bags (35 μm single-layer biaxially oriented polypropylene film) for 7 days	For preserving nutritional content (ascorbic acid, total ascorbic acid, dehydroascorbic acid, and total carotenoids) of the leaves; improving the texture maintenance; extending the shelf life	Glowacz et al. (2014)
	Spinach	Cool-white light fluorescent lamps	20 μmol m^{-2} s^{-1}	Continuous illumination	At 25 ± 2°C (samples floated on distilled water in petri dishes, containing sodium penicillate and streptomycin sulfate) for 6 days	For retarding protein loss (total, soluble, and insoluble) during the senescence (by lowering the rise in protease activity); slightly retarding the decrease in chlorophyll compared to the darkness	Kar and Choudhuri (1986)

Abbreviations: hr, hour; PAR, photosynthetically active radiation; RH, relative humidity.

the lighting intensity in the study of Costa et al. (2013) was reported to be lower than the photosynthesis light compensation point of basil leaves (50 μmol m^{-2} s^{-1}).

The storage conditions highly affect the catabolism of leaf pigments (Ferrante et al., 2004). In general, low temperatures slow down all the leaf metabolisms and thus preserve the quality (Ferrante et al., 2004). But, if the light intensity is sufficient, even at 4°C, the light reaction of photosynthesis can occur (Lester et al., 2010). However, yellowing in cabbage was reported to be prevented with the combined effect of elevated temperature and continuous illumination during the storage condition (Noichinda et al., 2007; Perrin, 1982). Liu et al. (2015) have also observed a positive effect with the combining effect of elevated temperature (22°C) with photoperiod illumination on green leafy vegetables, namely green leaf lettuce, cabbage, kale, and spinach. As aforementioned, the delayed postharvest senescence was observed by Costa et al. (2013) and Bárcena et al. (2020) at elevated temperatures (20°C) with photoperiod illumination. However, Büchert et al. (2010) have also studied the postharvest illumination at elevated temperatures (22°C) and observed that both periodic and continuous exposure to low-intensity white light (fluorescent) delayed the de-greening of broccoli heads but to a lesser extent in periodic exposure than that of under the continuous light treatment. Moreover, the continuous illumination (12 μmol m^{-2} s^{-1}) at 20°C has maintained the visual quality of broccoli heads (*B. oleracea* L. var. *italica* cv. Legacy) with higher content of glucosinolate contents (Casajús et al., 2021). Hence, both photoperiod and continuous illumination are appeared to be effective in preserving the visual quality of leafy and green vegetables even at elevated temperature conditions.

The leaf quality, chlorophyll, and ascorbic contents of spinach mustard were also reported to be preserved with intermittent or continuous illumination (Kozuki et al., 2015). The postharvest low-intensity continuous white fluorescent light (20–25 μmol m^{-2} s^{-1}) has been shown to increase total soluble carbohydrates and glucose contents and possibly enhance the synthesis of AsA in spinach leaves (Toledo et al., 2003). Here, the continuous illumination from white fluorescent light on spinach leaves has effectively supported the leave's photosynthetic capacity during the postharvest storage. Therefore, the higher availability of carbohydrates, precursors of AsA has been reported as the reason for the reducing rates of AsA loss in spinach which is stored under low-intensity continuous light (Glowacz et al., 2014). The continuous illumination (24 μmol m^{-2} s^{-1}; fluorescent) of fresh-cut broccoli combined with low storage temperature conditions has also been reported with a delayed deterioration of sensory qualities, preserved higher levels of AsA, and extended the shelf life compared to the darkness (Zhan, Hu, et al., 2012). Vitamin C in fresh-cut lettuce was reported to be positively impacted with postharvest continuous illumination provided with warm-white fluorescent light (Witkowska, 2013). Therefore, the increment of vitamin C and soluble carbohydrates with postharvest lighting have been hypothesized as the reasons for improving the visual quality and increasing the shelf life of fresh-cut lettuce (Bantis et al., 2018; Witkowska, 2013). Furthermore, the continuous high-intensity fluorescent lighting was also found to be effective in inhibiting tissue browning and maintaining the quality of fresh-cut romaine lettuce upon cold storage (Zhan, Li, et al., 2012).

The solute leakage of leaf tissue can be resulted due to tissue breakdown (Glowacz et al., 2014). An increase in solute leakage has been observed during the storage of baby leaf spinach (Allende, Luo, McEvoy, Artés, & Wang, 2004; Glowacz et al., 2014; Medina, Tudela, Marín, Allende, & Gil, 2012). However, the solute leakage of spinach leaves (Kar & Choudhuri, 1986) was reported to reduce by the exposure of postharvest continuous fluorescent light compared to the darkness. So also, as reported by Glowacz et al. (2014), continuous (24 hr) low-intensity light conditions (30–35 μmol m^{-2} s^{-1}) have improved the texture maintenance, extended the shelf life, and not reduced the nutritional quality (total AsA and total carotenoids) of spinach. But, the commercial flat-leaf "Lazio" and crinkle-leaf "Samish" spinach (*Spinacia oleracea* L.) types stored in clear, retail packaging (at 4°C) were reported to be enriched with nutrients with continuous illumination (26.9 μmol m^{-2} s^{-1}; fluorescent) compared to the continuous darkness (Lester et al., 2010).

In a study, the solute leakage of fresh-cut Romaine lettuce (Martínez-Sánchez et al., 2011) has been reported to reduce (after 10 days) by postharvest exposure of photoperiod cycle (12 hr of light and 12 hr of dark exposure per day) provided by fluorescent light compared to the darkness. As in photoperiod cycle illumination, Martínez-Sánchez et al. (2011) have observed a reduction in solute leakage on fresh-cut Romaine Lettuce illuminated with continuous postharvest lighting.

Therefore, postharvest lighting can reduce food quality degradation that occurs through senescence or nutrient loss (D'Souza et al., 2017; Zhan, Li, et al., 2012). Postharvest lighting has three potential contributions to this scenario. Namely, by improving or maintaining the visual appearance, increasing soluble carbohydrates (Noichinda et al., 2007; Toledo et al., 2003; Zhan, Hu, Pang, Li, & Shao, 2014), and increasing or maintaining the levels of phytochemicals such as vitamin C, secondary antioxidants, total phenolics, and anthocyanins (Bantis et al., 2018). It is because soluble carbohydrates are the substrate for respiration during postharvest storage (Bantis et al., 2018).

3.2 | Negative effect of postharvest illumination

Though most researchers have given positive evidence on postharvest fluorescent lighting, however, contrary results have also been observed by some researchers. The light during storage can negatively affect the quality of different vegetables due to an increase in physiological activity (Costa et al., 2013; Sanz, Olarte, Ayala, & Echávarri, 2009). Some research findings support this sentiment. The negative impacts of postharvest fluorescent/lighting treatment on leafy and non-leafy vegetables have been presented in Table 2. The light is reported to increase the respiration of freshly cut green vegetables which can cause accelerated browning in cut edges of leeks (Ayala et al., 2009), increased transpiration (Olarte et al., 2009) and fermentation in cauliflower (Cervera et al., 2007), and accelerated

TABLE 2 Negative impact of postharvest fluorescent/lighting on leafy and non-leafy vegetables

Leafy and non-leafy vegetable/ plant species	Cultivar/variety	Fluorescent/light (color temperature: K/W)	Light intensity (PAR/photon flux density/illuminance or radiance)	Treatment condition	Storage condition	Negative effect	References
Allium porrum L.	Leeks (minimally processed: *Allium porrum* L. -Selecta variety)	Cool white light fluorescent lamps (36 W)	2,600 lx (1.855 Wsr^{-1} m^{-2})	Continuous illumination	At 4 ± 1°C packaged with films consist of different permeability (perforated polyvinyl chloride film and P-plus films made of polypropylene) for more than 26 days	Light negatively affecting the quality parameters of leeks (for both texture and color parameters); accelerating the changes in appearance; causing for an increase in stomatal aperture and respiratory rate	Ayala, Echávarri, Olarte, and Sanz (2009)
Beta vulgaris L.	Swiss chard (fresh-cut)	Light	150 μmol m^{-2} s^{-1}	Photoperiod illumination (12 hr)	At 4–5°C for 12 days	Preserving the visual appearance better in dark storage; increasing the degradation rate of chlorophyll in light-treated samples whereas chlorophyll degradation did not occur in darkness	Ferrante et al. (2004)
	Chard (minimally processed: *Beta vulgaris* L. var. *vulgaris*)	Cool white light -fluorescent lamps (36 W)	2,600 lx	Continuous illumination	At 4 ± 1°C packaged with films consist of different permeability (perforated polyvinyl chloride film and P-plus films made of polypropylene) for more than 25 days	Causing a negative effect on the quality parameters, in both white and green part of the leaf; causing an increase in stomatal aperture, exchange of gases, respiratory rate (in the white part of the chard), and a significant reduction of shelf life	Sanz, Olarte, Ayala, and Echávarri (2008)
Brassica oleracea	Kale (*Brassica oleracea* cv. Acephala group)	Light	120 ± 10 μE m^{-2} s^{-1}	Continuous illumination	At 22°C	Causing green color loss at third day of storage than samples stored under darkness and the appearance at sixth and 15th day of storage was similar in both dark- and light-treated samples; may causing greater stress than constant darkness; leading to a significant increase in electrolyte leakage	Liu et al. (2015)
	Kale (*Brassica oleracea* cv. Acephala group)	Light	120 ± 10 μE m^{-2} s^{-1}	Continuous or photoperiod illumination	At 4°C	Giving more preservation in continuous darkness than continuous or photoperiod illumination at 22°C	Liu et al. (2015)
	Chinese kale (*Brassica oleracea* var. *alboglabra*)	Light-fluorescent tubes	21.8 μmol m^{-2} s^{-1} (low-intensity)	Continuous illumination	At 1°C and 95 ± 1% RH in perforated polyethylene bags for 10 days	Inducing higher weight loss	Noichinda et al. (2007)
	Cauliflower (minimally processed: Beluga variety)	Cool white light fluorescent lamps (36 W)	—	Continuous illumination	At 4°C, packaged with films consist of different permeability (microperforated	Stimulating the respiratory activity as cauliflower is a vegetable that is nonpigmented; considerable loss of water	Olarte et al. (2009)

TABLE 2 (Continued)

Leafy and non-leafy vegetable/ plant species	Cultivar/variety	Fluorescent/light (color temperature: K/W)	Light intensity (PAR/photon flux density/illuminance or radiance)	Treatment condition	Storage condition	Negative effect	References
					polyvinyl chloride film and P-plus films made of polypropylene) for more than 25 days	vapor in the packages stored under the illumination	
	Cauliflower (minimally processed: *Brassica oleracea* L. var. *botrytis*)	Light fluorescent light	-	Continuous and photoperiod (4 hr of light and 20 hr of darkness) illumination	At 4°C, packaged with films consist of different permeability (microperforated polyvinyl chloride film and P-plus films made of polypropylene) for more than 25 days	Deterioration occurs faster when exposed to light (continuous and photoperiod) than in total darkness; light accelerating the browning in the cut zones; prolonged exposure to the light (continuous illumination) condition reduced the shelf life for all the films tested; P-plus 120 film developed (from Day 3 of storage) an unpleasant odor (fermented vegetable) which became more intense with time	Cervera, Olarte, Echávarri, and Ayala (2007)
Rocket (*Eruca sativa* Mill.) and chicory (*Cichorium intybus* L.)	Fresh-cut: Rocket and chicory	Light	150 μmol m^{-2} s^{-1}	Photoperiod illumination (12 hr)	At 4–5°C for 12 days	Preserving the visual appearance better in dark storage; increasing the degradation rate of chlorophyll in light-treated samples whereas chlorophyll degradation did not occur in darkness; declining anthocyanins content (expressed as cyanidin-3-glucoside) after 4 days of storage in light-treated rocket samples, where no significant differences in dark-treated samples	Ferrante et al. (2004)
Lactuca sativa	Green leaf lettuce	Light	120 ± 10 μE m^{-2} s^{-1}	Continuous illumination	At 22°C	Leading to a significant increase in electrolyte leakage	Liu et al. (2015)
	Romaine lettuce (fresh-cut)	Light -fluorescent lights (58 W)	6 ± 1 μmol m^{-2} s^{-1}	Continuous illumination	At 4°C in modified atmospheric package (active) for 3 days and then transferred at 7°C for the rest of the storage	Significantly better visual quality in samples stored in darkness than under light conditions; packages exposed to continuous light showed higher oxygen partial pressures compared to the dark and thus can promote browning	Martínez-Sánchez et al. (2011)
Spinacia oleracea L.	Spinach (*Spinacia oleracea* L.) cv. Lazio (flat-leaf) and cv. Samish (semisavoy or crinkle-leafed)	Light fluorescent lamps (single-element 32 W)	26.9 μmol m^{-2} s^{-1}	Continuous illumination	At 4°C in clear-plastic containers for up to 9 days	Contributing to some leaf wilting after 3 days of storage ("Lazio" > "Samish" and baby-leafed size > older leaves) as measured by leaf blade bending	Lester et al. (2010)

(Continues)

TABLE 2 (Continued)

Leafy and non-leafy vegetable/plant species	Cultivar/variety	Fluorescent/light (color temperature: K/W)	Light intensity (PAR/photon flux density/illuminance or radiance)	Treatment condition	Storage condition	Negative effect	References
	Baby leaf spinach (*Spinacia oleracea* L. cv. Toucan- flat-leaf variety)	Light	130–140 μmol m^{-2} s^{-1} (high-intensity)	Continuous and photoperiod (6 hr light and 18 hr darkness) illumination	At 1 ± 1°C in commercial storage bags (35 μm single-layer biaxially oriented polypropylene film) for 7 days	Resulted in a decline in dehydroascorbic acid, ascorbic acid, and total ascorbic acid content; increasing membrane damage/solute leakage and water loss from spinach leaves	Glowacz et al. (2014)

Abbreviations: hr, hour; PAR, photosynthetically active radiation; RH, relative humidity.

chlorophyll loss in broccoli (Costa et al., 2013). For instance, the color changes in fresh-cut leafy vegetables namely rocket (*Eruca sativa* Mill.), swiss chard (*Beta vulgaris* L.), and chicory (*Cichorium intybus* L.) stored at 4–5°C in darkness or under 150 μmol m^{-2} s^{-1} light intensity with 12 hr photoperiod have been studied by Ferrante et al. (2004) and observed different adverse outcomes on minimally processed vegetables. The degradation rate of chlorophyll had been also observed and found out it has been increased in light-treated samples, whereas the visual appearance has been preserved better in dark storage (Ferrante et al., 2004). In another study also, the total chlorophyll content was reported to be declined in both light and dark-treated Chinese kale (*B. oleracea* var. *alboglabra*) samples; however, the decline was slow when the samples were stored under the light (Noichinda et al., 2007). Here, the chlorophyll-a has not degraded rapidly in their study, though the chlorophyll-b content dropped rapidly (Noichinda et al., 2007). Therefore, the first step of chlorophyll-b degradation has been hypothesized as the conversion to chlorophyll-a (Noichinda et al., 2007).

Though senescence and yellowing of broccoli were reported to delay with the exposure of continuous low-intensity fluorescent light (Büchert et al., 2010), the presence of light has accelerated the browning in minimally processed cauliflower which is a close relative of broccoli (Cervera et al., 2007; Liu et al., 2015). Similarly, postharvest fluorescent lighting exposure has been reported to improve the chlorophyll content of cabbage (Perrin, 1982) but increase in browning in fresh-cut romaine lettuce (Liu et al., 2015; Martínez-Sánchez et al., 2011). But, Martínez-Sánchez et al. (2011) have reported that the vitamin C and total phenolic content of fresh-cut Romaine lettuce samples (packed in active modified atmosphere packaging; active-MAP conditions) were not influenced by different lighting conditions namely, lighting for 24 hr, in darkness for 24 hr, and photoperiod for 12 hr light+12 hr darkness with photosynthetically active radiation (PAR) of 6 ± 1 μmol m^{-2} s^{-1}. However, as aforementioned, Ferrante et al. (2004) observed a reduced visual and nutritional quality on fresh-cut leafy vegetables when treated with high-intensity light conditions for 12 hr light + 12 hr darkness photoperiod.

A researcher has studied the impact of light intensity (dark, low-intensity, and high-intensity) and the treatment duration (photoperiod; 6 hr high-intensity and 18 hr dark) on quality changes of cold-stored spinach. Increased membrane damage and water loss in spinach were reported to occur by high-intensity light treatment as it causes oxidative stress, tissue damage, and quality loss (Glowacz et al., 2014). This high-intensity light condition has reduced the total AsA content in spinach samples (Glowacz et al., 2014). Postharvest exposure to strong light can therefore reduce shelf life by increasing water loss through transpirational water loss (Kozuki et al., 2015). Excessive exposure to light at a low-temperature condition is also reported in leading to photooxidative stress and the lower postharvest quality (D'Souza et al., 2015; Glowacz et al., 2014). Therefore, light intensity needs to be low enough as it does not cause any excessive oxidative stress and not leading to accelerated senescence.

However, low-intensity continuous lighting exposure could also accelerate the water loss of spinach and leads to wilting (Lester et al., 2010; Liu et al., 2015). Relatively low level (21.8 μmol m^{-2} s^{-1}) of continuous fluorescent lighting treatment during storage (at 1°C with 95 ± 1% relative humidity [RH]) of Chinese kale has been studied by Noichinda et al. (2007) and found with higher weight loss, partially preserve vitamin C content, and increased levels of glucose, fructose, starch, and carotenoids. According to Noichinda et al. (2007) stomata of Chinese kale leaves stored under light remained open whereas closed during storage under darkness (within 1 day of storage in the dark). The stomatal apertures account for 95% of water loss from plants (Kozuki et al., 2015). The weight loss in the light and the dark was observed as 3.9 and 1.8%, respectively, at the end of the storage period of 10 days (Noichinda et al., 2007). Therefore, the stomatal opening was found to be positively correlated with fresh weight loss (Noichinda et al., 2007).

The stomatal response to light can be ascribed to at least two different mechanisms, namely the response to PAR and blue light (Busch, 2014). According to Busch (2014), the response of stomata to PAR depends on higher light intensities and continuous illumination. The stomatal response to light is important to coordinate carbon dioxide assimilation and loss of water (Busch, 2014). Some researchers have explained stomatal opening under light and the closure under darkness in harvested plant organs. As reviewed in Martínez-Sánchez et al. (2011), the high resistance to gas transfer in harvested plant organs may be due to stomatal closure under the darkness. And the high transfer of gas exchange resulted from photosynthetic activities and respiration at the same time in the tissues exposed to light caused by the stomatal opening (Martínez-Sánchez et al., 2011). Therefore, water condensation within the packages (films consist of low permeability to water) of vegetables through the stomatic opening is theoretically possible when these packed products are stored under the light during the shelf life. It has been evidenced by Olarte et al. (2009) with P-Plus film (made of polypropylene) consists of low permeability to water vapor. Olarte et al. (2009) have reported that stomatic opening was stimulated by exposure to light and facilitating gas exchange between atmosphere within the package and plant tissue. Though significant weight loss has not been observed, a substantial water condensation has been observed within the packages in light-treated cauliflower and broccoli samples (Olarte et al., 2009). But, water condensation (through the stomatic opening) within the package has not been observed in samples stored in the dark (Olarte et al., 2009). Similar observations have been observed by Sanz et al. (2008) with minimally processed chard that was packed with P-Plus film and stored under the light.

Different degrees of weight loss were also found in leeks samples (packed in polyvinyl chloride film permeable to water vapor) kept in darkness or under lighting (Ayala et al., 2009). Ayala et al. (2009) have observed an increased weight loss in light-treated samples over darkness. This is explained since the stem stoma remains practically closed in darkness regardless of the white or the green cut (Ayala et al., 2009). Most importantly, the weight loss was higher in light-treated white cut than the green cut of leeks (Ayala et al., 2009). White cut in leeks contains greater water content and thus explaining the high weight loss in these areas when stomata are open over the green cut (Ayala et al., 2009). Because under lighting, a greater loss of moisture occurs due to the stomata opening, and thus moisture loss will be more intense in the area with greater water content (Ayala et al., 2009). Furthermore, it was observed greater respiratory activity in this white area compared to the green area as it is composed of higher metabolic activity (Ayala et al., 2009).

Ultimately as the number of studies conducted regarding continuous illumination is higher than photoperiod illumination, it is yet early to name which illumination is more effective. But according to the aforementioned results, pulsed lighting can be suggested as more effective than continuous lighting. Even so, low-intensity continuous illumination is also appeared to be effective and more in preserving postharvest quality and extending the shelf life, especially in some of the leafy vegetables. Though the lighting (light:dark cycles, low-intensity, and high-intensity) is beneficial, some contradictory results have also been obtained with the dark condition, especially in fresh-cut vegetables. And there is a shortage of studies regarding high-intensity postharvest illumination. But as wholesome, the light exposure may preserve the nutritional, textural, and visual quality of leaves unless the light intensity is not too high to cause tissue damage but high enough to induce an antioxidant response (Glowacz et al., 2014) and retard yellowing and senescence. Besides, it is yet a question whether the duration or intensity of the light treatment causes these beneficial effects. Therefore, more research on postharvest fluorescent lighting is required to clarify this concern. Nevertheless, it is important to consider both optimum light quality (intensity and duration) and the storage condition (temperature and RH) for each crop or fresh-cut produce without compromising their quality.

4 | UV LIGHT APPLICATION

UV light treatment has been reported to maintain the quality of postharvest vegetables during storage and extend their shelf life (Zhang & Jiang, 2019). As reported by, UV-A (320–400 nm) and UV-B (280–320 nm) wavelengths are less harmful compared to UV-C (200–280 nm) (Aiamla-Or et al., 2010; Zhang & Jiang, 2019). Though UV-C application proved to be effective in reducing the pathogenic microbial loads on fresh vegetables and fruits (Turtoi, 2013), it can also increase the nutritional composition of some vegetables and fruits (Fonseca & Rushing, 2008). Enhancing the nutraceutical properties of fresh vegetables and fruits with the application of UV-C hormesis is relatively recent (Nigro & Ippolito, 2016). However, among the available research studies, most have focused on UV-B and UV-C application, and the postharvest application of UV-A is hardly found (Zhang & Jiang, 2019). Interestingly, tomatoes and broccoli have drawn more attention to postharvest UV irradiation than other vegetable species. Therefore, the available information on the effect of UV irradiation is categorized and discussed separately as tomato, broccoli, and other vegetables.

4.1 | Irradiation (UV-A, UV-B, and UV-C) on tomato fruit

Different doses of UV-A (353, 365, and 400 nm) have been tested with fresh red ripe tomatoes ("Bull Heart," "Budenovka," and "Gina" varieties) to evaluate its effect on antioxidants and physicochemical characteristics (Dyshlyuk et al., 2020). All the studied wavelengths of UV-A (353, 365, and 400 nm) have contributed to increasing the total content of phenolic compounds, flavonoids, and carotenoids content in tomatoes (Dyshlyuk et al., 2020). As reported by the increased antioxidant activity of treated (365 nm, 360 min) ripe tomatoes has persisted for 2–3 days after irradiation (Dyshlyuk et al., 2020).

Castagna et al. (2013) have evaluated the impact of postharvest UV-B irradiation (daily 1 hr, 6.08 kJ/m^2 until red ripe stage) on nutraceutical and physical properties of tomatoes (*Solanum lycopersicum* L.) with two tomato genotypes (*high pigment-1 and* Money maker) at two ripening stages (turning and mature green). The time taken by two ripening stages to reach the red ripen stage has differed in both genotypes (Castagna et al., 2013). Therefore, postharvest UV-B treatment was generally less effective to modify tomato color, which seems to be controlled mainly by the harvesting stage (Castagna et al., 2013). In Money maker flesh and peel, UV-B irradiation increased the concentrations of carotenoids and AsA (Castagna et al., 2013). Hence, UV-B light appears to be good in modulating the antioxidant concentration in tomato fruits in both flesh and peel (Castagna et al., 2013). This result is interesting as the flesh accounts for a higher proportion of fruit weight, and peel is often removed, particularly in cooked or canned tomatoes, even though the peel is abundant in carotenoids (Castagna et al., 2013). But *high pigment-1* fruits went through only minor changes and thus suggesting that *high pigment-1* mutation decreased the ability of the fruit to respond to UV-B irradiation (Castagna et al., 2013). Hence, attention has to be paid to the cultivar of tomato as the positive effect of UV-B radiation on the nutraceutical properties appears to depend on genotype (Castagna et al., 2013). The firmness in tomatoes has negatively been affected by UV-B irradiation (regardless of the genotype) (Castagna et al., 2013). Here, tomatoes softened after the treatment (Castagna et al., 2013). This aspect, therefore, needs to be further studied (Castagna et al., 2013). But in another study, mature-green tomato (*Lycopersicon esculentum* cv. Zhenfen 202) exposed to 20 or 40 kJ/m^2 dose of UV-B irradiation and stored in dark (at 14°C, 95% RH for 37 days) was found to be most effective in delaying the color development and maintaining a high level of firmness (Liu et al., 2011). Moreover, 20 or 40 kJ/m^2 promoted the accumulation of total flavonoids and total phenolics and enhanced the antioxidant capacity of tomatoes during storage (Liu et al., 2011). Thus, 20 or 40 kJ/m^2 was the optimum dose of UV-B for enhancing antioxidant capacity and maintaining the sensory qualities of treated tomatoes (Liu et al., 2011). Here, the highest UV-B dose of 80 kJ/m^2 resulted in higher lycopene content with a negative effect on color, texture, and other antioxidants (Liu et al., 2011). Based on the results, it can be suggested that postharvest UV-B irradiation is a useful nonchemical way to maintain postharvest quality and enhance the antioxidant capacity of tomato fruit (Castagna et al., 2013; Liu et al., 2011).

Unlike UV-B, most studies regarding postharvest tomatoes have applied UV-C irradiation. Bu, Yu, Aisikaer, and Ying (2013) have treated cherry tomatoes (*S. lycopersicum* L. cv. Zhenzhu1) at the mature green stage with UV-C irradiation of 4.2 kJ/m^2 (for 8 min) and stored in the dark (at 18°C, 95% RH) for 35 days. The UV-C treatment was better in maintaining firmness in cherry tomatoes corresponding with higher contents of acid-soluble pectin and cellulose (Bu et al., 2013). According to the results obtained with transmission electron microscopy, UV-C irradiation has retarded the cell wall disassembly in cherry tomato pericarp (Bu et al., 2013). Moreover, UV-C irradiation has suppressed the transcriptional expression of major genes (pectin methylesterase:*PME* 2.1; cellulase:*Cel* 1; polygalacturonase:*PGcat*; expansin:*Exp* 1) involved in cell wall degradation and inhibited the activities of cellulase, polygalacturonase, and pectin methylesterase during the storage (Bu et al., 2013). And UV-C treatment has significantly inhibited ethylene production (Bu et al., 2013). Therefore, ethylene production inhibition, which in turn suppressed the expression of genes encoding the cell wall degrading enzymes, has been suggested as could be included in possible mechanisms of UV-C involved delaying softening of tomato fruit (Bu et al., 2013).

In another study, harvested tomato fruits (*S. lycopersicum* cv. Flavortop) at breaker ripening stage were treated in combination with UV-C (3.7 kJ/m^2) irradiation and 1-methylcyclopropene (1-MCP; 2 μl/L) and separately with both (Tiecher, de Paula, Chaves, & Rombaldi, 2013). Though UV-C treatment has inhibited ethylene production in the study of Bu et al. (2013), Tiecher et al. (2013) have observed induced ethylene production and delayed red color development with UV-C radiation. Here, compared to the control samples (without UV-C or 1-MCP application) UV-C irradiation has also delayed carotenoid accumulation (Tiecher et al., 2013). But, polyamine content was higher in UV-C-treated fruits than in untreated tomatoes (Tiecher et al., 2013). Therefore, increase in polyamine content in UV-C-treated tomato fruits suggests a possible relationship to ripening change (Tiecher et al., 2013).

Liu, Zabaras, Bennett, Aguas, and Woonton (2009) have studied harvested mature green (breaker-stage) tomatoes (*L. esculentum* cv. Red Ruby) by treating them daily with short bursts of UV-C (22.8 W/m^2) for up to 21 days, and control (untreated) samples have been kept in darkness for the same duration. The UV-C light treatment has increased the lycopene content in tomato exocarp during postharvest storage, and it has been significantly increased after the fourth day of storage (Liu et al., 2009). However, in comparison to control samples, the β-carotene content was reported as not affected by UV-C treatment (Liu et al., 2009). Esua, Chin, Yusof, and Sukor (2019) have shown the potential of using UV-C irradiation in combination with ultrasound energy (ultrasonic cavitation) as a postharvest treatment to improve bioactive compounds content (phytochemicals, total phenols, lycopene, AsA) and antioxidant activity on tomatoes (*S. lycopersicum* cv. Baby TM1536) during storage. Liu et al. (2012) have determined 4 or 8 kJ/m^2 of UV-C irradiation as the optimum dose for mature-green tomato fruit (*S. lycopersicum* cv. Zhenfen 202) in terms of enhanced antioxidant activity and increased phenolic content. In their study, the contents of quercetin, *p*-coumaric acid, chlorogenic acid, syringic acid, and gallic acid have

been significantly increased by the dose of 4 or 8 kJ/m^2 UV-C irradiation (Liu et al., 2012). UV-C irradiation at 2 or 16 kJ/m^2 has also enhanced the antioxidant activity in tomato fruit but to a lesser extent (Liu et al., 2012).

4.2 | Irradiation (UV-B and UV-C) on broccoli

The studies on broccoli have obtained positive results with both UV-B (Aiamla-Or et al., 2010; Darré et al., 2017) and UV-C (Costa et al., 2006; Dogan, Topcu, & Erkana, 2018) irradiation. Aiamla-Or et al. (2010) and Darré et al. (2017) have studied broccoli florets with different doses of UV-B irradiation. According to Aiamla-Or et al. (2010), broccoli florets (*B. oleracea* L. cv. endeavour) have been irradiated with different doses (4.4, 8.8, and 13.1 kJ/m^2) of UV-B and kept under darkness at 15°C. And it has been found that at least 8.8 kJ/m^2 of UV-B dose delay the decrease of hue angle value and chlorophyll-a and b contents efficiently (Aiamla-Or et al., 2010). The dose of 8.8 kJ/m^2 of UV-B has reduced the reduction of chlorophyll derivative levels (e.g., chlorophyllide *a* and 13^2-hydroxychlorohyll *a*) (Aiamla-Or et al., 2010). Moreover, the accumulation of pyropheophorbide-*a* and pheophorbide-*a* in broccoli florets was delayed effectively by UV-B treatment (Aiamla-Or et al., 2010). Hence, the floret yellowing and chlorophyll degradation of broccoli after harvest could be delayed by the use of UV-B irradiation (Aiamla-Or et al., 2010). The delayed chlorophyll degradation in these florets by UV-B irradiation could be due to the suppression of chlorophyll degrading enzyme activities, namely Mg-dechelatase, chlorophyll-degrading peroxidase, and chlorophyllase (Aiamla-Or et al., 2010).

In the study of Darré et al. (2017), the effect of UV-B irradiation dose (0, 2, 4, 8, and 12 kJ/m^2) and intensity (control: 0, low: 3.2, medium: 4.0, high: 5.0 W/m^2) on antioxidant capacity and quality retention of fresh broccoli (*B. oleracea* var. *italica*, cv. Legacy) florets during storage (in darkness at 4°C for 17 days) has been evaluated. Here, broccoli exposed to the low-intensity UV-B with 2.4 kJ/m^2 dose has improved chlorophyllide and chlorophyll retention, delayed yellowing, and reduced weight loss (Darré et al., 2017). Hence, low doses and intensities of UV-B on fresh broccoli may be helpful to complement the refrigeration (Darré et al., 2017). Further, the highest antioxidant capacity was observed in broccoli samples treated with high-intensity UV-B irradiation (Darré et al., 2017). And phenolic antioxidants were found to peak 6 hr after UV-B exposure, whereas aliphatic glucosinolates had increased levels 18 hr after the irradiation (Darré et al., 2017). Therefore, high-intensity UV-B application may be better as a pre-treatment to elevate the antioxidant capacity of broccoli before further processing, like freezing (Darré et al., 2017).

Short UV-C treatments have been suggested as a nonchemical method that could be useful in delaying senescence/chlorophyll degradation, reducing tissue damage and disruption, and maintaining the antioxidant capacity in broccoli (Costa et al., 2006). In the study of Costa et al. (2006), broccoli heads (*B. oleracea* L. var. *italica* cv. Cicco) have been treated with short UV-C treatments (4, 7, 10, and 14 kJ/m^2), loosely covered with polyvinyl chloride film and then stored in darkness for 5 days at 20°C. All UV-C treatments reported delaying chlorophyll degradation and yellowing at 20°C (Costa et al., 2006). But, the dose concentration 10 kJ/m^2 has delayed chlorophyll a and b degradation, yellowing, and lowered the activity of chlorophyll-peroxidase and chlorophyllase (Costa et al., 2006). Thus, it has delayed the increase in pheophytins during the storage of broccoli heads (Costa et al., 2006). Therefore, both UV-B and UV-C irradiations can be effective in delaying chlorophyll degradation and yellowing/senescence in broccoli.

Though Aiamla-Or et al. (2010) have studied UV-B irradiation and Dogan et al. (2018) have studied UV-C irradiation, the dosages studied by them are quite similar. But in the study of Dogan et al. (2018), different doses of UV-C irradiation (254 nm; 4.4, 8.8, and 13.2 kJ/m^2) combined with MAP at 0°C storage condition have been studied on the quality of minimally processed broccoli florets (*B. oleracea* L. *italica* "Naxos"). It has been found that the moderate level (8.8 kJ/m^2) of UV-C irradiation results in the best extension of shelf life and quality on minimally processed broccoli florets (Dogan et al., 2018). UV-C (8 kJ/m^2) irradiation can also be combined with hot air to increase the levels of phenolics and AsA contents in minimally processed broccoli (*B. oleracea* var. *italica*, cv. Cicco) florets (Lemoine, Chaves, & Martínez, 2010) which resulted in lower loss of AsA and higher levels of phenolics that have led to higher antioxidant activity in the treated samples (Lemoine et al., 2010). This combined treatment could also enhance the activity of enzymes (e.g., catalase and ascorbate peroxidase) involved in removing reactive oxygen species (Lemoine et al., 2010). Therefore, the combined treatment has been reported as effective because it contributes to enhancing protection against oxidative molecules (Lemoine et al., 2010).

In addition to the single effect, Martínez-Zamora, Castillejo, and Artés-Hernández (2021) have studied the combined effect of UV-C (9 kJ/m^2) and UV-B (15 kJ/m^2) on the quality of minimally processed broccoli sprouts (*B. olearacea* var. *italica*) for 10 days at 4°C. UV-B treatment has increased total phenolic content and total antioxidant capacity and enhanced sulforaphane content by 37.5% (Martínez-Zamora et al., 2021). Also, UV-B has increased the glucosinolate (indolyl) content by ~30% compared to control (Martínez-Zamora et al., 2021). Both UV-C and combined (UV-B + UV-C) irradiation has resulted in similar contents of total glucosinolate, total phenolic content, and total antioxidant capacity (Martínez-Zamora et al., 2021). Reason for this similar effect may be as UV-C and UV-B share same photoreceptors in the plant (Martínez-Zamora et al., 2021). UV RESPONSE LOCUS 8 (UVR8) protein is the UV-B receptor in plants (Martínez-Zamora et al., 2021). The action spectrum of UVR8 protein ranges from 250 to 310 nm, and it includes the UV-C region (Martínez-Zamora et al., 2021). Thus, both radiations may share the same photoreceptor (Martínez-Zamora et al., 2021).

4.3 | Irradiation (UV-A, UV-B, and UV-C) on other vegetables

A study concerning the effect of three different types of UV irradiation (UV-A, UV-B, and UV-C) on a vegetable is scarce. As a rare example, Kotepong and Phadung (2020) have studied all three UV

irradiation (UV-A, UV-B, and UV-C) on the quality of baby corn during the distribution. UV irradiation had a beneficial effect on maintaining quality and extending the shelf life of baby corn (Kotepong & Phadung, 2020). In this study, baby corn was packed in low-density polyethylene bags and exposed at 2 kJ/m^2 for 5 min per day (at 5°C) (Kotepong & Phadung, 2020). Here, the treated samples have been exposed to fluorescent lighting for 12 hr per day. Hence, it can be viewed as a combination of UV and fluorescent illumination and packaging. All UV-treated baby corn has resulted in a higher score on yellow color (*b**), lightness (*L**), vitamin C content, firmness, and total carotenoids than control samples during 28 days of distribution period (Kotepong & Phadung, 2020). In the study of Martínez-Zamora et al. (2021), radish sprouts have also been subjected to the same treatment condition as broccoli and have obtained similar results with UV-B on total phenolic content and total antioxidant capacity. UV-B has increased the glucosinolate content, which is mostly aliphatic glucosinolates (Martínez-Zamora et al., 2021). The sulforaphene content has highly increased by 72% in UV-B irradiated radish sprouts (Martínez-Zamora et al., 2021). As observed by Martínez-Zamora et al. (2021), UV-B irradiated radish sprouts had 60-fold more biologically active isothiocyanates and 5-fold more glucosinolate content than broccoli sprouts. Therefore, the UV-B treatment condition used in the study of Martínez-Zamora et al. (2021) is appeared to be more effective with radish sprouts to enhance nutritional quality.

In addition, UV-C irradiation has been studied with some other vegetables such as fresh-cut carrot (Li et al., 2021), peppers (Vicente et al., 2005), fresh-cut green onion (Kasim & Kasim, 2010), bitter gourd fruit (Prajapati, Asrey, Varghese, Singh, & Singh, 2021), spinach, leek and cabbage (Liao et al., 2016), garden cress (Kasim & Kasim, 2012), vegetable amaranth (Gogo et al., 2018; Gogo, Opiyo, Hassenberg, Ulrichs, & Huyskens-Keil, 2017), African nightshade (Gogo et al., 2017), and lettuce (Attia, Ouhibi, Urban, & Aarrouf, 2021). A study on fresh-cut carrots has also obtained beneficial effects by combining UV-C irradiation (2 kJ/m^2) with MAP (high-oxygen; 80% oxygen, 10% nitrogen, and 10% carbon dioxide) (Li et al., 2021). Compared to either treatment alone, after 15 days of cold storage, the combined treatment (UV-C + MAP) has inhibited total carotenoid, AsA, γ-aminobutyric acid decline, delayed bacterial growth, and reduced ethylene production and respiration rates (Li et al., 2021). UV-C + MAP could more strongly restrain total phenolic, whiteness index, lignin, and malondialdehyde increase as well as retarded the lignin synthesis more efficiently by suppressing phenolic metabolism-related enzyme activities (peroxidase, polyphenoloxidase, phenylalanine ammonialyase) and their gene expressions (Li et al., 2021).

Vicente et al. (2005) have treated peppers (*Capsicum annum* L. cv. Zafiro) with UV-C light (7 kJ/m^2) and then stored them for 18 days at 10°C. The UV-C treatments have reduced the decay, maintained the quality, kept the pepper fruits firmer, and resulted in lower carotenoid content and superficial color compared to the control samples (Vicente et al., 2005). Therefore, suggesting that the combined treatment (UV-C and refrigerated condition) could be useful in extending the postharvest life of peppers (Vicente et al., 2005). However, the UV-C treatment has not caused changes in sugar content in pepper fruits (Vicente et al., 2005), The UV-C effect on chilling injury has also been evaluated by storing the UV-C (7 kJ/m^2) treated pepper fruits at 0°C for 15 or 22 days and transferred at 20°C for 4 days (Vicente et al., 2005). The results revealed that UV-C irradiation has a useful effect in reducing chilling injury in peppers (Costa et al., 2006; Vicente et al., 2005). Also, UV-C treatment had delayed the increase in respiration rate, electrolyte leakage, and total phenols, suggesting lesser damage in response to low storage temperature (Vicente et al., 2005). However, further research is required to identify the UV-C protecting mechanism against the chilling injury in peppers (Vicente et al., 2005).

In the study of Kasim and Kasim (2010), fresh-cut onions (*Allium cepa* L.) treated with UV-C irradiation have been stored for 15 days at 5°C and 85–90% RH (Kasim & Kasim, 2010). According to their study, electrolyte leakage was getting high with higher UV-C doses (Kasim & Kasim, 2010). Besides, as both electrolyte leakage and decay percentage are lower at the 10th day of storage, lower UV-C doses can be used to have controlled pathogen growth (Kasim & Kasim, 2010). The green color of hollow green tissues was observed to be retained best in UV-C_3 (UV-C irradiation for 3 min) treatment whereas the *L** value of white stem tissues was maintained best in UV-C_5 (UV-C irradiation for 5 min) treatment (Kasim & Kasim, 2010). Higher weight losses have resulted in samples treated with higher UV-C treatments than in control (non-treated) and UV-C_3-treated samples during the storage (Kasim & Kasim, 2010). However, higher UV-C doses, especially UV-C_{15} (UV-C irradiation for 15 min) treatment on the fresh-cut green onion, have enhanced the antioxidant activity (Kasim & Kasim, 2010). But UV-C_{15}-treated onions have shown noticeable yellowing, though the inner leaf extension was controlled effectively (Kasim & Kasim, 2010).

Prajapati et al. (2021) have studied the effect of different UV-C (253.4 nm) irradiation times (20, 30, 40 min) on the postharvest quality of bitter gourd (*Momordica charantia* L. var. "Pusa Rasdar") fruit (at the immature green stage) during storage at 10°C (85–95% RH) for 16 days. Exposing UV-C for 40 min irradiation has been beneficial in reducing weight loss and decay percent and maintaining firmness in bitter gourd stored for up to 16 days (Prajapati et al., 2021). Due to the stress induced by the exposure to UV-C for 40 min, the total carotenoid, total chlorophyll, total phenols, and antioxidants content except vitamin C have increased in UV-treated samples (Prajapati et al., 2021).

As aforementioned, UV-C irradiation enhances the storage or shelf life of vegetables (Liao et al., 2016). However, the biochemical changes that occur in UV-C-treated leafy vegetables are largely unknown (Liao et al., 2016). Attia et al. (2021) have applied different doses of UV-C on lettuce leaves (*Lactuca sativa* L.) once a day for a week and observed the 0.85 kJ/m^2 as the suitable dose concerning visual aspects of lettuce. Because the other two doses of 1.71 and 3.42 kJ/m^2 they used resulted in many necrotic spots on leaves starting from the third day, whereas leaves received 0.85 kJ/m^2 resulted in an appearance identical to the control (without UV-C) samples (Attia et al., 2021).

Kasim and Kasim (2012) have studied UV-C on harvested garden cress (*Lepidium sativum* L.) leaves with different irradiation times such

as 10, 20, or 30 min and then stored for 7 days (at 5°C and 95% RH). And unlikely in fresh-cut green onions, the total chlorophyll content in garden cress leaves has increased with the increase of UV-C doses and higher in samples treated for 30 min compared to the other treatments (Kasim & Kasim, 2012). In the same way, b^* values were low, and the lightness (L^* value) was high in samples treated with UV-C for 30 min (Kasim & Kasim, 2012). The number of yellowing leaves was also low in this treatment (Kasim & Kasim, 2012). However, the electrolyte leakage was high in all UV-C-treated samples compared to the control samples (Kasim & Kasim, 2012). Hence, though the UV-C treatment on fresh-cut garden cress leaves has increased chlorophyll content, prevented chlorophyll degradation and leaf yellowing, it increased the electrolyte leakage in leaves due to tissue damage (Kasim & Kasim, 2012).

Liao et al. (2016) have exposed leaf vegetable leek, spinach, and cabbage, respectively, to single and multiple UV-C irradiations (2.46 kJ/m^2) and subsequently stored for 5 days at 4°C. It has been found that multiple irradiations are significantly more effective than single irradiation ($p < .05$) in maintaining postharvest quality parameters (Liao et al., 2016). By contrast, the contents of chlorophyll-a, soluble protein, and vitamin C of leaf vegetables during 5 days storage can be better preserved with multiple UV-C treatments (Liao et al., 2016). Hence, the multiple UV-C treatment can be effective in maintaining quality and enhancing the shelf life of harvested leaf vegetables (leek, spinach, and cabbage) (Liao et al., 2016).

African indigenous leafy vegetables namely, African nightshade (*Solanum scabrum* Mill. cv. Olevolosi) and vegetable amaranth (*Amaranthus cruentus* L. cv. Madiira) have been subjected to postharvest application of hormic UV-C dosages (1.7 or 3.4 kJ/m^2) (Gogo et al., 2017). The fresh weight loss in both African indigenous leafy vegetables has been significantly reduced by the lower UV-C dosage (1.7 kJ/m^2) (Gogo et al., 2017). The lignin content has been increased significantly in African nightshade, whereas the cellulose and hemicellulose content has been increased significantly in vegetable amaranth following UV-C treatment (Gogo et al., 2017). Besides, though the yeast and aerobic mesophyllic counts were reduced significantly by UV-C irradiation, mold counts have not been affected (Gogo et al., 2017). Gogo et al. (2018) have subjected vegetable amaranth to the same experimental condition to evaluate the effect of UV-C on health-promoting secondary compounds and evidenced that the accumulation of secondary compounds depended on UV-C dosage, storage duration, and temperature. Compared to untreated control, the carotenoids (β-carotene, lycopene, lutein); phenolic acids (coumaric, ferulic, and caffeic acid derivatives); flavonoids (quercetin and kaempferol derivatives); vitamin E; antioxidant capacity; and glutathione peroxidase activity have increased in UV-C irradiated vegetable amaranth leaves (Gogo et al., 2018).

According to gathered information, types of UV irradiation have been either applied as a single preservation technique or combined with other preservation techniques such as refrigeration, use of 1-MCP, ultrasound energy, packaging (MAP), hot air application, and postharvest illumination from fluorescent lighting. Moreover, UV irradiation has preserved chlorophyll and carotenoid/lycopene content, improved phenolic, flavonoid content, and antioxidant capacity, enhanced antioxidant enzyme activity, maintained firmness, and reduced weight loss. Postharvest irradiation from UV-B on broccoli (Aiamla-Or et al., 2010; Darré et al., 2017) and UV-C on broccoli (Costa et al., 2006), leafy vegetables (leek, spinach, cabbage, garden cress) (Kasim & Kasim, 2012; Liao et al., 2016), and bitter gourd (Prajapati et al., 2021) has preserved chlorophyll content. Therefore, both UV-B and UV-C irradiation is appeared to be effective in preserving chlorophyll content in leafy and green vegetables. Postharvest UV irradiation (UV-A, UV-B, UV-C) has shown to have the potential to increase carotenoid content in vegetables, such as tomato, baby corn, fresh-cut carrot, bitter gourd, and vegetable amaranth (Castagna et al., 2013; Dyshlyuk et al., 2020; Gogo et al., 2018; Kotepong & Phadung, 2020; Li et al., 2021; Prajapati et al., 2021). Moreover, UV irradiation (UV-A, UV-B, UV-C) has also caused increased phenolic content and enhanced antioxidant capacity in a variety of vegetables, namely tomatoes (Dyshlyuk et al., 2020; Esua et al., 2019; Liu et al., 2011, 2012), broccoli (Darré et al., 2017; Lemoine et al., 2010), broccoli sprouts and radish sprouts (Martínez-Zamora et al., 2021), fresh-cut onions (Kasim & Kasim, 2010), bitter gourd (Prajapati et al., 2021), and vegetable amaranth (Gogo et al., 2018). Therefore, postharvest UV irradiation has been beneficial in delaying senescence and inducing bioactive compounds accumulation in some vegetable species. The effect of postharvest UV light treatment on vegetables may be diverse depending on the dose (Castagna et al., 2013; Liu et al., 2011), intensity (Darré et al., 2017), previous treatments/conditions, and surface subjected for irradiation (e.g., species, cultivar and harvesting stage) (Castagna et al., 2013; Fonseca & Rushing, 2008). Among the available studies, some research has concerned either dosage or irradiation duration. But especially in tomato and broccoli, mostly the UV dosage has been concerned over irradiation time.

As mentioned above, UV-B treatment is composed of lower destructive power and a greater potential compared to the UV-C treatment (Zhang & Jiang, 2019). But according to the current research studies (Castagna et al., 2013; Liu et al., 2011), the UV-B irradiation effect on the postharvest quality of vegetables is not stable (Zhang & Jiang, 2019). Moreover, there is a dose-dependent effect (Aiamla-Or et al., 2010; Castagna et al., 2013; Darré et al., 2017; Liu et al., 2011; Zhang & Jiang, 2019). Hence, the universal boundary line dose of UV-B is reported as difficult to determine (Zhang & Jiang, 2019).

Though UV-C irradiation has mainly been used in sanitation and food safety as it is composed of germicidal effects, it also affects the prevention of nutritional losses (Gogo et al., 2017; Li et al., 2021; Prajapati et al., 2021). Based on the existing studies, UV-C application has a relatively steady effect on the postharvest storage of vegetables (Costa et al., 2006; Lemoine et al., 2010; Liu et al., 2012; Zhang & Jiang, 2019). And the measurement dose of UV-C treatment is appeared to be generally uniform (Zhang & Jiang, 2019) as 2.0–9.0 kJ/m^2. However, as mentioned by Zhang and Jiang (2019), more research is required to explore the postharvest application of UV irradiation on vegetables.

5 | FUTURE ASPECTS/RECOMMENDATIONS

The aforementioned findings highlight the need for more research regarding the intensity (e.g., high intensity) and duration (especially on photoperiod illumination) of postharvest fluorescent lighting on physical (color, fresh weight, and texture/firmness) and nutritional (e.g., AsA, total phenolic, carotenoid, other antioxidants) quality of leafy and non-leafy (intact and fresh-cut) vegetables. There is a lack of studies concerning the effect of types of UV irradiation (UV-A, UV-B, and UV-C) on vegetables separately and in a combined manner. The postharvest UV irradiation combined with other preservation techniques, especially 1-MCP, ultrasound energy, hot air application, and fluorescent lighting, should be further studied. The effect of UV irradiation (UV-A, UV-B, and UV-C) on carotenoid content can be studied further with other carotenoid-rich vegetables (e.g., kale and sweet peppers). The effect of postharvest UV-C irradiation on reducing chilling injury should be studied further with different pepper varieties and maybe with other vegetables such as asparagus, bean, and okra which are susceptible to chilling injury. Multiple UV-C irradiation technique has only been studied on a few leafy vegetables, and thus there is a lack of studies on this irradiation technique on postharvest vegetables. As vegetable amaranth and African nightshade obtained beneficial effects from UV-C irradiation, these vegetables can be studied with multiple UV-C irradiations. In addition, as UV-A and UV-B wavelengths are less harmful, more attention can be given to their effect on vegetables, especially on leafy vegetables. As evidenced in the present study, illumination (fluorescent and UV) on postharvest vegetables can complement the existing technologies on effectively preserving the physical, nutritional or functional properties and microbial quality of vegetables during storage. Therefore, as postharvest illumination from fluorescent (photoperiod and continuous), UV-B, and UV-C light are appeared to be effective in preserving the visual quality of leafy and green vegetables, future research may direct toward quantifying their postharvest loss under such illumination conditions and different storage temperatures. Besides, attention has to be given to consumer acceptance of fluorescent and UV illuminated vegetables. Furthermore, with the accessibility of more research data and innovative strategies, the future of postharvest illumination may not be limited only to research purposes, but must steer toward implementing on a commercial scale (e.g., storage and/or transportation) vegetable producers. Then, it will potentially contribute to preserving the quality, extending the marketable period, increasing the availability of fresh vegetables, and ultimately reducing the postharvest loss. Expectantly as a trend, convenience stores are willing to use leafy vegetable displays combined with postharvest illumination, low temperature, and high RH condition to reduce the postharvest loss that occurs at the retail stage.

6 | CONCLUSION

In this review, current information on the postharvest application of fluorescent and UV lighting is separately presented based on the vegetable species. According to the existing studies, both photoperiod and continuous (low-intensity) fluorescent lighting treatments were beneficial more toward preserving the quality (delaying senescence and deterioration) of postharvest vegetables, mainly leafy vegetables. However, inconsistent results are also possible with the light quality (intensity and duration) of postharvest fluorescent lighting treatment. For example, postharvest illumination from fluorescent light may promote browning in cut edges of vegetables such as leeks, cauliflower, and romaine lettuce. Also, fluorescent lighting may lead to increase fresh weight loss in some vegetables (e.g., spinach and Chinese kale) due to the stomata opening under the lighting condition. But as wholesome, the light exposure may preserve the nutritional, textural, and visual quality of vegetables unless the light intensity is not too high to cause tissue damage, but high enough to induce an antioxidant response and retard yellowing and senescence. Further, it is yet unclear whether the intensity or duration of postharvest lighting causes these beneficial effects. According to gathered information, both UV-B and UV-C postharvest irradiation has been beneficial in delaying senescence and chlorophyll degradation and inducing bioactive compounds accumulation in some vegetable species. UV-C application is appeared to have a relatively steady effect on the postharvest storage of vegetables. The measurement dose of UV-C treatment was generally uniform as 2.0–9.0 kJ/m^2. But UV-B irradiation effect on the postharvest quality of vegetables was appeared to be dose dependent and not stable. In conclusion, it is important to consider vegetable (species, cultivar, harvesting age, and intact or fresh-cut), previous treatments/conditions, optimum postharvest lighting condition (illumination source, dose, intensity, and duration), and the storage condition (temperature and RH) for a successful implementation of postharvest illumination. More research is required to explore the postharvest application of fluorescent and UV (UV-A, UV-B, UV-C) irradiation on vegetables.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interests.

AUTHOR CONTRIBUTIONS

W. P. T. D. Perera: Conceptualization; validation; writing – original draft; writing – review and editing.

S. B. Navaratne: Funding acquisition; project administration; supervision; writing – review and editing.

I. Wickramasinghe: Funding acquisition; project administration; supervision; writing – review and editing.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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