Application of light emitting diodes (LEDs) for food preservation, post-harvest losses and production of bioactive compounds: a review

Amrita Poonia *, Surabhi Pandey and Vasundhara

Abstract

Light-emitting diode (LED) technology is a new non-thermal food preservation method that works by converting light energy into heat. LED has potential to revolutionize crop production, protection and preservation. This technology is economical and environmentally friendly. LEDs have been shown to improve the nutritive quality and shelf life of foods, control the ripening of fruits, induce the synthesis of bioactive compounds and antioxidants and reduce the microbial contamination. This technology also has great scope in countries, where safety, hygiene, storage and distribution of foods are serious issues. While comparing this technology with other lighting technologies, LEDs can bring numerous advantages to food supply chain from farm to fork. In case of small growing amenities which exploit only LEDs, energy expenditure has been successfully reduced while producing nutritious food. LEDs can be used to give us better understanding and control over production and preservation of food with relation to spectral composition of light. LEDs also play significant role in food safety by inactivating the food borne pathogens. Therefore, LED lighting is a very effective and promising technology for extending shelf life of agricultural produce by increasing disease resistance and with increased nutritional values.

Keywords: Light emitting diodes, Food preservation, Anti-microbial, Bioactive compounds, Non-thermal
Introduction
Although ultraviolet (UV) radiation is well known for its sterilising properties, under some conditions, visible light has been proven to have bactericidal characteristics, allowing it to play an important role in food preservation. Visible light plays an evident role in food production, as well as in agriculture and horticulture, because it stimulates photosynthesis, which is essential for plant growth and development. However, its use in other elements of food preparation receives less attention. Low light levels are now known to help the crops to retain postharvest quality by reducing senescence and enhancing phytochemical and nutritional content in a variety of species (Costa et al. 2013; Braidot et al. 2014; Glowacz et al. 2014). In agriculture and food industry, artificial light treatments are being used to disinfect water and food, as well as to enhance plant health and development by employing light energy of various wavelengths (Koutchma and Orlowska, 2012; Lian et al. 2010; Song et al. 2016).

LEDs operate in a solid-state environment which produce light with limited emission wavelengths, high photoelectric efficiency and photon flux or irradiance, low heat production, compactness & mobility and easy integration into electronic systems. It is a non-thermal food processing method that uses light radiation with wavelengths ranging from 200 to 780 nm (Prasad et al. 2020). The spectrum features, radiant or luminous intensity, and temporal settings of the light produced may be easily controlled because of LEDs special capabilities (Branas et al. 2013). LEDs constructed from semiconductor materials that produce monochromatic illumination are used in agriculture and food industries due to their benefits over conventional sources. Certain wavelengths of light, as well as pulsed and continuous operating modes can remove hazardous germs in food and water and thus making LEDs very effective. LEDs operate on the electroluminescence concept, which means they produce light under the influence of electric or magnetic field. In order to reach lower energy states, excited electrons in an electric or magnetic field produce light and release energy as electromagnetic radiation. LEDs are made of semiconductor materials that are impurity-laced to create a boundary or interface (known as a p-n junction) among the two categories of semiconductor materials, one being sufficient in holes (the positive or p-type) and the other (the negative or n-type) being sufficient in electrons (Prasad et al. 2020). The colour and wavelength of light produced are determined by the impurities and semiconductors employed in the LEDs manufacturing process. A semiconductor of p-type could possibly be constructed by infusing an element such as magnesium (Mg) belonging to group II, over any group III element substrate to create more cavities. An n-type semiconductor is created by doping a group IV element into a group III element substrate to provide additional free electrons (Bohn et al. 2009).
Effect of LEDs in food system

The effectiveness of LED therapies for solid meals is determined by the kind and character of the end food products, its constituents, as well as the water activity (a*) and surface features of the food. Significant elements that need to be considered are light wavelength, treatment time, dosage, illumination temperature, relative humidity and microbiological conditions. In Salmonella inoculated fresh-cut papaya, LEDs producing light with a wavelength 405 nm caused a depletion of 1–1.2 log CFU/cm². The papaya was given a complete dose of 1.7 kHz cm² for 48 h at 4°C (Kim et al., 2017b). Another study supporting the antibacterial efficacy of 405 nm LEDs on freshly-cut mango was conducted by Kim et al. (2017c), utilizing a total dosage of 2.6–3.5 kHz cm² over 36–48 h and cell counts in a three-strain cocktail of E. coli O157:H7, three serotypes of L. monocytogenes, and five serotypes of Salmonella spp. and reported that all three strains were decreased to less than 1.6 log CFU/cm². The effects of visible light LED therapy on the sanitation of fresh-cut fruits have also been explored. Ghate et al. (2017) investigated the antibacterial impact of a 460 nm LED on freshly-cut pineapples infected with a cocktail of S. enterica at various illumination temperatures and irradiances. A maximum reduction of 1.72 log CFU/g was achieved with 92 kHz cm² irradiance at 16°C illumination temperature in E. coli O157:H7, S. typhimurium, E. coli K12, and S. enteritidis. Lacombe et al. (2016) used a 405 nm LED to treat shelled almonds and found highest decrements of 2.44, 0.96, 1.86, and 0.7 log CFU/g, respectively. Srimagal et al. (2016) investigated the inactivation of E. coli in milk using blue LEDs with wavelengths of 405, 433, and 460 nm, at 5, 10 and 15°C, and treatment periods ranging from 0 to 90 min. Inactivation of microbes was found to be greater at higher temperatures and shorter wavelengths, with an E. coli O157:H7 reduction of 5.27 log CFU/mL after 60 min at 405 nm irradiation. The 460 nm LED resulted in a 2 to 5 log decrease, similar to the findings of Ghate et al. (2016), with a greater effect on bacterial inactivation at higher temperatures. Both studies showed significant color changes in food items (orange juice and milk) after exposure to blue LEDs, suggesting that the blue LEDs had an impact on the quality of liquid meals. LED lights in the blue wavelength inhibit bacterial activity, mostly owing to photodynamic inactivation (PDI) of the microorganisms. Akgun and Unluturk (2017) used UVC-LEDs at 254 nm (0.3 kHz cm²) and 280 nm (0.3 kHz cm²), as well as UVC-LEDs combined with 365 nm (0.8 kHz cm²) and 405 nm (0.4 kHz cm²), to inactivate E. coli K12 in both hazy and clear apple juice. With reductions of 2.0–2.01 and 2.0–2.04 log CFU/mL, the turbid apple juice showed the highest antibacterial activity when treated with 280 nm alone and a combination of 280 nm/365 nm, respectively after 40 min of LED treatment. In cases of clear apple juice, there was much more inactivation than in the cloudy apple juice. With a log decrease of 4.4 log CFU/mL, transparent apple juice treated alone with 280 nm (771.6 kHz cm², 40 min.) showed the greatest log decrement.

Effect of LEDs on nutritional profile

Horticultural produce are significant sources of human nutrition. LEDs have been extensively used and

Table 1 Effect of LED treatment in prevention of post-harvest losses

| Food                                      | Led Used | Applications                                                                 | References                  |
|-------------------------------------------|----------|-------------------------------------------------------------------------------|-----------------------------|
| Broccoli (Brassica oleracea L. var. italica) | Red (660 nm) | Delaying of senescence in vegetables; Reduced yellowing and less ethylene production observed as compared to blue and white LED | Ma et al. (2014) |
| Broccoli (B. oleracea Var. italica, cv. You-xiu) | Red (At a fluence rate of 50 Wm⁻²) | Inhibit yellowing and degradation of chlorophyll and reduced weight loss | Jiang et al. (2019) |
| Mature green tomatoes (Solanum lycopersicum L. cv. Dotaaerang) | Blue (440–450 nm) | Delaying of ripening; Slows down the rate of color change from green to red and loss of firmness observed compared with red light | Dhakal and Baek (2014b) |
| Strawberries (Fragaria ananassa) | Deep UV (272, 289 and 293 nm) | Preventing food spoilage by Mold growth (Botrytis cinerea) | Britz et al. (2013) |
| Lamb’s lettuce (L. ollitoria L. Pollich) | Warm White | A slower decrease of carotenoids content observed compared with dark control | Braidot et al. (2014) |
| Solanum lycopersicum | Blue | Prevent post-harvest spoilage; reduced spore germination of A. niger | Murdoch et al. 2013 |
| Lettuce (Lactuca sativa L.) | White LED At a fluence rate of 150 Wm⁻² at 6°C | Improved quality of lettuce for one week at 6°C by decreasing browning, minimizing weight loss and respiration, compared with control | Charles et al. (2018) |
| Pak-choi (Brassica rapa ssp. Chinensis) | Red and Blue At a fluence rate of 0, 10, 35, and 70 Wm⁻² | Red LEDs inhibited the senescence and reduces loss of photochemical efficiency, while blue light has weaker effect | Shezi et al. (2020) |
| Chinese Bayberries (Mynica rubra) | 470 nm (Blue) 40 μmol m⁻² s⁻¹ | Enhanced anthocyanin content as compared to control sample | Shi et al. (2014) |
### Table 2: Application of LED against various spoilage causing microorganisms in different food products

| LED Wavelength | Food | Micro organisms | Observations | References |
|----------------|------|-----------------|--------------|------------|
| 80 μmol m$^{-2}$ s$^{-1}$ (Light intensity) | Grapevine Vitis vinifera | B. cinerea | Induced resistance against bacterial population | Ahen et al. (2015) |
| 585 nm | Fruits and vegetables | B. cereus | Reduction of 0.7, 1.1 and 1.3 log CFUg$^{-1}$ on surface of plums, apricots and cauliflower respectively, as compared to control | Aponiene et al. (2015) |
| Blue: 410–540 nm Green: 470–620 nm: Red: 580–670 nm for 3 days at 5°C | Citrus fruit ‘Fallglo’ tangerines | Penicillium digitatum, Penicillium citri and Penicillium italicum | Significantly inhibited the fungal pathogenic microorganism | Alferez et al. (2012) |
| At three wavelengths 200 nm, 300 nm and 365 nm | Food matrix | Campylobacter jejuni | A four log cycle reduction was observed | Soro et al. (2021) |
| 461 nm (Blue LED): 18 h at 25°C | Citrus fruits | Penicillium digitatum and Penicillium italicum | Controlled the fungal infections | Lafuente and Alferez (2015) |
| Blue: 50-150 μmol m$^{-2}$ s$^{-1}$ | Solanum lycopersicum | B. cinerea | Induced resistance against moulds | Imada et al. (2014) |
| Three wavelengths 272, 293 and 289 nm; 9 days | Citrus fruits | Botrytis cinerea | Significantly inhibited the infections | Papoutsis et al. (2019) |
| 395 nm; 1115 s | Food matrix | Escherichia coli | The bacterial population of E. coli K-12 in maximum recovery diluent was decreased by 1.3 log CFU mL$^{-1}$ | Birmpa et al. (2014) |
| 405 and 520 nm; at 25, 10 and 4°C for 9 h | Soy agar | Bacillus cereus ATCC 14579, Listeria monocytogenes 1/2a BAA-679 Staphylococcus aureus ATCC 35932 Pseudomonas aeruginosa ATCC 10145 Salmonella Typhimurium ATCC 14028 Escherichia coli O157:H7 EDL 933 | B. cereus was reduced by about 2.3 log L. monocytogenes was reduced by 1.9 log S. aureus was reduced by 4.0, 2.1 and 1.9 log at 25, 10 and 4 °C, respectively. P. aeruginosa was most resistant S. typhimurium and E.coli O157:H7 showed moderate susceptibility | Kumar et al. (2015) |
| LED: 460–470 nm at 4°C for 4 days | Packaged sliced cheese | Listeria monocytogenes and Pseudomonas fluorescens Salmonella | Injured the RNA, peptidoglycan metabolism, protein and also caused disruption of cell membrane and cytoplasmic components | Hyun and Lee (2020) |
| 405 ± 5 nm | At 20°C for 24 h | Fresh cut Mango | Escherichia coli O157:H7, Listeria monocytogenes, Salmonella | LED-illumination inactivated 1.0–1.6 log CFU/cm² of populations at 4 and 10°C for 36–48 h (total dose, 2.6–3.5 kJ/cm²) | Kim et al. (2017c) |
| 405 and 460 nm | Cantaloupe rind | Listeria monocytogenes and Salmonella spp | Significant antibacterial effect | Josewin et al. (2018) |
| Blue LED: 95, 405, 415, and 425 nm | Apple juice | Escherichia coli O157:H7 | 6 to 7 log reductions | Kim and Kang (2021) |
| 461 nm at 7.5 h 10-15°C | Tryptophan soya broth | Staphylococcus aureus | Decreased approximately 5.2 and 4.7 log CFU mL$^{-1}$, respectively | Ghate et al. (2015) |
| 460 nm (Blue LED) (At irradiances of 92, 147.7 and 254.7 mW/cm² and temperatures of 4, 12, and 20 °C) | Orange Juice | Salmonella | Inactivation of Salmonella ranged from 2 to 5 log CFU/mL | Ghate et al. (2016) |
| 405 nm(MBL LED) Time: 0, 1, 2, 4, 6, 8, and 10 min. | Shelled Almonds | Pathogenic E. coli O157:H7, non-pathogenic E. coli K12, pathogenic S. enteritidis (PT30, Stanley, and Anatum), and non-pathogenic S. typhimurium strain Chi3985 | Reduction of 2.44 and 1.44 log CFU/g E. coli O157:H7 S. enteritidis, 0.7 and 0.55 log CFU/g reduction S. typhimurium, 0.54 and 0.97 log CFU/g reduction E. coli K12, 1.85 and 1.63 log CFU/g | Lacombe et al. (2016) |
| LEDs in Green, blue, red and white | Blueberries | Bacillus amyloliquefaciens and Lactobacillus brevis for fermentation and Propionibacterium acnes and Staphylococcus | White and green LEDs were efficient in improving fermentation and antibacterial activity | Jeong et al. (2018) |
| 405 (UV-Vis), 433, and 460 | UHT skim | E. coli ATCC 25922 | A 406 nm LED treatment at 13.8°C for | Srimagal |
considered as a useful source of lighting and are preferred for horticultural produce because they regulate the light source for plant growth. LEDs have the ability to enhance agricultural yield and also improving nutritional value (Mitchell et al. 2012). Taulavuori et al. (2017) reported that the use of blue LEDs is associated with its effect on several metabolic pathways and accumulation of phenolic compounds, polyphenols, carotenoid, ascorbic acid and anthocyanin. Similar trend was reported by (Hasperue et al. 2016). The authors studied the effect of white-blue LEDs on outer and inner leaves of Brussels sprouts for 10 days storage at 22 °C and reported lower respiration rate, better visual quality, with more than 10 times chlorophylls, higher contents of antioxidants and total flavonoids than controls. DiNardo et al. (2018) investigated the total phenolic content (TPC) and antioxidant capacity of Yellow European plums using high performance liquid chromatography. The authors reported that TPC and ferric reducing antioxidant potential were highest for freeze dried samples extracted at 60 °C. LED treatment also increases the antioxidant activity of tomato, Chinese cabbage, pea and Chinese Kale during storage (Hee-Sun Kook, 2013). Kang et al. (2020) studied the effect of LEDs on overall nutritional profile of cabbage and reported the enhancement of total phenolic content, total chlorophyll content, ascorbic acid and decrease in reactive oxygen species.

**Effect of LEDs on post-harvest preservation**

One of the most significant functions of food processing procedures is to reduce quality loss. Experts in agriculture continue to confront issues such as fruit rotting after harvest and the protection of standing crops from disease assault. LEDs are gaining popularity as a useful medium for sustainable agricultural operations. Various studies have been conducted to support the effectiveness of LED treatment in food system as listed in (Table 1). Tomatoes can be pre-treated with blue light to lengthen their ripening period before being stored in the dark. (Dhakal and Baek 2014a; 2014b). The authors pre-treated the mature green tomatoes with blue light (440–450 nm) emitted from blue light emitting diodes (LEDs) for one week and found that the pre-treatment of green tomatoes with blue light had delayed the softening. These tomatoes ripened fully after three weeks of storage in darkness due to the increased levels of lycopene. Blue light treatments at 40 μmol m⁻² s⁻¹ for 5 to 7 days decreased soft rot area, mycelial development, and sporulation of several fungi (Penicillium digitatum, Penicillium italicum, and Phomopsis citri) on the surface of fruits when compared to white light LED and darkness (Alferez et al. 2012; Liao et al. 2013). Disease resistance to a wide range of phytopathogens can be induced in standing crops using particular wavelengths of light, particularly red, blue, and green LEDs (Kim et al. 2013; Ahn et al. 2013). When compared to the effects of white fluorescent light, red light reduces lesion growth, activates the expression of defence-associated genes, and also promotes the synthesis of stilbenic components (Ahn et al. 2015). Plant defensive responses are aided by stilbenes, also known as phytoalexins (Jeandet et al. 2002). Furthermore, after using different wavelengths of LED illumination of plant products, enhanced production of stilbenes was detected along with increased expression of 16 defence-related genes (Ahn et al. 2013; Ahn et al., 2015). LEDs can potentially cause the expression of defence-related genes and as a result, the production of ginsenosides in Ginseng plants (Ali et al. 2006).

**Table 2** Application of LED against various spoilage causing microorganisms in different food products (Continued)

| LED Wavelength | Food | Microorganisms | Observations | References |
|----------------|------|----------------|--------------|------------|
| nm (blue) LED; Time: 90 min Illumination temperature: 5–15 °C | milk(< 0.5% fat) | E. coli K12 (ATCC 25,253) | 37.83 min. Can result in 5 log decrease with slight colour change | and Sahu, (2016) |
| 254, 280, 365, and 405 nm (UV LEDs) | Clear and cloudy apple juice | A reduction of 4 to 5 log was found in E. coli, S. typhimurium; L. monocytogenes | | Ghan et al. (2017) |
| 460 nm | Pineapples | A fusion of five serovars of Salmonella enterica Gaminara, Montevideo, Newport, Saintpaul, Typhimurium | Inactivation of microbes varied from 0.61 to 1.72 log CFU/g | Unluturk, (2016) |
| 266, 270, 279, and 275 nm | Sliced camembert cheese | | A reduction of 4 to 5 log was found in E. coli, S. typhimurium; L. monocytogenes | Kim et al. (2016) |
| Radiation intensity: 4 W/cm² | | | | |

**Action of LED against microbes**

Recently, it was found that various diseases can be inactivated by using light from LEDs (Prasad et al. 2020). *Listeria monocytogenes* can survive a variety of stresses,
LED Light used  | Light Intensity  | Crops  | Secondary metabolites/ biological activity  | References  
--- | --- | --- | --- | ---  
Blue: 470 nm  | Fluence rate 40 W m⁻²  | Immature strawberries  | Total phenolic content increased by 13.0%  | Kim et al. (2011)  
Blue: 525 nm  | At a fluence rate of 20 Wm⁻²  | Immature broccoli  | Total phenolic content increased by 1.80%  | Zhan et al. (2012a, 2012b)  
Red: 635 nm, Blue: 460 nm  |  | Pea sprouts  | Total phenolic content and total flavonoid contents of pea sprouts under blue, red and white fluorescent light were 1.46, 1.25, 1.45 times and 24.55, 21.01, 24.29 times, respectively  | Liu et al. (2016)  
Yellow: 585 nm  |  |  |  |  
Red  | 50 μmol m⁻² s⁻¹  | Malus domestica Borkh  | Anthocyanin production  | Lekkham et al. (2016)  
Blue: 460 nm  | 133 ± 5 μmol m⁻² s⁻¹  | Green oak leaf (Lactuca sativa var. crispa)  | Chlorophyll content was highest(1.31 mg/g) with red LED plus florescent light  | Chen et al. (2014)  
UV-A: 365 nm, UV-B: 311 nm  | 300 μW cm⁻²  | Ziyan leaves (Camellia sinensis L.)  | The anthocyanin content was the highest under UV-A treatment (66.0% (107.98 mg/100 g FW) and delphinidin, cyanidin, and pelargonidin contents increased by 64.57, 80.12, and 49.34%, respectively, compared with control  | Li et al. (2020)  
Red: 638 and 665 nm  | 300 μmol m⁻² s⁻¹ for 16 h  | Mustard  | Total β-carotene content increased from 0.028–0.073 mg/g.  | Brazaityte et al. (2016)  
Blue and white  | 20 μmol s⁻¹ m⁻²  | Chinese kale sprouts  | Total phenolic content of sprouts increased by 34.55 and 69.09%, respectively under blue and white LEDs  | Qian et al. (2016)  
Blue and red  | 80 μmol m⁻² s⁻¹  | Chinese cabbage and lettuce  | Total phenolic content production  | Li et al. (2012), Lin et al. (2013)  
Red and blue  |  | Strawberry (Fragaria × ananassa)  | Highest contents of total anthocyanin was 136 μg·g⁻¹ and Pelargonidin 3-glucoside 121.8 μg·g⁻¹ when treated with blue LED. Increased fuc punishan content (25.5 mg/g)  | Zhang et al. (2018)  
Blue 450 nm–470 nm  | –  | Panax ginseng  | Total ginsenosides increased from 2.0 to 74.0%  | Park et al. (2012)  
370 and 385 nm (UV-A LEDs)  | 30 W/m⁻² for 5 days  | Kale  | Total phenolic content at UV-A 370 nm increased by 14.0%  | Lee et al. (2019)  
Purple: 380 nm, Blue: 440 nm, Red: 660 nm  | 50–80 μmol m⁻² s⁻¹  | Vitis vinifera  | Trans-resveratrol and cis-piceid accumulation were increased with concentrations of 18.2 and 53.7 μg·g⁻¹ FW, respectively in blue and red LED treated leaves  | Ahn et al. (2015)  
Blue + Red  | 168 μmol m⁻² s⁻¹  | Carrot (Daucus carota L.)  | Phenolic acids and rutin increased by 45.0 and 65.0%, respectively compared to darkness  | Castillejo et al. (2021)  
50–80 μmol m⁻² s⁻¹  | B. rapa, B. oleracea var. capitata  | Vitamin C and polyphenolic content production  | Lee et al. (2014)  
Blue 440–450 nm  | 85–150 μmol m⁻² s⁻¹  | Solanum lycopersicum L. (Mature green tomatoes)  | γ - aminobutyric acid (GABA) increased to 797 μg·g⁻¹ dw treated with blue LED  | Dhakal et al. (2014a)  
Green  | ~ 200 μmol m⁻² s⁻¹  | Lactuca sativa, Lens culinaris, Trilcium aestivum L.  | Phenolic content, vitamin C, tocopherol and anthocyanin production  | Bantis et al. (2016)  
Yellow  | ~ 100 μmol m⁻² s⁻¹  | Raphanus sativus, Malus sp., S. lycopersicum, C. annum  | Vitamin C, α and β-tocopherol and lutein production  | Samuoliene et al. (2011); Kokali et al. (2016)  
Red and Blue  | Red, 45; Blue, 86; RB, 52 μmol/m² s⁻¹  | Chinese Cabbage (CR Ha Gwang) and Kale  | The total polyphenols in 'CR Ha Gwang' were increased by red + blue LED by (3.889), Red (3.817), Blue LED (3.776 μg·mL), and in ‘Kale TBC’ by RB (3.738), Red (3.722), Blue (3.722)  | Lee et al. (2016)  
(Blue: 430 nm + Red: 660) (Blue+Red+Far-Red: 730 nm)  | 173 and 197 μmol m⁻² s⁻¹ for B + R and B + R + FR, respectively  | Carrot (Daucus carota L.)  | Both LEDs treatments (B + R and B + R + FR) increased the phenolic content (phenolic acids and rutin) by 45 and 65%, respectively compared to darkness.  | Martinez et al. (2021)  
UVC Radiation  | 1.0, 3.0, and 12.2 kJ m⁻² for 1, 3, or 12 h  | Light red tomatoes  | The lycopene content was found to increased by 14.0%  | Hu et al. (2019)  

**Table 3** LED employed for enhancement of secondary metabolites and biological activity in fruits and vegetables.
which contributes to its widespread dispersion and distinct pathogenic characteristics. Using 405-nm LED illumination at 4 °C for 150 min, the survival of L. monocytogenes was studied after exposure to oxidative stress (0.04% H₂O₂), UV irradiation (253.7-nm), low temperature (4 °C), osmotic pressure (10, 15, or 20% NaCl), SGF (pH 2.5), or bile salts (2%). The pathways responsible for differences in stress tolerance were uncovered by studying the transcriptional responses and membrane integrity of L. monocytogenes. It was found that 405-nm LED treatment lowered L. monocytogenes resistance to all stresses, suggesting that it might be utilised effectively for prevention of L. monocytogenes contamination across the food-processing chain-line, from production to consumption (Kang et al. 2019). Furthermore, the antibacterial impact of blue 460-nm LEDs on Salmonella in orange juice was investigated. Salmonella enterica serovars Gaminara, Montevideo, Typhimurium, and Saintpaul were injected into pasteurised orange juice and illuminated with 460-nm LEDs at irradiances of 92, 147.7, and 254.7 mW/cm² at 4, 12, and 20 °C. With D-values of 1580 and 2013 J/cm², the most bactericidal pairings were 92 mW/cm² irradiance and temperatures of 12 and 20 °C, respectively. The findings revealed the efficacy of 460-nm LEDs in preserving fruit juices in retail markets and reducing the danger of salmonellosis (Ghate et al. 2016). Depending on the target requirements, LED systems can be programmed to deliver continuous or pulsed treatments. Kim et al. (2017a) used a pulsed LED producing light at 405 nm to test its effect on S. enteritis inoculation on cooked food. Using 4 °C, with a cumulative dose of 3.8 kJ/cm² resulted in a 0.8–0.9 log CFU/cm² reduction. Table 2 summarizes some of the examined LEDs wavelength ranges against various microorganisms.

**Effect of LEDs on synthesis of bioactive compounds**

The utilization of LEDs under controlled conditions in agricultural produce could be a most suitable choice for increasing the nutritional profile of various crops (Kozai, 2016). Lee et al. (2008) reported that a combined effect of red and blue light can increase the accumulation of bioactive compounds such as total polyphenols, anthocyanins and flavonoids. Red LEDs has a great impact on anthocyanin as compared to blue LEDs. Phenylalanine ammonia-lyase (PAL) enzyme plays an important role in induction of secondary metabolites by LEDs in plants. Red and blue LEDs stimulate the PAL and thus increase the synthesis of bioactive compounds in plants. Wang et al. (2009) studied that blue and red light helps in the build-up of flavonoids and glycosides. Blue light is also important in activating the metabolic pathway in production of phenolic compounds. They also reported that photosynthetic activity and stomatal opening by inducing photophorylation is promoted by red light.

LEDs are swiftly gaining popularity as a viable tool for growing greenhouse crops and preserving food (Mitchell et al. 2012). Light quality has a considerable influence on the accumulation of numerous bioactives in plants (Bian et al. 2015). Individual single-spectral red or blue LEDs greatly boosted the concentration of primary and secondary plant metabolites (e.g., soluble sugars, starch, vitamin C, soluble protein, and polyphenols) (Kim et al. 2013). Various spectrum of LEDs, including red, blue, green, and even white light, can enhance the accumulation of vitamin C, anthocyanins, total phenols and nutritional content of harvested vegetables (Lee et al. 2014, Kanazawa et al. 2012) as shown in (Table 3). The red LEDs aid in moisture retention in tissues of fruits and vegetables. This can also help to prevent water from evaporating too quickly, boosting its visual quality and market acceptability (Lee et al. 2014, Muneer et al. 2014, Massa et al. 2008). Furthermore, red or blue LEDs delay fruit senescence by reducing ethylene and ascorbic acid production (Ma et al. 2014). The use of single-spectral blue or red LEDs has been shown to boost the quality and productivity of vegetables and fruits (e.g., cucumber, pepper, and strawberry fruits) (Choi et al. 2015, Hao et al. 2012, Li et al. 2016).

**Future prospects and conclusions**

Very few studies had been reported about the applications of LEDs in spices & condiments, dairy products and medicinal herbs. Future studies and research might be conducted on phytochemical content, antioxidants, and other important nutrients. Different wavelengths of LEDs can be explored to enhance the various bioactive compounds, health promoting components and increased storage life (Hasan et al. 2017).

LEDs are novel technology that may be employed in a wide range of food processing applications, including the disinfection of solid and liquid food items. LEDs have several advantages over traditional light sources, such as the ability to emit a narrow range of light, high purity and effectiveness, compact size,

### Table 3 LED employed for enhancement of secondary metabolites and biological activity in fruits and vegetables (Continued)

| LED Light used      | Light Intensity | Crops                          | Secondary metabolites/ biological activity                                                                 | References            |
|---------------------|-----------------|--------------------------------|-----------------------------------------------------------------------------------------------------------|-----------------------|
| Blue and Red        | 167 lx for 12 h | Radish Sprouts (Raphanus sativus) | Sprouts grown under blue LED light had about 110% higher content of phenolic compounds than sprouts grown under red LED light | AbdElgader et al. (2015) |
longer shelf-life, and lower power consumption. A combination of different wavelengths of LEDs in variable concentrations during postharvest processing may improve the nutritional content, regulates the ripening rates, reduce the pathogenic microbial load in fresh produce. LEDs also regulates various processes such as photosynthesis and bioactive compounds yields in fruits and vegetables. LEDs technological and operational benefits might be enhanced by merging desirable wavelengths.

Abbreviations
UV: Ultraviolet; LEDs: Light Emitting Diodes; ATCC: American Type Culture Collection; CFU: Colony Forming Units; TSS: Total Soluble Solids

Supplementary Information
The online version contains supplementary material available at https://doi.org/10.1186/s43014-022-00086-0.

Additional file 1.

Acknowledgements
The authors would like to thank the Journal Editor and reviewers for thoughtful reading of the manuscript and constructive comments.

Authors’ contributions
AP contributed to all sections and writing of the article. AP also contributed the idea and extracted data and review the literature. SP and Vasundhara contributed to all sections and writing of the article. The author(s) read and approved the final manuscript.

Funding
Not Applicable.

Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on request.

Declarations
Ethics approval and consent to participate
Not required.

Consent for publication
All authors agree to publish.

Competing interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Received: 18 December 2021 Accepted: 3 March 2022
Published online: 28 March 2022

References
Abdelagader, A., Asemia-Or, S., Wong-Aree, C., Jitareerat, P., & Uthairatanakij, A. (2015). Effect of LED lighting on the quality of radish sprout. Agric Sci J, 46(3), 888–891.
Ahn, S. Y., Kim, S. A., Bae, K. H., & Yun, H. K. (2013). Inhibiting wildfire and inducing defense-related gene expression by led treatment on Nicotiana benthamiana. J Plant Pathol, 95, 477–483.
Ahn, S. Y., Kim, S. A., & Yun, H. K. (2015). Inhibition of Botrytis cinerea and accumulation of stilbene compounds by light-emitting diodes of grapevine leaves and differential expression of defense-related genes. Eur J Plant Pathol, 143(4), 753–765. https://doi.org/10.1007/s10658-015-0725-5.
Akgün, P. M., & Unlütürk, S. (2017). Effects of ultraviolet light emitting diodes (LEDs) on microbial and enzyme inactivation of apple juice. Int J Food Microbiol, 260, 65–74. https://doi.org/10.1016/j.ijfoodmicro.2017.08.007.
Alferez, F., Liao, H. L., & Burns, J. K. (2012). Blue light alters infection by Penicillium digitatum in tangerines. Postharvest Biol Technol, 63(1), 11–15. https://doi.org/10.1016/j.postharvbio.2011.08.001.
Ali, M. B., Yu, K. W., Hahn, E. J., & Paek, K. Y. (2006). Methyl jasmonate and salicylic acid elicitation induces ginsenoside accumulation, enzymatic and nonenzymatic antioxidant in suspension culture Panax ginseng roots in bioreactors. Plant Cell Reprod, 25(6), 613–620. https://doi.org/10.1007/s00299-005-0065-6.
Aponiene, K., Paškevičius, E., Reklaitis, I., & Luksiene, Z. (2015). Reduction of microbial contamination of fruits and vegetables by hypericin-based photosensitization: Comparison with other emerging antimicrobial treatments. J Food Eng, 144, 29–35. https://doi.org/10.1016/j.jfoodeng.2014.07.012.
Banis, F., Ouzounis, T., & Radoglou, K. (2016). Artificial LED lighting enhances growth characteristics and total phenolic content of Ocimum basilicum, but variably affects transplant success. Sci Hortic, 198, 277–283. https://doi.org/10.1016/j.scienta.2015.11.014.
Bian, Z. H., Yang, Q. C., & Liu, W. K. (2015). Effects of light quality on the accumulation of phytochemicals in vegetables produced in controlled environments: A review. J Sci Food Agric, 95(5), 869–877. https://doi.org/10.1002/jsfa.6789.
Birmpa, A., Vantarakis, A., Paparrodoropoulos, S., Whyte, P., & Lyng, J. (2014). Efficacy of three light technologies for reducing microbial populations in liquid suspensions. BioMed Res Int, 3, 9–12. https://doi.org/10.1155/2014/679399.
Bohn, P. W., Elmleisch, M., Georgiadis, J. G., Mariñas, B. J., & Mayes, A. M. (2009). In: Nanoscience and technology: A collection of reviews from journals. Singapore: World Scientific Publishing Co.
Braidot, E., Petrussa, E., Peressou, C., Patui, S., Bertolini, A., Tubaro, F., … Zancani, M. (2014). Low-intensity light cycles improve the quality of lamb’s lettuce (Valerianella olitiora [L. Pollich]) during storage at low temperature. Postharvest Biol Technol, 90, 15–23.
Branas, C., Azzando, F. J., & Alonso, J. M. (2013). Solid-state lighting: a systems review. Indus Electron Mag, 7(4), 6–14. https://doi.org/10.1109/ME.2013.228038.
Brazaityte, A., Sakalauskien, S., Viršil, A., Januškien, J., Samuolien, G., Širutautas, R., … Novickovas, A. (2016). The effect of short-term red lighting on Brassicaceae microgreens grown indoors. Acta Hortic, 1123(1123), 177–183. https://doi.org/10.17660/Acad.Hortic.2016.1123.25.
Britz, S., Gaska, I., Shitrum, I., Bilenko, Y., Shatalov, M., & Gaska, R. (2013). Deep ultraviolet (DUV) light-emitting diodes (LEDS) to maintain freshness and phytochemical composition during postharvest storage. In CLEO: San Jose: Optical Society of America.
Castilejo, N., Gomez, P. A., & Artes-Hernández, F. (2021). Amelioration effect of LED lighting in the bioactive compounds synthesis during carrot sprouting. Agronomy, 11, 304. https://doi.org/10.3390/agronomy11030304.
Charles, F., Niliprapruck, P., Roux, D., & Sallanon, H. (2018). Visible light as a new tool to maintain fresh-cut lettuce post-harvest quality. Postharvest Biol Technol, 131, 53–56. https://doi.org/10.1016/j.postharvt.2017.08.024.
Chen, X., Guo, W., Xue, X., Wang, L., & Qiao, X. (2014). Growth and quality responses of ‘green oak leaf’ lettuce as affected by monochromatic or mixed radiation provided by fluorescent lamp (FL) and light-emitting diode (LED). Sci Hortic, 172, 168–175. https://doi.org/10.1016/j.scienta.2014.04.009.
Choi, M. K., Chang, M. S., Eom, S. H., Min, K. S., & Kang, M. H. (2015). Physicochemical composition of buckwheat microgreens grown under different light conditions. J Korean Soc Food Sci Nutr, 44, 709–715. https://doi.org/10.3374/jfsn.2015.44.5.709.
Costa, L., Millan, Montano, Y., Carrion, C., Rolny, N., & Guiamet, J. J. (2013). Application of low-intensity light pulses to delay postharvest senescence of Ocimum basilicum leaves. J Food Eng, 90, 46–51. https://doi.org/10.1016/j.jfoodeng.2013.06.017.
Dhakal, R., & Baek, K. H. (2014a). Metabolic alternation in the accumulation of free amino acids and γ-amino butyric acid in postharvest mature green tomatoes following irradiation with blue light. Hortic Environ Biotechnol, 55(1), 36–41. https://doi.org/10.1007/s13580-014-0125-3.
Dhakal, R., & Baek, K. H. (2014b). Short period irradiation of single blue wavelength light extends the storage period of mature green tomatoes.
Hu, L., Yang, C., Zhang, L., Feng, J., & Xi, W. (2019). Effect of light-emitting diodes

Imada, K., Tanaka, S., Ibaraki, Y., Yoshimura, K., & Ito, S. (2014). Antifungal effect of

Ghate, V., Kumar, A., Kim, M. J., Bang, W. S., Zhou, W., & Yuk, H. G. (2017). Effect of 460 nm light emitting diode illumination on survival of Salmonella spp. on fresh-cut pineapples at different irradiances and temperatures. J Food Eng, 196, 130–138. https://doi.org/10.1016/j.jfoodeng.2016.10.013.

Ghate, V., Kumar, A., Zhou, W., & Yuk, H. (2016). Irradiance and temperature influence the bacterial effect of 460-nanometer light emitting diodes on Salmonella in orange juice. J Food Protect, 79, 553–560.

Ghate, V., Kumar, A., Zhou, W., & Yuk, H. G. (2015). Effect of organic acids on the photodynamic inactivation of selected foodborne pathogens using 461 nm LEDs. Food Control, 57, 333–340. https://doi.org/10.1016/j.foodcont.2015.04.029.

Glowacz, M., Mogren, L. M., Reade, J. P. H., Cobb, A. H., & Monaghan, J. M. (2014). High-but not low-intensity light leads to oxidative stress and quality loss of cold-stored baby leaf spinach. J Sci Food Agric, 95(9), 1821–1829. https://doi.org/10.1002/jsfa.6880.

Hao, X., Zheng, J. M., Little, C., & Khosla, S. (2012). LED inter-lighting in year-round greenhouse mini-cucumber production. Acta Hort, 960(556), 335–340. https://doi.org/10.17660/ActaHortic.2012.956.38.

Hase, M., Bashir, T., Ghosh, R., Lee, S. K., & Bae, H. (2017). An overview of LEDs' effects on the production of bioactive compounds and crop quality. Molecules, 22(9), 1420. https://doi.org/10.3390/molecules22091420.

Hasperue, J. H., Guardianelli, L., Rodoni, L. M., Chaves, A. R., & Martínez, G. A. (2014). Microwave treated blue light-emitting diodes (LEDs) as a potential postharvest intervention to improve the quality of longan (Dimocarpus longan L.) fruit with probiotic bacteria to yield bioactive compounds. Food Research International, 59, 461–468. https://doi.org/10.1016/j.foodcont.2015.04.029.

Hee-Sun Kook, K. K. (2013). The effect of blue-light-emitting diodes on spoilage bacteria at different temperatures. Food Res Int, 59, 158–166. https://doi.org/10.1016/j.lwt.2013.07.023.

Hase, M., Bashir, T., Ghosh, R., Lee, S. K., & Bae, H. (2017). An overview of LEDs' effects on the production of bioactive compounds and crop quality. Molecules, 22(9), 1420. https://doi.org/10.3390/molecules22091420.

Hastings, A. J., Guardanelli, L., Rodoni, L. M., Chaves, A. R., & Martínez, G. A. (2014). Microwave treated blue light-emitting diodes (LEDs) as a potential postharvest intervention to improve the quality of longan (Dimocarpus longan L.) fruit with probiotic bacteria to yield bioactive compounds. Food Research International, 59, 461–468. https://doi.org/10.1016/j.foodcont.2015.04.029.

Hase, M., Bashir, T., Ghosh, R., Lee, S. K., & Bae, H. (2017). An overview of LEDs' effects on the production of bioactive compounds and crop quality. Molecules, 22(9), 1420. https://doi.org/10.3390/molecules22091420.

Hee-Sun Kook, K. K. (2013). The effect of blue-light-emitting diodes on spoilage bacteria at different temperatures. Food Res Int, 59, 158–166. https://doi.org/10.1016/j.lwt.2013.07.023.

Hase, M., Bashir, T., Ghosh, R., Lee, S. K., & Bae, H. (2017). An overview of LEDs' effects on the production of bioactive compounds and crop quality. Molecules, 22(9), 1420. https://doi.org/10.3390/molecules22091420.

Hasperue, J. H., Guardianelli, L., Rodoni, L. M., Chaves, A. R., & Martínez, G. A. (2014). Microwave treated blue light-emitting diodes (LEDs) as a potential postharvest intervention to improve the quality of longan (Dimocarpus longan L.) fruit with probiotic bacteria to yield bioactive compounds. Food Research International, 59, 461–468. https://doi.org/10.1016/j.foodcont.2015.04.029.

Hee-Sun Kook, K. K. (2013). The effect of blue-light-emitting diodes on spoilage bacteria at different temperatures. Food Res Int, 59, 158–166. https://doi.org/10.1016/j.lwt.2013.07.023.

Hase, M., Bashir, T., Ghosh, R., Lee, S. K., & Bae, H. (2017). An overview of LEDs' effects on the production of bioactive compounds and crop quality. Molecules, 22(9), 1420. https://doi.org/10.3390/molecules22091420.

Hasperue, J. H., Guardianelli, L., Rodoni, L. M., Chaves, A. R., & Martínez, G. A. (2014). Microwave treated blue light-emitting diodes (LEDs) as a potential postharvest intervention to improve the quality of longan (Dimocarpus longan L.) fruit with probiotic bacteria to yield bioactive compounds. Food Research International, 59, 461–468. https://doi.org/10.1016/j.foodcont.2015.04.029.

Hee-Sun Kook, K. K. (2013). The effect of blue-light-emitting diodes on spoilage bacteria at different temperatures. Food Res Int, 59, 158–166. https://doi.org/10.1016/j.lwt.2013.07.023.

Hase, M., Bashir, T., Ghosh, R., Lee, S. K., & Bae, H. (2017). An overview of LEDs' effects on the production of bioactive compounds and crop quality. Molecules, 22(9), 1420. https://doi.org/10.3390/molecules22091420.

Hasperue, J. H., Guardianelli, L., Rodoni, L. M., Chaves, A. R., & Martínez, G. A. (2014). Microwave treated blue light-emitting diodes (LEDs) as a potential postharvest intervention to improve the quality of longan (Dimocarpus longan L.) fruit with probiotic bacteria to yield bioactive compounds. Food Research International, 59, 461–468. https://doi.org/10.1016/j.foodcont.2015.04.029.

Hee-Sun Kook, K. K. (2013). The effect of blue-light-emitting diodes on spoilage bacteria at different temperatures. Food Res Int, 59, 158–166. https://doi.org/10.1016/j.lwt.2013.07.023.

Hase, M., Bashir, T., Ghosh, R., Lee, S. K., & Bae, H. (2017). An overview of LEDs' effects on the production of bioactive compounds and crop quality. Molecules, 22(9), 1420. https://doi.org/10.3390/molecules22091420.
