Comprehensive REVIEWS in Food Science and Food Safety

Application of Light-Emitting Diodes in Food Production, Postharvest Preservation, and Microbiological Food Safety

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Abstract: Light-emitting diodes (LEDs) possess unique properties that are highly suitable for several operations in the food industry. Such properties include low radiant heat emissions; high emissions of monochromatic light; electrical, luminous, and photon efficiency; long life expectancy, flexibility, and mechanical robustness. Therefore, they reduce thermal damage and degradation in crops and foods and are suitable in cold-storage applications. Control over spectral composition of emitted light results in increased yields and nutritive content of horticultural or agricultural produce. Recently, LEDs have been shown to preserve or enhance the nutritive quality of foods in the postharvest stage, as well as manipulate the ripening of fruits, and reduce fungal infections. LEDs can be used together with photosensitizers or photocatalysts to inactivate pathogenic bacteria in food. UV LEDs, which are rapidly being developed, can also effectively inactivate pathogens and preserve food in postharvest stages. Therefore, LEDs provide a nonthermal means of keeping food safe without using chemical sanitizers or additives, and do not accelerate bacterial resistance. This article provides a review of the technology of LEDs and their role in food production, postharvest preservation, and in microbiological safety. Several challenges and limitations are identified for further investigation, including the difficulty in optimizing LED lighting regimens for plant growth and postharvest storage, as well as the sensory quality and acceptability of foods stored or processed under LED lighting. Nevertheless, LED technology presents a worthy alternative to current norms in lighting for the growth and storage of safe and nutritious food.

Keywords: agriculture, food safety, light-emitting diode (LED), nonthermal processing, postharvest

Introduction

The role of visible light in food production, as in agriculture and horticulture, is obvious, as light drives photosynthesis, which is crucial for plant growth and development. However, less recognition is given to its usefulness in other aspects of food processing. It is now understood that low quantities of light can maintain the postharvest quality of crops by mitigating senescence, and improving phytochemical and nutrient content in several species (Costa and others 2013; Braidot and others 2014; Glowacz and others 2014; Pogson and Morris 2004). The sterilizing capabilities of ultraviolet (UV) radiation are well known, yet visible light has been shown to have bactericidal effects under certain conditions, hence playing a role in food safety. High-intensity discharge (HID) lighting, including high-pressure sodium (HPS), metal halide and xenon lamps, as well as fluorescent and incandescent lamps, have been common lighting sources in food production and preservation. Such lighting systems are characterized by broad spectral power distribution, with limited control over the emissions of UV or infrared (IR) radiation. This presents several problems especially in terms of undesirable growth and development of plants, or in excessive heating due to IR radiation (Morrow 2008; Mitchell and others 2012). To control the temperature in different applications, such as in greenhouses, storage facilities, or in various food processing operations, more energy will therefore be required to remove excess heat. Moreover, fluorescent lights and low-pressure mercury lamps contain mercury, and therefore need to be handled carefully to prevent damage and leakage of the toxic heavy metal (Lui and others 2014).

Light-emitting diodes (LEDs) are solid-state lighting devices that emit light with emission wavelengths of narrow bandwidths, high photoelectric efficiency and photon flux or irradiance, low thermal output, compactness, portability, and which are easily integrated into electronic systems. The unique properties of LEDs allow for the convenient manipulation of the spectral characteristics, radiant or luminous intensity, and temporal settings of the light produced (Branas and others 2013). When LEDs were in the early stages of development after the 1960s, they were of low power and were used mainly as indicator lamps. In subsequent

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years, the development of LEDs was rapid as new semiconductor materials were incorporated, crystal growth techniques and optics were improved, and better means of thermal dissipation in junctions were implemented (Bourget 2008; Yeh and Chung 2009; Chang and others 2012; Branas and others 2013). As a result, LEDs have become ubiquitous and are utilized in many lighting applications.

With the current state of technology, LEDs have become increasingly feasible and advantageous as a form of lighting that can be used in conjunction with the above lighting systems, or as a substitute. In the areas of horticulture and agriculture, LEDs are regarded as novel and easily controlled light sources for plant growth, and have been shown to enhance the production of crops while improving their nutritional content (Morrow 2008; Yeh and Chung 2009; Mitchell and others 2012). The most recent literature sources on postharvest preservation of plants use LEDs because of their low radiant heat emissions and better efficiency at lower temperatures. Moreover, as food safety is a major concern in the food industry during the production, postharvest, and storage stages, the success of therapeutic applications of LEDs in the medical field has motivated the development of similar strategies to decontaminate food and keep it safe for consumption.

Because of the long life expectancies of LEDs, their robustness, and compactness, LED lighting systems have the potential to be a very cost-effective technology to adopt. In addition, LEDs are rapidly becoming more efficient and cheaper, hence it is expected that LED technology will become more attractive to the food industry in the near future. Research in the literature pertaining to LEDs in the food industry mainly focuses on 3 different aspects, namely, food production, postharvest storage, and food safety. This review will highlight the unique properties of LEDs and the quality of light they emit, which are not present in previous lighting technologies, and relate these properties to their ability to effectively enhance the quality of food produced and stored, and to efficiently inactivate harmful foodborne pathogens via light-mediated phenomena. The most significant and recent findings from these 3 fields, as well as the current limitations that need to be addressed and ways to overcome, are presented together in this review, to show that LEDs have the potential to be adopted and tailored to the food industry as an efficient and increasingly inexpensive means of producing and distributing acceptable and safe foods.

Properties of LEDs

Overview of LED technology

A LED is a semiconductor diode capable of producing light through electroluminescence. It comprises a p-side and an n-side, with an interface termed the p–n junction. Current only flows from the p-side to the n-side, resulting in electrons and holes flowing toward the junction when a voltage is applied. Electroluminescence occurs when an electron–hole interaction causes an electron to fall to a lower energy level, thereby releasing a photon. This results in the emission of light of a distinct wavelength (Gupta and Jatothu 2013). Hence, LEDs are capable of producing monochromatic light, consisting of a narrow bandwidth of wavelengths, which appears as distinct colors to the eye.

The color of the emitted light depends on the band gap energy of the material of the semiconductor. Gallium arsenide is used for red and IR light; indium gallium aluminum phosphide for green, yellow, orange, and red lights; and gallium nitride and silicon carbide for blue lights (Yeh and Chung 2009; Gupta and Jatothu 2013). In addition, LEDs emitting UV radiation are available, typically composed of aluminum gallium nitride or indium gallium nitride, with a wavelength as low as 210 nm (Shur and Gaska 2010). Despite LED chips having monochromatic output, white LEDs have been created as well. One means of producing white light includes a UV-LED and tri-color phosphor coating combination, or a blue LED with yellow phosphor (Park and others 2014). Alternatively, white light can be produced by mixing the light from red, blue, and green LEDs (DenBaars and others 2013). This method affords greater control over the spectral composition of the emitted white light.

LED packages can produce a large amount of visible light energy in terms of lumens per unit input electrical power (lm W^{-1}), and therefore have high luminous efficacy. In January 2013, the U.S. Dept. of Energy (2013) determined that the current luminous efficacy of LED luminaries was similar to fluorescent and HID luminaries but were expected to surpass them in the future. Similarly, the photon efficiency, or the number of photons produced per unit of input electrical energy (μmol J^{-1}), for LEDs is similar to HPS lamps and slightly higher than fluorescent lamps (Nelson and Bugbee 2014), as shown in Table 1. Another means of evaluating LED performance is through measuring the electrical efficiency, which represents the percentage of output power in the form of light per unit of input electrical power. According to a comparison of electrical efficiencies of different lighting technologies based on product catalogues and other sources, the electrical efficiency of LEDs is approximately the same as HPS lamps but higher than fluorescent lamps (Pinho and others 2012). Blue LEDs have reached electrical efficiencies of above 60%. In contrast, the electrical efficiency of UV LEDs is still limited, at an estimated 10% (Dobrinsky and others 2012). The maximum electrical efficiency of UV LEDs of peak emission of 275 nm reached is 8%, compared with the 15% efficiency of medium-pressure mercury lamps, which emit UV radiation in the range of 200 to 300 nm (Ibrahim and others 2013). Opportunities for improving the luminous efficiency include improving the light extraction efficiency, achieved by reducing total internal reflection within the chip, or device encapsulation (Zhmakin 2011; Dobrinsky and others 2012). Hence, the prospects of further improvement in light output and efficiency are attractive and advantageous over current lighting technologies.

Another important advantage of LEDs is the low emissions of radiant heat in the form of IR radiation, which reduces undesirable or detrimental effects of heat on food or plant quality (Morrow 2008; Mitchell and others 2012). However, a substantial amount of heat is produced at the p–n junction and compromises the luminous efficacy of the LED. Therefore, proper cooling via heat sinks, or other devices, such as fans, is necessary. This allows LEDs to be particularly useful in cold-chain transport and storage as they emit little radiant heat, operate at a higher luminous efficacy at lower temperatures, and their robust designs prevent damage through vibration and other mechanical forces (United States Department of Energy 2012).

Other useful characteristics include long life expectancies, which can last for around 50000 to 100000 h compared with 15000 h for conventional lighting, and their compact size which allows for better flexibility when designing lighting systems for various purposes such as in *in vitro* plant tissue cultures (Gupta and Jatothu 2013). LEDs also have an instant on-off feature which most conventional lighting lack, and this allows for dimming or pulsed lighting periods in horticulture or food safety applications (Yeh and Chung 2009; Branas and others 2013). With the expected further energy- and cost-saving prospects of LEDs, it is timely to

Table 1–Table comparing the properties of LEDs to two commonly used lighting technologies.

Properties	LEDs	Compact fluorescent lamps	HPS lamps	References
Spectral composition	Monochromatic. UV LEDs, IR LEDs and White LEDs available.	Broad spectrum, cannot be controlled. Radiation in UV and IR range present.	Broad spectrum, cannot be controlled. Radiation in UV and IR range present.	DenBaars and others (2013); Mitchell and others (2012)
Size and compactness	Chips are small and compact (2 to 5 cm) and can be assembled into different formations, shapes, and fixtures.	Bulky	Bulky	Mitchell and others (2012); U.S. Dept. of Energy (2012)
Luminous efficiency	Color-mixed white LEDs: 100 to 150 lm/W, projected to increase to approximately 250 lm/W by 2025	45 to 80 lm/W	65 to 150 lm/W	U.S. Dept. of Energy (2013)
Photon efficiency	0.89 to 1.70 μmol J^{-1}	0.95 μmol J^{-1}	1.30 to 1.70 μmol J^{-1}	Nelson and Bugbee (2014)
Time to full light output after switching on.	Almost instantly, with no restrike delay. High-frequency pulsing and dimming possible.	Approximately 3 min to full brightness.	Approximately 10 min of warm up time and up to 20 min restrike time delay.	U.S. Dept. of Energy (2012)
Life expectancy	50000 h	10000 to 17000 h	10000 to 17000 h	Nelson and Bugbee (2014); Gupta and Jatothu (2013)
Durability	Not affected by mechanical force.	Brittle components in bulb and fixtures.	Brittle components in bulb and fixtures.	U.S. Dept. of Energy (2012)

consider how this technology can be further developed to support the needs of the food industry.

Metrics used in quantifying light

Pinho and others (2012) discuss methods of quantifying light in the relevant literature and their limitations. The 2 common metrics used in all studies pertaining to food include (1) photon flux, which is the number of moles of photons received per unit area per second (typical units in μmol m^{-2} s^{-1}); and (2) irradiance, which is the power of light energy received per unit area (W m^{-2}). The 2 units carry distinct meanings, as photon flux quantifies the number of photons that contact a surface but disregards the wavelength or energy that the photons possess. In contrast, irradiance quantifies the rate of energy received on the surface, which depends on the spectral composition of light as photons at different wavelengths possess different energy. An additional unit, the Einstein, which is denoted by "E" (as in μE m^{-2} s^{-1}), could either be interpreted similarly to the photon flux in terms of moles per unit area and time, or it could be interpreted as the irradiance in terms of the radiant energy in watts per unit area and time. Because of the ambiguity of its definition, it is not an SI Unit and its usage is generally discouraged (Thimijan and Heins 1983), although it is still used occasionally (Braidot and others 2014; Dhakal and Baek 2014a,b).

Photon flux is commonly used in the literature involving plant subjects because the photon, which is the "particle" form of light, is more suitable for describing the photochemical interaction between light and photoreceptors like chlorophyll during photosynthesis (Pinho and others 2012). Light in the visible range (400 to 700 nm) is assumed to be utilized by plants, therefore electromagnetic radiation in that wavelength range is termed photosynthetically active radiation (PAR). However, plants do not utilize light within the PAR range evenly, as green light is absorbed in lesser quantities than red or blue light (Zhu and others 2008). Moreover, it is also understood that radiation outside of the PAR range of wavelengths is biologically significant (Carvalho and others 2011; Pinho and others 2012). Therefore, in addition to stating the photon flux, it is necessary to be specific with the spectral profile of light for a holistic evaluation of the light utilized in a photochemical reaction.

In contrast, since monochromatic light is required in studies involving LEDs in food safety (see section *LEDs in Food Safety*), the spectral composition of light is not relevant. Microbial inactivation depends on the light dosage, which is the amount of light energy received per unit area of sample (J m^{-2}). The dosage of a treatment is calculated by multiplying time with the irradiance measured at the surface of a sample (Maclean and others 2009; Luksiene and Paskeviciute 2011b; Ghate and others 2013; Aponiene and others 2015). Therefore, while irradiance is used to quantify the amount of monochromatic light in microbial inactivation operations in terms of light energy, photon flux is preferred in most literature sources relating to plants, but must be interpreted cautiously because of the fact that the total energy of the emitted light is not represented, and that plants utilize photons in different proportions depending on their wavelength.

LEDs in Food Production and Horticulture

Sunlight is the main source of energy for crop cultivation. However, only 4.6% to 6.0 % of the total incident solar radiation energy is utilized through photosynthesis for plant biological activity (Long and others 2006). One cause is the poor distribution of natural sunlight throughout the full canopy as leaves on the topside of the canopy receive PAR in excess of the maximum photosynthetic capacity, whereas leaves that are below will receive light in quantities below the photosynthetic capacity. Also, approximately 10% of PAR is reflected because of the green pigment chlorophyll (Zhu and others 2008).

LEDs present a solution to this natural limitation, following the development of the red LED and subsequent invention of the blue LED (Morrow 2008). Portable LEDs can be deployed within the canopies, and employing only blue and red LEDs reduces energy costs by omitting green light. A substantial number of studies have demonstrated the usefulness of LEDs in the cultivation of crops, and to a smaller extent in other aspects of food production and agriculture such as in fisheries and poultry rearing, ingredients, and other applications (Table 2). The properties of LED that are useful in horticultural production include the ability to control

Table 2—The applications of LED lighting in food production, their features, and the effectiveness of the application on quality.

Application	Role of LED lighting	LED treatment	Summary of effect of treatment on food quality	Reference
Small-scale crop production	Food production unit in space station.	Red (630 nm) and blue (455 nm); 95:5 ratio	"Targeted" LED lighting technique, or switching on LEDs directly above plant surface instead of indiscriminate irradiation, supported lettuce growth (*Lactuca sativa* L. cv. "Waldmann's Green") and reduced energy consumption to less than 1 kWh g^{-1} dry mass.	Poulet and others (2014)
		Red (632 nm), green (525 nm), and blue (468 nm); 7:2:1 ratio; photon flux of 220 and 400 μmol m^{-2} s^{-1}	Irradiated using lower photon flux of 220 μmol m^{-2} s^{-1} resulted in higher photosynthetic rate for lettuce (*L. sativa* L. cv. Lollo Rossa) and radicchio (*Cichorium intybus* L. cv. Bianca di Milano).	Ilieva and others (2010)
		Red and blue (wavelength not specified), 9:1 ratio. Photoperiod of 12 to 24 h	The effects of irradiation of 600 μmol m^{-2} s^{-1} of both red and blue LEDs on lettuce (*L. sativa* L. cv. Dasusheng) was compared with white fluorescent light. The power consumption of the LED system was lower at 0.5 kWm^{-2} compared with the fluorescent lamp at 1.1 kWm^{-2}. A continuous 24 h photoperiod treatment resulted in greatest total soluble sugar, crude fiber and vitamin C content, and lowest nitrate content compared with fluorescent treatment.	Shen and others (2014)
		Red (650 nm) and blue (470 nm); 7:1 ratio.	Biomass production, sugars, and vitamin C of Chinese cabbage (*Brassica chinensis* L. cv. Vesnyanka) grown under LED system was less than those under HPS. The LED treatment might not be suitable for the cultivar or plant age.	Avercheva and others (2014)
	Hydroponic farming	Red, blue, and white (various wavelength ranges), photon flux ranging from approximately 220 to 300 μmol m^{-2} s^{-1}	Various combinations of photon fluxes and photoperiods of red, blue, and white LEDs typically resulted in good growth for lettuce (*L. sativa* L.) shown by higher specific leaf area, total soluble sugars content, sensory scores, and lower nitrate content than samples under fluorescent light.	Lin and others (2013); Kang and others (2013)
Greenhouse crop production	Intracanopy lighting to supplement sunlight or conventional light sources	Red (667 nm) and blue (465 nm), 221 μmol m^{-2} s^{-1}	Supplementary intracanopy light increased marketable yield of cucumber fruit (*Cucumvis sativus* "Samona") for 2 wk after harvest, after which yield decreased significantly. Blue LED light resulted in curling of leaves which reduced absorption of light.	Hao and others (2012); Trouwborst and others (2010)
Research	Ease of manipulating spectral output, intensity and temporal effects to better understand plant physiological and nutritional growth.	Far-red (735 nm), red (660 nm), orange-red (630 nm), blue (460 nm), and violet (405 nm).	Control of spectral quality of light by mixing output of 2800 LED chips of violet, blue, orange-red, red and far-red light to study phototrophic curvature of oat coleoptiles.	Yano and Fujiwara (2012)
		Red (630 nm) and blue (470 nm).	Pulsed-width modulation dimming of blue and red LEDs on *Arabidopsis thaliana* growth	Shimada and Taniguchi (2011)
		170 red LEDs, 30 blue LEDs. Wavelength not specified,	Smart illumination system using field programmable gate array to manipulate intensity, spectrum, pulse frequency, and width to study chlorophyll fluorescence in tomato plant	Olvera-Gonzalez and others (2014)
		Green LEDs (510, 520, and 530 nm)	Narrow bandwidth of wavelength allowed for peak wavelength differences of 10 nm between different LEDs, which gave greater precision in understanding effect of peak wavelength in green range on photosynthesis on lettuce (*Lactuca sativa* L. cv Banchu Red Fire).	Johkan and others (2012)
Food ingredients	Production of various food components through aquatic algae and photosynthetic bacteria.	Red and blue LEDs	Combination of blue and red LEDs are most effective in driving photosynthesis in algal cultures. Blue LED light promoted the growth and production of carotenoids in *Rhodopseudomonas palustris*, *Haematococcus pluvialis*, and *Dunaliela salina*.	Schulze and others (2014); Yeh and others (2014)
	Steviol glycoside	Red (660 nm)	Application of red LED beyond the short-day photoperiod of *Stevia rebaudiana* Bertoni plants increased the yield of steviol glycoside to twice the amount compared with the control after a 7-wk treatment period.	Ceunen and others (2012)
Animal rearing	Improving fish breeding, biomass accumulation, and stress response.	Various	Red LED light treatment for 14 h improves reproductive performance of sapphire devils (*Chrysiptera cyanea*).	Yeh and others (2014)

(Continued)

Table 2–Continued

Application	Role of LED lighting	LED treatment	Summary of effect of treatment on food quality	Reference
	Stimulating growth of broiler chickens	Red (600 to 630 nm), yellow (580 to 590 nm), green (510 to 530 nm), and blue (450 to 460 nm)	Atlantic cod grown under blue, green, or white LED light with short wavelengths were reported to have a higher dry weight than red. Atlantic salmon (*Salmo salar*) exposed to white LED or blue LED light below 0.99 W m^{-2} do not experience any stress response compared with blue LED above 2.7 W m^{-2}. Yellow LED light appeared to cause greatest weight gain per feed intake for 3 wk only compared with white, blue, red, green LEDs, and incandescent light control.	Kim and others (2013)

the quality of light, the limited amount of heat generated, as well as the ease of integration into electronic systems to give greater control over the emitted light.

Control over spectral composition of output light from LEDs

Plants contain various pigments and photoreceptors that are stimulated by certain wavelengths, which correspond to photosynthetic or photomorphogenic responses in a plant. In general, red and blue light are both required together for maximum photosynthetic rate and healthy growth as they correspond to the absorption peaks of chlorophyll. Blue light, which is absorbed by cryptochrome, is responsible for photomorphogenic functions such as stomatal control, stem elongation, and phototropism. The ratio of red to far-red light is detected by phytochrome and a low ratio stimulates stress responses such as elongation growth, apical dominance, and flowering (Carvalho and others 2011). Although light in the green range is generally assumed to have a smaller effect on plant growth and photosynthesis as it is not easily absorbed, there is evidence that mixing 24% of green fluorescent light (500 to 600 nm) with red and blue LEDs (630 and 470 nm, respectively) on a photon flux basis results in a greater leaf area and shoot fresh and dry weight compared with a red-blue LED-only treatment. The authors attributed it to the ability of green light to penetrate the plant canopy more effectively than red or blue light (Kim and others 2004). Moreover, green LED light at high intensity was found to promote growth in red-leaf lettuce (*Lactuca sativa* L. cv. Banchu Red Fire), suggesting that at higher photon fluxes green light might be utilized by plants (Johkan and others 2012). Also, mixing a small amount of green light aids in visually assessing the leaves, as using red and blue lights causes leaves to appear dark purple, making it difficult to detect growth defects or diseases (Kim and others 2004; Massa and others 2008).

With greater understanding of the relationship between light wavelengths and the effect on growth and morphology, LEDs can also be used to control the spectral composition of light, or the light quality, thereby reducing energy usage and preventing the undesirable effects of certain regions of the light spectrum. Currently, conventional sources of lighting suffer from inflexible and broad spectral compositions that might be sub-optimal for growth. Incandescent and HPS lamps have higher emissions in the red region, resulting in excessive stem elongation, in contrast to fluorescent lamps which emit a higher proportion of light in the blue region and are hence limited to small-scale *in vitro* growth (Mitchell and others 2012; Pinho and others 2012). LEDs emit light in a narrow bandwidth of wavelengths and can therefore be used to supplement sunlight or current lighting systems used in greenhouses to enhance the spectral composition of light (Mitchell and others 2012).

Lower radiant heat produced by LEDs

Long-wave radiation emitted from light sources like HID lamps causes surface-heating on plants, but LEDs produce very minimal amounts of such radiation (Mitchell and others 2012). Hence, LEDs can be placed closer to crops, making them suitable for small-scale horticultural applications such as small hydroponic farms or space stations (Table 2). This feature also allows for the prospects of intracanopy lighting, whereby LEDs are placed close between the canopies of plants to supply more light to the bottom parts of the canopy, which tend to receive less light from above. However, recent experimental data from studies on cucumbers and tomatoes show limited success. Plants were treated with intracanopy lighting where HPS lamps were supplemented using blue (465 nm) and red (667 nm) LEDs. The treatment did not result in a significant increase in the cumulative fresh weight of cucumbers over a 13-wk period and the leaves tended to show curling as well (Trouwborst and others 2010; Hao and others 2012). However, as the cumulative photon flux of intracanopy lighting configuration using top-lighting HPS lamp combined with LEDs was similar to the control using a top-lighting HPS lamp alone, it appears acceptable to not have observed any significant difference. More importantly, there is a potential for energy savings, as it was shown that energy efficiency was the highest for tomato plants treated with intracanopy lighting (Dueck and others 2012).

Integration of LEDs into electronic systems for automation and other functions

As solid-state devices, LEDs can easily be integrated into electronic systems such as digital control systems. Together with the ability for quick on-off operation with short warm-up time, this property allows for unique functions such as continuous dimming (Branas and others 2013). Furthermore, various types of sensors such as light and heat sensors can be used to control the lighting settings and operations of LEDs in integrated control systems. For instance, through feedback loop systems, LED lighting can be dimmed during daylight and brightened at sunset in greenhouses (Morrow 2008; Mitchell and others 2012).

As such, a variety of lighting regimens can also be programmed. For example, the spectral composition can be tuned finely and changed with time or over space. Yano and Fujiwara (2012) developed a system that consisted of an array of violet, blue, orange-red, red, and far-red LEDs whose respective photon flux densities could be controlled by a computer. Over an experimental period of 23 h, a gradient of increasing blue LED light (460 nm) from 0

to 1 μmol m^{-2} s^{-1} was created over 40 cm. It was demonstrated that the curvature of oat coleoptiles was orientated toward the region of higher blue light photon flux, hence oat coleoptiles are phototropic toward blue light and not toward other wavelengths. Hence, a similar strategy could be used to conduct research on the proper spectral requirements of other plants, whereby the spectral composition can be adjusted in minute amounts over space to find the best spectral composition. This can even be combined with the quick switch-on and switch-off time of LEDs, which can make available different forms of pulsed lighting that can save costs on energy (Yeh and Chung 2009). This can be useful in determining the lighting requirements of various plant crops (Shimada and Taniguchi 2011; Olvera-Gonzalez and others 2014).

Enhancing the nutritional quality of plant crops through LED irradiation

Light stimulates the production of various nutrients, antioxidants, and secondary metabolites in plants, which function to provide defence against reactive oxidation species (ROS) produced during photosynthesis or light stress (Darko and others 2014). Bian and others (2015) reviewed the effects of LED light quality, intensity, and photoperiod on nutrient accumulation in various vegetables in controlled growth environments. In general, research has shown that various LED light treatments result in the accumulation of bioactive compounds and antioxidants in crops such as varieties of lettuces (Li and Kubota 2009; Samuolienė and others 2012, 2013), pea seedlings (Wu and others 2007), Chinese cabbage (Avercheva and others 2014), tartary buckwheat (Tuan and others 2013), and other plants. The nutritional quality of other plant parts such as fruits can also be enhanced. The skin of grape berries which were irradiated for 3 h after sunset and 3 h before sunrise had a greater content of anthocyanins and sugars after irradiation with blue LED (450 nm) or red LED (660 nm) at 50 μmol m^{-2} s^{-1}, compared with the control, which received no additional light treatment (Kondo and others 2014).

The exact biological mechanisms of how nutritional content is enhanced through light are not fully understood. However, recent research appears to be moving toward tracking the changes in terms of biochemical responses by correlating changes in nutrition with gene expression using techniques like real-time quantitative reverse transcription polymerase chain reaction (qRT-PCR) analysis (Thwe and others 2014). Therefore, the flexibility in tuning the spectral composition of LED light will be useful in finding the optimal spectral composition of light for food crops, and also in better understanding the biological response to different spectral compositions of light. This would allow food producers to manipulate the lighting regimens increase the nutritive quality of their products in the future.

Evaluation of LEDs in food production

It is known that although blue and red light is sufficient for growth, small amounts of other wavelengths can still improve plant growth, development, and nutritional quality. Optimal spectral composition differs between various species or cultivars (Lin and others 2013), and different spectral compositions are more suitable for different growth stages of a plant (Chen and others 2014). LEDs have high photon efficiency, and can be used to easily modify the spectral composition of light so as to limit light emitted at unwanted wavelengths. Therefore, LED lighting systems are theoretically more economical options when comparing on an energy consumption basis. However, up-front costs of installing an LED lighting system are high and can be a deterrent to adopting the technology. Nelson and Bugbee (2014) estimated that LED fixtures were 5 to 10 times higher than HPS fixtures when compared on an initial capital cost per photon basis. Furthermore, they stated that although maintenance costs were low relative to electric costs, there were several disadvantages, such as the inconvenience and cost of replacing a single LED chip in a system, and the possibility that cooling equipment and wiring in LED systems might fail prematurely before the LED chips themselves, which would cause unexpected reduction in LED performance and in itself require maintenance. Yet, there is optimism that as LED technology matures, the up-front costs are expected to decrease (Gupta and Jatothu 2013), resulting in substantial long-term savings using LEDs due to lower operating and maintenance costs, and increased profits due to shorter propagation and growing times leading to greater yield (Mitchell and others 2012).

As an economic consideration, instead of completely replacing an existing lighting system with LED lighting, a greenhouse could supplement their current greenhouse lighting system with LEDs. This would be a cheaper option. However, LEDs as a source of supplementary light in large greenhouse applications has shown limited success. Combining LEDs as supplementary lighting with HPS in greenhouse applications tended to be less efficient at stimulating bioactive compound production compared with using LEDs in controlled growth environments, possibly because of the fluctuations in light quality and intensity of sunlight during the day (Samuolienė and others 2013). However, high-wire tomatoes have been reported to grow successfully using LEDs as supplementary lighting to HPS lamps (Dueck and others 2012; Mitchell and others 2012). Given the complexity of optimizing supplementary lighting together with LEDs, considering the high number of variables involved such as the main source of lighting (solar, HPS, and others), the light quality of supplementary LED component, photoperiod considerations and others, more research is required to find an optimal means of including LEDs as supplementary lighting. So far, LEDs have proven to be very useful in small-scale horticultural cultivation, most crucially in space plant growing facilities, as energy is limited and the nutritional needs of space crew is crucial. Greater plant photosynthetic rate was observed (Ilieva and others 2010), greater biomass production was measured per unit energy (Poulet and others 2014), and irradiated food was more nutritious (Shen and others 2014).

As LEDs are more flexible in tuning the output spectra, it would be a more attractive technology to invest in as it will allow for convenient adjustments according to the crop that is chosen to be cultivated, or the desired lighting regimen as and when more relevant information is available regarding the optimal light requirements of the crop.

LEDs in Postharvest Preservation

An important function of food processing techniques is to reduce postharvest losses in terms of quality and quantity. Good postharvest quality encompasses the acceptable visual, textural, nutritional, and flavor qualities of food, the absence of foodborne pathogens, as well as the delay of food spoilage by microorganisms. In general, the critical conditions for prolonging postharvest quality include using the optimal combination of temperature and relative humidity, and concentrations of oxygen, carbon dioxide and ethylene, depending on the type of produce (Kader and Rolle 2004).

In addition, it has been observed that certain foods like leafy vegetables that are exposed to small quantities of light retain their quality better than when stored in the dark, but there is still a lack of

clarity on the precise effect of light on postharvest quality of plants (Braidot and others 2014). As such, a greater understanding of the relationship between light and postharvest quality could potentially lead to useful postharvest applications. Relatively recent interest in the effect of LEDs on postharvest quality has yielded several noteworthy studies in the literature, which are reviewed in the following sections according to the effects that LEDs have been observed to have on various postharvest properties.

Delay of senescence and enhancement of nutritional status of foods through LEDs

Senescence is a genetically controlled process that serves to ensure the survival of plants through the relocation of nutrients and macromolecules from dying plant tissue to new or developing tissue. This leads to undesirable loss of quality in harvested plants. There is evidence that light can prevent senescence in detached leaves, stems, and flowers (Pogson and Morris 2004). However, implementing an effective treatment is challenging as the optimal delivery of light depends on the intensity, spectral composition, and duration or photoperiod considerations (Noodén and Schneider 2004). Excessive administration of light at a low temperature could lead to photo-oxidative stress and lower postharvest quality (Glowacz and others 2014).

The light compensation point, defined as the amount of light required for the rate of photosynthesis to be equivalent to the rate of respiration, is a guide to selecting a suitable light intensity. If the photon flux is below the light compensation point, there is a net loss of sugars, which might accelerate senescence (Noodén and Schneider 2004). However, there are exceptions. Pulsed white fluorescent light which was supplied to basil leaves (*Ocimum basilicum* L.) at a photon flux below the compensation point was still effective in delaying senescence (Costa and others 2013). Previous studies in leafy vegetables employed a low photon flux of white light, typically no greater than 30 μmol m^{-2} s^{-1} (Noichinda and others 2007; Lester and others 2010), and pulsed lighting of various forms (Costa and others 2013; Gergoff-Grozeff and others 2013). In these respects, LEDs can easily provide the requisite quantity of light, with the desired pulsed-lighting program. Several studies have been conducted using LED systems to delay postharvest senescence (Table 3).

Leaves are the main site of photosynthesis, hence leafy vegetables are of significance in postharvest studies involving light. Although many studies have been performed on leafy vegetables using continuous white fluorescent light as mentioned above, there are unexpectedly very few studies using continuous irradiation of white LED light. In one study, a warm white LED light was used for pulsed lighting on lamb's lettuce (Braidot and others 2014). A very low average photon flux of approximately 1.4 μE m^{-2} s^{-1} was irradiated on the lettuce for 8 h in total, with either 8 cycles of 1-h pulses or 16 cycles of 0.5-h square wave pulses. Both pulsed lighting methods resulted in a delay in senescence as observed from an increase in the chlorophyll a/b ratio above the initial ratio, and slower reduction in pheophytin levels. Consequently, the pro-oxidant capacity of lipophilic extracts of the plant showed that there was less potential oxidative damage in plants that had pulsed-light treatments. However, using 16 cycles of shorter pulses was more effective in retarding the degradation of chlorophylls a and b and retaining carotenoid levels. There was no significant difference between control and light treatments for ascorbate. It is noteworthy that glucose content in leaves was approximately equally lower than the initial glucose content regardless of light treatment or control. The authors suggested that pulsed light in low doses were insufficient for a substantial amount of photosynthesis to occur. Therefore, it resulted in an overall net loss of glucose, but could still induce the production of the above pigments. However, the spectral composition of white light emitted from the LED contained a peak at 570 nm, with a large width that ranged from 500 to 700 nm. Dougher and Bugbee (2001) reported that yellow light within the range of 580 to 600 nm suppressed the growth of lettuce (*Lactuca sativa* cv. Grand Rapids). Hence, the deleterious effect of yellow light might have also prevented photosynthesis, hence explaining the loss in glucose.

The availability of UV LEDs opens up more interesting spectral compositions and potential applications. Although UV radiation is not part of the visible range of electromagnetic radiation, it is still present in sunlight and in other sources of broad-spectrum lighting. UV LEDs are reported to stimulate the production of flavonoids and phenylpropanoids as reported by Kanazawa and others (2012). Watercress and garden pea sprouts were irradiated with a UVA LED (375 nm) for 160 min per day for 3 d at a photon flux of 33 μmol m^{-2} s^{-1}, then stored in darkness. After 6 d from the start of irradiation, quercetin-glycoside contents in the vegetables were significantly greater compared with the dark control set. Flavonoids absorb in the UV range and hence protect plants against UV damage. Moreover, given the antimicrobial properties of UV radiation (which are covered in section *UV LEDs*), UV LEDs are suitable for postharvest purposes in enhancing nutritional quality and delaying undesirable microbial growth.

Apart from leafy vegetables, other edible plant parts have different lighting requirements for prolonged postharvest storage. Red LED treatment of broccoli (*Brassica oleracea* L. var. *italica*) at 50 μmol m^{-2} s^{-1} for 4 d caused a slower rate of ethylene production, higher ascorbic acid content, and visually less yellowness of treated samples than the blue LED treatment and dark control (Ma and others 2014). Similarly, the flavedo of Satsuma mandarins (*Citrus unshiu* Marc.) that were exposed to red LED (660 nm) light of 50 μmol m^{-2} s^{-1} for 6 d had a greater total carotenoid content compared with blue LED (470 nm) treated samples and dark control (Ma and others 2011). Hence, it is possible that edible flowers or fruits can be nutritionally enhanced by using continuous lighting of larger photon flux.

Accelerating or delaying the ripening of fruits using LEDs

For food that is transported over large distances, it is important to delay the rate of ripening so that fruits are not overripe when they reach their destination. Light has varying effects on different types of fruits. The ripening time of tomatoes can be extended with pre-treatment of blue light prior to storage in the dark (Dhakal and Baek 2014a,b). Mature green tomatoes irradiated with blue light (440 to 450 nm) for a period of 7 d had slower rate of color change from green to red compared with mature green tomatoes stored in darkness or irradiated with red light (650 to 660 nm) for an equivalent duration (Table 3). In addition, the tomatoes treated with blue-LED were firmer than dark and red LED-treated tomatoes. Tomatoes treated with red-LED had the least firmness after 21 d. Similarly, blue light irradiation caused a slower rate of lycopene accumulation. Hence, blue light pre-treatment is a potentially effective method of slowing down the ripening time for tomatoes and extending their postharvest commercial value.

In contrast, blue LED light (470 nm) was shown to accelerate secondary ripening in strawberries (Table 3), evidenced by the increase in respiration, ethylene production, and faster development of red color (Xu and others 2014a,b). Apart from blue light, Kanazawa and others (2012) reported that unripe

Table 3–Effect of LED lighting in postharvest preservation and effectiveness of treatments.

Application	Food	LED (wavelength)	Intensity	Treatment time	Effectiveness	Source
Delaying of senescence in vegetables	Lamb's lettuce (*Valerianella olitoria* L. Pollich)	Warm white	1.4 μE m^{-2} s^{-1}	Eight cycles of 1 h and 16 cycles of 0.5 h	Chlorophyll degradation was delayed, higher pheophytin levels, and lower pro-oxidant capacity observed compared with dark control.	Braidot and others (2014)
	Broccoli (*Brassica oleracea* L. var. *italica*)	Red (660 nm)	50 μmol m^{-2} s^{-1}	Continuous	Reduced yellowing and less ethylene production observed compared with blue and white LED	Ma and others (2014)
Accelerating secondary ripening processes	Strawberries (*Fragaria ananassa* Duch cv. Fengguang)	Blue (470 nm)	40 μmol m^{-2} s^{-1}	Continuous	Increase in ethylene production, respiration, color development, total antioxidant activity, and antioxidant enzyme activity compared with control.	Xu and others (2014a,b)
Delaying of ripening	Mature green tomatoes (*Solanum lycopersicum* L. cv. Dotaerang)	Blue (440 to 450 nm)	85.7 μE m^{-2} s^{-1}	Continuous	A slower rate of color change from green to red and loss of firmness observed compared with red light.	Dhakal and Baek (2014b)
Enhancing or delaying loss of postharvest nutritional content	Lamb's lettuce (*V. olitoria* L. Pollich)	Warm white	1.4 μE m^{-2} s^{-1}	Sixteen cycles of 0.5 h	A slower decrease of carotenoids content observed compared with dark control.	Braidot and others (2014)
	Watercress (*Nasturtium officinale* R. Br.) and garden pea sprouts (*Pisum stivum* L.)	UVA (375 nm)	33 μmol m^{-2} s^{-1}	160 min daily for 3 d	Higher in quercetin glycoside content observed compared with dark control	Kanazawa and others (2012)
	Broccoli (*Brassica oleracea* L. var. *italica*)	Red (660 nm)	50 μmol m^{-2} s^{-1}	Continuous	Higher ascorbic acid content observed compared with blue and white LED.	Ma and others (2014)
	Satsuma mandarins (*Citrus unshiu* Marc.)	Red (660 nm)	50 μmol m^{-2} s^{-1}	Continuous	Increased total carotenoids measured in the flavedo compared with blue LED light and dark control.	Ma and others (2011)
	Chinese bayberries (*Myrica rubra*)	Blue (470 nm)	40 μmol m^{-2} s^{-1}	Continuous	Greater total anthocyanin content measured compared with dark control.	Shi and others (2014)
	Mature green tomatoes (*Solanum lycopersicum* L. cv. Dotaerang)	Blue (440 to 450 nm)	85.7 μE m^{-2} s^{-1}	Continuous	Higher content of glutamic acid and γ-aminobutyric acid measured compared with red light.	Dhakal and Baek (2014a)
	Strawberries (*Fragaria ananassa* cv. Sulhyang)	UVA (385 nm), blue (470 nm), green (525 nm), red (630 nm).	Unspecified. 20 mA current used for each LED	Continuous	Blue, red, and green LED improved anthocyanin content of immature strawberries compared with dark storage; blue and green LED improved the vitamin C content. Total phenolics stimulated most by blue LED, total soluble solids improved most by green LED.	Kim and others (2011)
	Cabbage "Dongdori"	White, blue (436 nm), green (524 nm), red (665 nm)	Unspecified. Electrical power stated as 1.380, 1.455, 1.515, and 1.065 W for	Continuous	All LED treatments improved the total chlorophyll, vitamin C, and total phenolics compared with dark	Lee and others (2014)

(Continued)

Table 3–Continued

Application	Food	LED (wavelength)	Intensity	Treatment time	Effectiveness	Source
			white, green, blue, and red LEDs, respectively.		control. Green LED was most effective for increasing chlorophyll content, whereas blue LED increased vitamin C. All LED treatments increased phenolic content. Moisture content for all treatments decreased by less than 5% only, and pH increased at the same rate for all treatments.	
Preventing food spoilage	"Fallglo" Tangerines	Blue (456 nm)	40 μmol m^{-2} s^{-1}	Continuous	Reduced fungal colonization of *Penicillium digitatum* on surface of fruit compared with dark and white light treatments.	Alferez and others (2012); Liao and others (2013)
	Strawberries (*Fragaria ananassa*)	Deep ultraviolet (272, 289, and 293 nm)	20 mW m^{-2}	Continuous	Mold growth, suspected to be *Botrytis cinerea*, was absent in LED treated samples after 9 d, whereas those stored in dark had extensive growth after 6 d.	Britz and others (2013)
	Detached leaves of tomato plant (*Solanum lycopersicum* L. cv. Moneymaker)	Blue (405 nm)	50 mW m^{-2}	15 min h^{-1} during light period of growth	Average lesion diameter of *Botrytis cinerea* inoculated on tomato leaves was approximately 7 cm when irradiated with blue LED, compared with approximately 16 cm when treated with white light.	Imada and others (2014)

strawberries exposed to green light from a green lamp (500 to 600 nm) also developed a deep red color faster due to the production of anthocyanins. However, no data were given for the rate of respiration or production rate of the ethylene from the strawberries, and there was no account of the radiant heat from the green lamp received by the strawberries, which might have affected the rate of ripening. Kim and others (2011) reported that irradiation of immature strawberries with LEDs emitting light with wavelengths of 525 and 630 nm resulted in significant increases in anthocyanins after 3 to 4 d, which were slightly less than the effect of blue LED at 470 nm, suggesting that although blue LEDs are most effective at increasing anthocyanin levels and color intensity of strawberries, other LEDs in the visible range might still be feasible. Ultimately, it is of interest to explore the effect of monochromatic LED light of various wavelengths on various other climacteric fruits, such as bananas, and to compare the effects of other wavelengths on secondary ripening processes in produce existing in the literature such as strawberries.

Preventing fungal spoilage through LEDs

Fungal infection of fruits is a primary cause of postharvest loss. Several studies have been conducted on the effect of LED light on preventing fungal infections in citrus fruits. In general, blue LED light at a moderate intensity was found to be sufficiently effective in preventing fungal infection. Blue light treatments at 40 μmol m^{-2} s^{-1} over a period of 5 to 7 d, depending on fungal species, were able to dramatically reduce the soft rot area, mycelial growth, and sporulation of various fungi (*Penicillium digitatum*, *Penicillium italicum*, and *Phomopsis citri*), on the surface of fruits compared with white light LED and darkness (Alferez and others 2012; Liao and others 2013). Real-time qRT-PCR analysis showed that blue LEDs increased the expression of phospholipase A_2 (PLA_2) in citrus fruits. Lysophosphatidylcholine, which is a product of phosphatidylcholine hydrolysis by PLA_2, is involved in regulating the resistance of citrus fruits to fungal infection and growth. In contrast, red LEDs accelerated fungal infection by down-regulating the expression of phospholipase D (PLD), which also provides anti-fungal defense (Alferez and others 2012). Moreover, blue LEDs induced an increase in octanal content in the flavedo of "Fallglo" tangerines and sweet oranges. Octanal reduced fungal growth, sporulation, and soft rot at concentrations of 0.5 mM *in vitro*. Overall, the mechanism of blue LED light on fungal inhibition could be due to a combination of reduced polygalacturonase activity from the fungi (Liao and others 2013) and from the upregulation of PLA_2 and production of octanal in the flavedo.

The duration of irradiation affects the efficacy of the treatment. Alferez and others (2012) treated tangerines with LED light for 3 d before inoculation with spore suspensions. After inoculation, it was reported that a 12-h irradiation with blue light, followed by 12 h of darkness daily, was more effective at reducing mycelial growth of *P. digitatum* compared with continuous irradiation. However, when fruits were inoculated immediately after harvesting, continuous blue light treatment had a similar effect to 12 h of irradiation for mycelial growth and soft rot area of *P. digitatum*, and it was more effective than the latter in reducing soft rot growth of *P. italicum* and

mycelium area of *P. citri* (Liao and others 2013). However, since both lighting regimens were capable of reducing fungal infections to negligible within 12 h, it is possible to consider using 12 h irradiation regimens for energy savings.

Yu and Lee (2013) highlighted an interesting synergistic application of antagonistic bacteria and LED irradiation when *Bacillus amyloliquefaciens* JBC36 was applied as a biofilm to the surface of fruit (Table 3). The application of red LED light (645 nm) *in vitro* was more effective in enhancing the antifungal effect of the bacteria by enhancing the motility and biofilm formation at 240 μmol m^{-2} s^{-1} compared with other wavelengths. Moreover, analysis of the cell-free supernatant of bacteria treated with red LED revealed a higher production of iturin and fengycin, which are antifungal lipopeptides. An increased expression of *fen*A gene was found as well, indicating that red light has an effect on the expression of genes encoded in JBC36 (Ramkumar and others 2013). Such a synergistic strategy may be useful in overcoming limitations that LED irradiation possesses. In particular, the low penetration depth of LED light was insufficient to inactivate any fungus below the surface of the fruit, which would result in a re-emergence of infection when LED treatment was discontinued (Alferez and others 2012). It could be that stimulating the growth of antagonistic biofilms might prevent fungal growth of fruits after LED irradiation is stopped. Further studies should be conducted to verify this.

Britz and others (2013) constructed a system involving deep ultraviolet (DUV) LEDs of wavelengths 272, 289, or 293 nm to irradiate strawberries bought from the supermarket at 20 mW m^{-2} over a period of 9 d. Their results showed that the strawberries were not affected by mold growth (suspected *Botrytis cinerea*) up to 9 d, whereas mold growth was significant on strawberries stored in 6 d in darkness at the same temperature and relative humidity. In addition, it was reported that DUV LEDs retained the anthocyanin and total soluble sugar levels in irradiated strawberries, whereas there was a significant decrease in strawberries stored in the dark. Hence, DUVs could be incorporated into LED systems to stimulate nutritional content in strawberries while preventing the growth of mold. *B. cinerea* was also shown to be inhibited by LEDs at 405 nm, although the study was conducted on detached tomato leaves (Table 3), which are not usually consumed (Imada and others 2014). However, the authors showed through *in vitro* studies that blue light was responsible for the production of ROS through endogenous porphyrins in the mold, hence providing another possible mechanism as to how mold growth is suppressed on foods. Furthermore, using blue LEDs is more preferable than using DUV LEDs, as exposure to UV radiation is hazardous to the skin and eyes (Shama 2014).

Evaluation of LEDs in postharvest preservation

The role of light in postharvest applications has been receiving greater attention only in recent years. Together with the recent developments in LED technology, research on LEDs in postharvest applications has been limited up till the present time. There has been success in using LEDs to preserve and improve the quality of certain plant parts, including edible flowers and fruits such as broccoli, citrus fruits and strawberries (Table 3). Several of such studies have even shown a correlation between exposure to LED light and biomolecular responses in terms of gene expression. For example, blue LEDs upregulate the gene expression of certain steps in the phenylpropanoid pathway, hence increasing flavanoid and anthocyanin content (Kanazawa and others 2012, Shi and others 2014). Red light upregulated carotenoid metabolism-related genes in Satsuma mandarins (Ma and others 2011). Similar studies can be conducted on other foods to verify the relation between monochromatic light and biological pathways.

However, few studies have examined the effect of LEDs on the postharvest quality of leafy vegetables in particular. This could be due to the complications in selecting the appropriate lighting regimen that would not cause oxidative damage, but extend postharvest life. To overcome this, the flexibility of LEDs can be exploited to develop LED lighting systems that can facilitate the optimization of lighting regimens in terms of light quantity and quality for leafy vegetables. As most research has focused on the effect of white light, an interesting path would be to study the effects of various component colors of white light on the senescence and nutritive content of such vegetables. Lee and others (2014) investigated the effect of white, blue (436 nm), green (524 nm), and red (665 nm) LEDs on the nutrient content of cabbages over a period of 18 d. Their results suggested that LED treatment generally improved the nutritional quality of the cabbages compared with those stored in darkness. Green and white LEDs were most effective at stimulating chlorophyll production, followed by red and blue LEDs. Blue and white LEDs were generally better at increasing Vitamin C and total phenolics. However, the irradiances or photon flux received by the cabbages were not specified, although the electrical power of each LED was provided. The input electrical power ranged from 1.0 to 1.5 W for each LED system, which made it a suitable low-power source of lighting for a refrigeration system. The study demonstrates an interesting area of research with regard to postharvest storage whereby monochromatic light is used instead of white light.

As postharvest processing ultimately seeks to provide consumers with nutritious and flavorful food, the acceptability of such produce in terms of color, texture, and even flavor should be evaluated. For example, it has been noted in plant growth studies that blue light stimulates stomatal conductance and transpiration in leaves (Massa and others 2008; Muneer and others 2014), which might lead to greater moisture loss during postharvest storage. Lee and others (2014) found no significant differences between dark and LED treatments after 18 d in terms of moisture loss. However, on the 12th day, the moisture content appeared to be higher under red LEDs or dark storage, as compared with blue, green, and white LED treatment. Low moisture content can result in wilted leaves and lower consumer acceptance. Therefore, although some research has shown that LED irradiation has a positive impact on the nutritional quality of food, more work should be done to assess the consumer acceptability of treated food.

LEDs in Food Safety

In the food industry, producing, processing, and delivering safe food is of prime priority. For microbial safety, thermal techniques are the most efficacious methods of eliminating pathogens, but are unsuitable for certain types of foods such as fresh produce in ready-to-eat salads, and so on. Currently, consumers demand minimally processed food that is free from chemical sanitizers and other additives. Moreover, the increased frequency of antimicrobial resistance has led to an urgent need to find alternative effective food safety technologies for food processing facilities (Capita and Alonso-Calleja 2011). Several emerging technologies are being developed for these purposes. These include natural antimicrobials including bacteriocins and essential oils, and novel nonthermal technologies including high-pressure processing, high-intensity ultrasound, and pulsed electric field processing.

Alongside the development of such new technologies, the potential of light as a nonthermal decontaminating technology is promising. Light induces cell damage, injury, and death in microorganisms through several mechanisms, including damage through UV light, through ROS production in photodynamic inactivation (PDI), or through photocatalytic oxidation through nanoparticles. Currently, the above mechanisms form the basis for decontamination in other applications, such as in the medical field and in water sterilization plants, and are relatively well-established and researched. However, focus is now shifting to the applicability of light in food-related decontamination processes, with LEDs having a major role as a suitable source of light. Apart from the potential energy savings that LEDs offer, the nonthermal aspects of the technology are attractive since food quality is significantly affected by heat. Hence, drawing from currently available research on food pathogens and food systems, or in other related fields, the role of LEDs in food safety, specifically via PDI, photocatalytic inactivation, and UV radiation is reviewed in this section.

PDI using exogenous photosensitizers

Thus far, PDI is one of the most prevalent and promising modes of decontamination studied in food-related applications and has been reviewed comprehensively by Luksiene and Brovko (2013). In summary, PDI causes cell destruction when a photoactive molecule, called a photosensitizer, is subjected to light of a specific wavelength corresponding to the energy required to excite the photosensitizer. ROS are generated when the photosensitizer returns to ground state through 2 pathways. The Type I mechanism involves the transfer of an electron from the excited photosensitizer to molecular oxygen, which is subsequently reduced to superoxide anion, hydrogen peroxide, and hydroxyl ($^{\bullet}$OH) radicals. These ROS cause extensive damage to the cellular components, especially those made up of lipid or fatty acids such as in the cell membrane. The Type II mechanism transfers energy from the photosensitizer to triplet oxygen ($^3O_2$), causing its excitation to the reactive singlet oxygen ($^1O_2$). Singlet oxygen reacts with a variety of other biochemical components to produce a range of cytotoxic compounds. This results in damage to the cell membrane, DNA, and various enzymes, which leads to lethal injury and death. As the above mechanisms cause indiscriminate destruction of the cellular components, resistant strains are more difficult to evolve. Photosensitizers that are suitable and effective in food applications and found in natural sources such as in plants include hypericin, curcumin, alpha-terthienyl, and chlorophyllin (Luksiene and Brovko 2013).

In vitro studies have shown that Gram-positive bacteria are more susceptible to PDI as photosensitizers tend to be trapped in the peptidoglycan layer of the cell wall. Gram-negative bacteria are less permeable to such compounds because of their double cell membrane structure which acts as a barrier (Demidova and Hamblin 2004), but increasing the concentration of photosensitizer or using cationic photosensitizers has been shown to improve their uptake. Furthermore, photosensitizers can be conjugated to antimicrobial peptides or other compounds that selectively bind to the target cells (Luksiene and Brovko 2013). For example, eosin Y was conjugated to an antimicrobial peptide, $(KLAKLAK)_2$ and shown to destroy target Gram-positive and -negative bacteria without binding to or destroying red blood cells or other mammalian cells (Johnson and others 2012). This is achieved when the conjugate binds only to the lipid membranes of the bacterial cells, before irradiation produces ROS that disrupt the membrane (Johnson and others 2014).

PDI through endogenous photosensitizers

Although photosensitizers can be applied externally to food systems, there are endogenous photosensitizers produced within bacterial pathogens, usually in the form of intracellular components like "porphyrins, cytochromes, flavins, and NADH" (Lubart and others 2011). This form of PDI has been gaining more attention in recent years as the addition of external photosensitizing agents is not required. Blue light or near-UV radiation has been found to be most effective in inactivating bacteria while red light has minimal effect (Table 4). Experiments on various bacteria and fungi show that, within the band of 400 to 450 nm, LEDs with a peak wavelength of 405 nm are most effective as the peak coincides with the absorption maximum of porphyrins, or the Soret band (Endarko and others 2012; Imada and others 2014; Maclean and others 2008, 2014). Hence, porphyrins are mainly responsible for causing ROS production within the bacterial cell, and consequently, inducing bacterial inactivation. There was significant inactivation of *Salmonella* Typhimurium, *Escherichia coli* O157:H7, *Listeria monocytogenes*, and *Staphylococcus aureus* in tryptic soy broth without the addition of exogenous photosensitizers. Irradiation treatments were performed using blue LED (461 nm) for 7.5 h at temperatures of less than 15°C, resulting in a total energy dose of 597 J cm^{-2}. However, inactivation was insignificant at 20°C, indicating that a low temperature was necessary for successful inactivation. Furthermore, treatment with blue LEDs caused the greatest amount of sublethal injury to bacteria, indicating that blue LEDs can greatly weaken surviving populations of bacteria, which can be further reduced by adding salt or lowering the pH.of the system (Ghate and others 2013). Similarly, *Campylobacter spp.* was inactivated by near-UV radiation at 395 nm *in vitro* and on chicken meat (Haughton and others 2012).

Bacterial susceptibility to PDI through endogenous photosensitizers appears to vary widely among bacterial species. For example, *C. jejuni* required a much lower dosage of blue light at 405 nm than *Salmonella* Enteritidis and *E. coli*, the reason attributed to the greater susceptibility of microaerophilic *C. jejuni* to ROS. Authors cautioned that because of the ability of *Campylobacter* spp. to become viable but non-culturable (VBNC), the successful results required more rigorous confirmation (Murdoch and others 2010). Experiments using a LED of 405 nm at an irradiance of 8.6 mW cm^{-2} showed that *Listeria* spp. were most easily inactivated, followed by *E. coli*, *Shigella sonnei*, and *S.* Enteritidis (Endarko and others 2012). Several authors posit that Gram-positive bacteria are more susceptible than Gram-negative species (Maclean and others 2009; Birmpa and others 2014), whereas others posit that susceptibility is not determined by Gram nature, but nonetheless varies greatly among different species (Ghate and others 2013). Within species, it was found that there were differences in susceptibility between *Campylobacter* spp. isolates when exposed to the same treatment. Such intra-species variation in susceptibility is suggested to be due to the inherent differences in endogenous porphyrin concentrations within species (Maclean and others 2009; Haughton and others 2012). Recently, Kumar and others (2015) quantified the content of coproporphyrins and showed that Gram-positive bacteria tended to contain a higher amount of coproporphyrin. However, within Gram-positive species, there was no direct and strong correlation between coproporphyrin content and the extent of inactivation. It was suggested that other components in bacterial cells, such as pyocyanin in *P. aeruginosa*, is capable of quenching ROS, and hence, a more in-depth study is required to profile other similar ROS-quenching compounds in bacterial cells.

Table 4–Effect of PDI on foodborne pathogens using endogenous photosensitizers and LED irradiation *in vitro*.

Pathogen	LED peak wavelength	Intensity	Treatment time	Effect	Source
Bacillus cereus	400 nm	20 mW cm^{-2}	20 min	Bacterial populations were incubated in 7.5 mM of 5-aminolevulinic acid (ALA), a nonphotosensitizing metabolic precursor to endogenous photosensitizers. Irradiation for 20 min in Luria-Bertoni (LB) medium caused reduction of up to 6.3 log cycles. Treatment was carried out at 37°C	Luksiene and others (2009)
	405 nm	21 mW cm^{-2}	9 h	Bacterial populations in TSB held at 15 and 10°C were reduced by approximately 2.3 log CFU mL^{-1}.	Kumar and others (2015)
Salmonella Typhimurium.	461 nm	596.7 J cm^{-2}	7.5 h	Bacterial populations in tryptic soy broth (TSB) held at 15 and 10°C were reduced by 5.0 and 4.6 log CFU mL^{-1}, respectively after 7.5 h, compared with approximately 1.7 log CFU mL^{-1} at 521 nm. No significant reductions at 641 nm.	Ghate and others (2013)
	405 nm	21 mW cm^{-2}	9 h	Bacterial populations in TSB held at 25°C were reduced by approximately 0.6 log CFU mL^{-1}. No significant reductions observed when irradiated at 4 or 10°C	Kumar and others (2015)
	400 nm	20 mW cm^{-2}	20 min	Bacterial populations were incubated in 7.5 mM of 5-aminolevulinic acid (ALA). Irradiation for 20 min in LB medium caused reduction of up to 6 log CFU mL^{-1}. Treatment was carried out at 37°C	Buchovec and others (2009)
Escherichia coli	461 nm	596.7 J cm^{-2}	7.5 h	Bacterial populations of *E. coli* O157:H7 in TSB held at 15 and 10°C were reduced by approximately 5 log CFU mL^{-1} after 7.5 h, compared with 1.0 and 1.8 log CFU mL^{-1}, respectively at 521 nm. No significant reductions at 641 nm.	Ghate and others (2013)
	405 nm	378 J cm^{-2}	NR	When treated with light at 70 mW cm^{-2} at 22°C, bacterial populations of *E. coli* NCTC 9001 TSB were reduced by 5 log CFU mL^{-1} to below detection levels.	McKenzie and others (2014)
	405 nm	21 mW cm^{-2}	9 h	Bacterial populations of *E. coli* O157:H7 in TSB held at 15 and 10°C were reduced by approximately 1 log CFU mL^{-1}.	Kumar and others (2015)
	395 nm	36 J cm^{-2}	1115 s	Bacterial of *E. coli* K-12 populations in maximum recovery diluent were reduced by 1.37 log CFU mL^{-1}.	Birmpa and others (2014)
Listeria monocytogenes	461 nm	596.7 J cm^{-2}	7.5 h	Bacterial populations in TSB held at 15 and 10°C were reduced by 4.3 and 5.2 log CFU mL^{-1}, respectively, after 7.5 h, compared with 0.9 and 1.5 log CFU mL^{-1} at 521 nm. No significant reductions at 641 nm.	Ghate and others (2013)
	405 nm	21 mW cm^{-2}	9 h	Bacterial populations in TSB held at 15 and 10°C were reduced by approximately 1.9 log CFU mL^{-1}.	Kumar and others (2015)
	405 nm	185 J cm^{-2}	5 h	Bacterial populations in TSB were reduced by 5 log CFU mL^{-1} to below detection limits after treatment with irradiance of 8.6 mW cm^{-2}.	Endarko and others (2012)
	405 nm	84 J cm^{-2}	NR	When treated with light at 70 mW cm^{-2} at 22°C, bacterial populations TSB were reduced by 5 log CFU mL^{-1} to below detection levels.	McKenzie and others (2014)
	400 nm	20 mW cm^{-2}	20 min	Bacterial populations were incubated in 7.5 mM of ALA. Irradiation for 20 min in LB medium caused reduction of up to 4 log cycles. Treatment was carried out at 37°C.	Buchovec and others (2010)

(Continued)

Table 4–Continued

Pathogen	LED peak wavelength	Intensity	Treatment time	Effect	Source
Listeria innocua	395 nm	36 J cm^{-2}	1115 s	Bacterial populations in maximum recovery diluent were reduced by 2.74 log CFU mL^{-1}	Birmpa and others (2014)
	405 nm	21 mW cm^{-2}	9 h	Bacterial populations in TSB were reduced by approximately 4 log CFU mL^{-1} when irradiated at 25°C, and approximately 2 log CFU mL^{-1} when irradiated at 4 or 10°C.	Kumar and others (2015)
Staphylococcus aureus	461 nm	596.7 J cm^{-2}	7.5 h	Bacterial populations in TSB held at 15 and 10°C were reduced by approximately 5.2 and 4.7 log CFU mL^{-1}, respectively after 7.5 h, compared with 1.7 and 1.5 log CFU mL^{-1} at 521 nm. No significant reductions at 641 nm.	Ghate and others (2013)
Campylobacter spp.	395 nm	0.06 to 18.00 J cm^{-2}	5 min	At a distance of 3 cm from LED, 10 isolates of *C. jejuni* and *C. coli* were inactivated from around 6 to 7 log CFU mL^{-1} to below detection limit after 5 min. As distance increased, Treatment time required for inactivation increased. Certain strains took longer to inactivate.	Haughton and others (2012)
	405 nm	18 J cm^{-2}	30 min	Bacterial populations were reduced from 5.25 log CFU mL^{-1} to below detection limit.	Murdoch and others (2010)

Increasing susceptibility can be also achieved through the external addition of 5-aminolevulinic acid (ALA), which is a nonphotoactive metabolic precursor to various endogenous photosensitizing porphyrins. The addition of ALA as a means of stimulating photosensitizer production in suitable cells is acceptable in food applications because ALA is not colored and does not affect taste, yet its use is effective against a wide range of foodborne pathogens, yeasts and fungi, viruses, and even certain protozoa (Harris and Pierpoint 2012; Luksiene and Brovko 2013). Other than vegetative cells such as *S.* Typhimurium (Buchovec and others 2009), ALA treatment was found to be effective against *Bacillus cereus* spores (Luksiene and others 2009) and *L. monocytogenes* biofilms on packaging surfaces (Buchovec and others 2010) when treated with LED light at 400 nm for as little as 15 min.

Studies detailing the inactivation kinetics of PDI through endogenous photosensitizers are few. Recently, Ghate and others (2013) reported *D* values for treatments using LEDs at 461 nm at 10°C ranged from 1.19 h for *L. monocytogenes* to approximately 1.4 to 1.5 h for *E. coli* O157:H7, *S.* Typhimurium, and *S. aureus*. Kumar and others (2015) modeled the inactivation curves of *B. cereus*, *E. coli* O157:H7, *S. aureus, S.* Typhimurium*, L. monocytogenes,* and *Pseudomonas aeruginosa* treated with 405 and 521 nm LEDs at 4, 10, and 25°C. As the above were *in vitro* studies, there is scope for performing more inactivation studies on food systems and packaging and contact surfaces.

However, exploiting endogenous photosensitizers for PDI may not be as effective as treatment using exogenous photosensitizers. Endarko and others (2012) noted that a higher dosage of 185 J cm^{-2} was required to inactivate *L. monocytogenes* NCTC11994 *in vitro* using a blue LED at 405 nm only, compared with treatment together with a sodium chlorophyllin (Na-Chl) photosensitizer, whereby only 36 J cm^{-2} was sufficient for a 7 log inactivation for a thermoresistant *L. monocytogenes* 56 Ly strain *in vitro* (Luksiene and others 2010). Nevertheless, PDI through endogenous photosensitizers is in principle more attractive as the treatment does not require the addition of any external substance and is therefore more convenient.

Effect of PDI on microbiological, nutritional, and organoleptic quality of food

For a better appreciation of the effect of PDI on food, other properties, such as the flavor, appearance, texture, and others, need to be evaluated. Although most studies on PDI in food safety have focused on *in vitro* studies, less is understood about the effect on organoleptic properties of treated foods. Foods whose sensory quality and acceptability have been evaluated usually include fruits and vegetables, and they have been reported to have a reduction of around 2 log cycles of bacteria in an approximate time frame of up to an hour. For example, the *B. cereus* population in apricots, plums and cauliflowers treated with hypericin was significantly decreased after only 30 min of irradiation with green LED light (585 nm) with irradiance of 3.84 mW cm^{-2}. Similarly, *L. monocytogenes* populations on strawberries were decreased after treatment with Na-Chl as photosensitizer, combined with irradiation with blue LED (400 nm) light at 12 mW cm^{-2} for 20 min (Luksiene and Paskeviciute 2011b). The natural microflora on fruits and vegetables tend to be challenging to remove, with approximately 1 log cycle being inactivated (Aponiene and others 2015). As a contrast to fruits and vegetables, *S. aureus* inoculated onto chicken meat was reduced by 1.7 log cycles after irradiation with curcumin as the photosensitizer (Table 5).

Because of the minimal radiant heat emitted, LEDs cause little increase in temperature on the surface or interior of foods, which is beneficial in preserving the acceptability of such foods to consumers. The surface temperature of apricots, plums, and cauliflowers held at room temperature of 20°C increased to a maximum of 25°C after an irradiation dose of 12 J cm^{-2} (Aponiene and others 2015). Likewise, it was reported that the surface temperature of treated strawberries increased from 20 to 25°C after

Table 5–Efficacy of PDI on food systems and surfaces using LEDs and exogenous/endogenous photosensitizers.

Photosensitizer	Pathogen	Wavelength of LED	Intensity	Treatment time	Food/surface	Effect	Source
PDI with external application of photosensitizer to food (exogenous photosensitization)							
Curcumin-polyvinylpyrrolidone (PVP-C) and NovaSol®-Curcumin formulation (NovaSol®-C)	*S. aureus*	435 nm	9.4 mW cm^{-2}	24 h	Cucumber (*Cucumvis sativus*)	Reduction of 2.6 log CFU achieved relative to control when concentration of 50 or 100 μM of PVP-C was used	Tortik and others (2014)
					Peppers (*Capsicum spp.*)	Reduction of 2.5 log CFU achieved relative to control when concentration of 50 μM of PVP-C was used	
					Chicken meat	Reduction of 1.7 log CFU/achieved relative to control when concentration of 50 or 100 μM of NovaSol®-C was used	
Hypericin	*B. cereus*	585 nm	3.84 mW cm^{-2}	30 min	Apricots (*Prunus armeniaca*); Plums (*Prunus domestica*); Cauliflower (*Brassica oleracea*)	Reduction of 1.1, 0.7, and 1.3 log CFU g^{-1} on surface of apricots, plums, and cauliflower respectively, compared with initial inoculated concentration. No significant change in antioxidant content detected in extracts.	Aponiene and others (2015)
Sodium-chlorophyllin (Na-Chl)	*L. monocytogenes*	400 nm	12 mW cm^{-2}	20 min	Strawberries (*F. ananassa* Dutch)	Reduction of 1.8 log CFU of *L. monocytogenes* achieved. Mesophils were reduced by 1.7 log, whereas yeasts and molds were reduced by 0.86 logs. Surface temperature remained under 27°C. There was significant increase in antioxidant activity, but no change in total soluble phenolics or anthocyanins.	Luksiene and Paskeviciute (2011b)
PDI without external application of photosensitizer (endogenous photosensitization)							
NA	*Campylobacter spp.*	395 nm	7 mW cm^{-2}	5 min	Skinless chicken fillet	Reduction of 1.43 log CFU g^{-1} of pathogen on surface of chicken compared with initial microbial load. Minimal increase in L^* value measured for color.	Haughton and others (2012)
Self-sterilization via packaging materials using exogenous photosensitizers							
Na-Chl	*L. monocytogenes* $ATC_{L3}C$ 7644	405 nm	20 mW cm^{-2}	5 min	Polyolefine packing trays	Planktonic cells attached to surface were reduced by 4.5 log CFU cm^{-2} after treatment with 1.5×10^{-7} M of Na-Chl solution and LED. Biofilms attached to surface were reduced by 4.5 log CFU mL^{-1} after LED treatment with higher concentration of 7.5×10^{-4} M Na-Chl solution	Luksiene and others (2010)
Na-Chl	*L. monocytogenes* $ATC_{L3}C$ 7644	405 nm	20 mW cm^{-2}	5 min	Polyolefine packing trays	Planktonic cells attached to surface were reduced by 4.5 log CFU cm^{-2} after treatment with 7.5×10^{-7} M of Na-Chl solution and LED. Biofilms attached to surface were reduced by 4.5 log CFU mL^{-1} after LED treatment with higher concentration of 1.5×10^{-4} M Na-Chl solution	Luksiene and Paskeviciute (2011a)

(Continued)

Table 5–Continued

Photosensitizer	Pathogen	Wavelength of LED	Intensity	Treatment time	Food/surface	Effect	Source
Na-Chl	*B. cereus* ATCC 12826	405 nm	20 mW cm^{-2}	5 min	Polyolefine packing trays	Planktonic cells attached to surface were reduced by 4.5 log CFU cm^{-2} after treatment with 7.5×10^{-7} M of Na-Chl solution and LED. Spores attached to surface were reduced by approximately 5 log CFU cm^{-2} after LED treatment with higher concentration of 7.5×10^{-5} M Na-Chl solution	Luksiene and Paskeviciute (2011a)
5-Aminolevulinic acid	*B. cereus* spores	400 nm	20 mW cm^{-2}	15 min	Polyolefine packing trays	Reduction of spores from approximately 6 log CFU cm^{-2} to 3.3 log CFU cm^{-2} after LED treatment with 7.5 mM of ALA	Luksiene and others (2009)
5-Aminolevulinic acid	*L. monocytogenes*	400 nm	20 mW cm^{-2}	15 min	Polyolefine packing trays	Reduction of planktonic cells by 3.7 log CFU cm^{-2} after LED treatment with 10 mM of 5-aminolevulinic acid solution and incubated for 60 min. *L. monocytogenes* biofilms were reduced by 3.0 log CFU cm^{-2} after LED treatment with 5-aminolevulinic acid solution.	Buchovec and others (2010)
Sterilization of contaminated surfaces (endogenous photosensitizers)							
No photosensitizer used.	*Campylobacter spp.*	395 nm	Minimum of 0.12 J cm^{-2}	ND	Stainless steel and polyvinylchloride cutting board	Population reduced from an initial inoculated microbial load of 4 log CFU/cm^2 to no detectable pathogen.	Haughton and others (2012)
	Salmonella Enteritidis, *L. monocytogenes*	405 nm	110 mW cm^{-2}	Variable	Acrylic and polyvinyl chloride surfaces	On PVC, *S. enterica* was fully inactivated by 2.19 log CFU/plate, whereas *L. monocytogenes* was reduced by 0.90 log CFU/plate after treatment of 7.5 min (dosage of 45 J cm^{-2}). On acrylic, *S. enterica* was reduced by 1.63 log CFU/plate, whereas *L. monocytogenes* was reduced by 0.42 log CFU/plate after treatment of 10 min (dosage of 60 J cm^{-2}).	Murdoch and others (2012)
	E. coli, *L. monocytogenes*	405 nm	36 J cm^{-2}		Nitrocellulose membrane	*E. coli* and *L. monocytogenes* were reduced by 26% and 13%, respectively, upon exposure to light with irradiance of 60 mW cm^{-2}. When pre-treated with acid at pH 3, inactivation was 95% and 99%, respectively.	McKenzie and others (2014)

20 min, which is lower than the effective treatment temperature from high power pulsed lighting, which could reach 80°C (Luksiene and Paskeviciute 2011b). The surface temperature of skinless chicken fillet exposed to near-UV radiation (395 nm) at a dose of 4.2 J cm^{-2} increased from approximately 25 to 30°C (Haughton and others 2012). Hence, LED treatments do not cause excessive overheating of food items and would not be expected to cause thermal degradation.

Apricots, plums, and cauliflower treated with hypericin and irradiated with green LED light were found to have similar antioxidant activity and color compared with the control samples (Aponiene and others 2015). It is possible that the short irradiation time of 30 min was not sufficient to effect any degradation of antioxidant compounds, or the stimulation of antioxidant capacity in apricots, plums and cauliflowers treated with hypericin, Na-Chl and LED irradiation, as compared with longer irradiation

times used in postharvest applications. However, although anthocyanin and total soluble phenolics content did not increase after Na-Chl and LED treatment on strawberries, an increase in total antioxidant capacity was reported. Both studies by Aponiene and others (2015) and Luksiene and Paskeviciute (2011b) were measured using the ferric reducing ability of plasma (FRAP) method. Although this seems to contradict the results of Aponiene and others (2015) who reported that antioxidant capacity is not enhanced by PDI, a higher concentration of 1 mM of Na-Chl was used in the study by Luksiene and Paskeviciute (2011b) compared with 1.5×10^{-2} mM used in the treatment by Aponiene and others (2015). Na-Chl possesses high antioxidant capacity (Luksiene and Paskeviciute 2011a), hence the apparent increase in antioxidant activity could be due to the addition of Na-Chl and not a result of biological response to LED light.

Ultimately, the acceptability of the food to consumers is a crucial factor in determining whether a postharvest treatment is successful. Sensory studies should be conducted to ascertain that the taste and flavor of treated foods is not altered drastically by PDI. A simple preliminary sensory study on strawberries treated with Na-Chl and irradiated in blue light suggested that the flavor of treated strawberries was indistinguishable from the control (Luksiene and Paskeviciute 2011b). More rigorous sensory testing is still lacking in the literature.

Another area worth exploring is the properties of naturally occurring ingredients or food compounds that can either contribute to PDI, or be degraded upon irradiation and hence cause quality defects. For example, greater than 5 log CFU mL^{-1} of *S. aureus* suspended in 4 mM solution of gallic acid was inactivated when irradiated with an LED at 400 nm at 80 mW cm^{-2} for up to 15 min, following the generation of hydroxyl radicals from the photo-oxidation of gallic acid (Nakamura and others 2012). Similarly, polyphenol solutions consisting of caffeic acid, gallic acid, epigallocatechin, epigallocatechin gallate, and chlorogenic acid were shown to have varying extents of inactivation on several species of bacteria like *Enterococcus faecalis*, *S. aureus*, *Streptococcus mutans*, *Aggregatibacter actinomycetemcomitans, E. coli,* and *P. aeruginosa* (Nakamura and others 2015). The presence of hydroxyl radicals in brandy irradiated by white LED was attributed to gallic acid, which suggests that PDI might be effective on certain beverages with high content of gallic acid (Espejo and Armada 2014). Similarly, riboflavin is another natural ingredient in foods such as milk, which has been shown to have photosensitizing properties. Under blue LED light of 462 nm at an irradiance of 1.5 mW cm^{-2}, DNA integrity in *E. coli* strains was damaged due to ROS production when riboflavin was absorbed by bacteria. However, with increasing time, the amount of riboflavin decreased as it was decomposed into lumiflavin and lumichrome (Liang and others 2013). Although using riboflavin in PDI of beverages and similar foods is suggested by the authors, the degradation of riboflavin in foods such as milk, beer, and cheese might also lead to unacceptable appearance and flavor to consumers due to lipid oxidation (Cardoso and others 2012). Since PDI may therefore not be suitable for all types of foods, this highlights the importance of evaluating the suitability of a food for PDI as some types of food might be predisposed to undergoing quality deterioration upon treatment.

PDI in decontamination of food packaging and surfaces

Apart from direct application onto surfaces of foods, photosensitizers can be incorporated onto the surfaces of packaging materials in order to aid in the decontamination of foods when exposed to the appropriate light conditions (Table 5). Chlorophyllin-based photosensitizers attached to polyolefin packaging materials were able to inactivate a variety of pathogens including *L. monocytogenes* (Luksiene and others 2010) and *B. cereus* (Luksiene and Paskeviciute 2011a) by approximately 4 log cycles when irradiated by LEDs with wavelength of 405 nm for 15 min at 20 mW cm^{-2}. In comparison, chemical treatment of the same surface by 200 ppm sodium hypochlorite could only inactive around 1.6 to 2.2 log CFU cm^{-2} of the *L. monocytogenes* or *B. cereus* cells (Luksiene and Paskeviciute 2011a). Although the authors claimed that chlorophyllin-based photosensitizers did not modify physicochemical, mechanical nor gas permeability properties of the polyolefin packaging material that it was coated onto, and that the migration of photosensitizer from the material was negligible, it would be of interest to better understand the effect of coating packaging materials or surfaces using photosensitizers on the above properties of packaging material.

Other than incorporating photosensitizers onto food contact surfaces or packaging like polyolefin packaging materials, Luksiene and Brovko (2013) suggest that photosensitizers such as chlorophyllin could be incorporated onto various polymer-based films and coatings that are used on foods like meat and poultry. Upon irradiation with an appropriate light treatment, PDI can be initiated on the surface of the food to ensure its microbial safety. However, there are very few studies on such "photosensitizer-based edible biopolymeric films and coatings." López-Carballo and others (2008) examined the effects of an irradiation system which produced white light using a quartz/halogen lamp combined with UV and IR filters, as well as a fan to maintain the temperature of the system below 30°C. At a luminous output of 30000 lux for 15 min, the treatment was applied to cooked frankfurters containing chlorophyllin-coated gelatin film or coating, showing that it reduced populations of *S. aureus* and *L. monocytogenes* by approximately 1.5 log cycles. However, to date there have been no known studies that have been conducted with regard to this application using LEDs. Because of the lower radiant heat capabilities, LEDs would be a better alternative to the lighting system described by López-Carballo and others (2008). Despite the low efficacy of their method, it is plausible to use the method in cold storage to further inhibit the growth of low microbial loads of pathogens on meats. However, more studies will first have to be done to understand the effect of the coating on the organoleptic properties of foods, such as color, flavor, and texture.

UV LEDs

UV light treatment is an effective technology employed in the food industry to sterilize surfaces and liquids. At a wavelength range of 200 to 280 nm (UVC) and 280 to 315 nm (UV-B), it has a damaging effect on DNA replication and transcription. Direct exposure to UVC or UV-B results in dipyrimidine dimers, "pyrimidine (6–4) pyrimidine photoproducts," pyrimidine hydrates, or cross-links between proteins and DNA. Hence, it is capable of inactivating a variety of pathogens such as bacteria, viruses, fungi, protozoa, and other pathogenic and parasitic organisms (Lui and others 2014).

A UVA LED system constructed by Hamamoto and others (2007) was shown to inactivate pathogenic species such as *Vibrio parahaemolyticus*, *S. aureus*, *S.* Enteritidis, and an enteropathogenic *E. coli* (EPEC) strain *in vitro*. The LEDs provided irradiation at 70 mW cm^{-2} at 25°C and could inactivate up to 5 to 6 log cycles of the bacteria within 150 min. *V. parahaemolyticus* was inactivated by 6 log cycles to below detection levels the fastest within 20 min,

followed by EPEC and *S. aureus* within 60 min, whereas *S.* Enteritidis was inactivated by 5 log cycles only after 150 min. It was determined that the UVA LED system resulted in more oxidative damage to DNA than UVC radiation (254 nm) produced by a low-pressure mercury lamp, as indicated by greater levels of 8-hydroxy-2′-deoxyguanosine. However, the UVA LED system resulted in less direct DNA damage than UVC as evidenced by lower levels of cyclobutane pyrimidine dimer (Hamamoto and others 2007). Furthermore, the effect of UVA LED (365 nm) irradiation on the inactivation of *E. coli* DH5α inoculated onto lettuce and cabbage leaves in cold storage of 4°C was evaluated. The UVA LED had an output of 125 mW cm^{-2} was placed 5 cm above the surface of the vegetable leaves. Irradiation of 90 min resulted in a decrease of 3.5 log cycles, with no loss of vitamin C and no detection of nitrites or nitrates reported, and less than 5% moisture content loss (Aihara and others 2014). Although it would be worth measuring the changes in other nutritional and organoleptic quality factors, the study indicated that UVA LEDs are an effective means of keeping leafy vegetables microbiologically safe.

Another experiment focused on the efficacy of UVA LEDs (365 nm) on the microbiological safety of beverages. *E. coli* DH5α was irradiated at 70 mW cm^{-2} for 30 min at 25°C on solutions containing artificial colorants in varying concentrations, as well as commercially available orange juice. In general, the lower the concentration of colorants in the solutions, the greater the log reduction of the bacteria. Orange juice subjected to similar treatment also had a lower log reduction compared with the control containing phosphate buffer solution. There was variation between the 2 juices, whereby the log reduction in one juice was approximately 0.5 log cycles, whereas the log reduction was 2.5 log cycles in the second juice. To account for differences in log reduction between solutions containing different colorants and concentrations, it was suggested that efficacy could be reduced if the absorbance band of the colorant overlapped at 365 nm. Efficacy might be reduced by colorants that have antioxidant properties and quench ROS produced during the process. Furthermore, pigments and particles such as fiber might scatter, reflect, or absorb light, thereby reducing the penetration power of the UV radiation (Lian and others 2010). More studies are required to verify these claims, although the experiment gives good insight into the applicability of UV LED irradiation into beverages.

The bactericidal effect of UVC irradiation and application on food systems is well known (Shama 2014), yet the evaluation of the bactericidal effect of direct irradiation using UVC LEDs is still lacking. However, UVC LEDs have been more thoroughly investigated in the field of water treatment and sterilization. Despite current technical challenges in producing efficient UV LEDs, predicted improvements in production techniques will allow UV LEDs to surpass mercury tube technology in the near future. More importantly, UV LEDs offer features that mercury tube lamps cannot, such as the ability to produce pulses with no warm-up time, tunable wavelengths as opposed to specifically fixed wavelengths, and no toxic mercury content (Lui and others 2014).

Photocatalytic oxidation using UV LEDs

Similar to PDI, photocatalytic oxidation occurs when UV light is irradiated onto a photoactive inorganic nanoparticle materials such as titanium dioxide (TiO_2), zinc oxide (ZnO), and other variants such as silver-titanium oxide hybrids (de Azeredo 2013) and other materials. Irradiation with UVA excites an electron in the material's valence band to the conduction band. The resultant electron-hole pair eventually leads to ROS generation, which inactivates surrounding microbes such as *E. coli*, *S. aureus*, *P. aeruginosa*, *Enterococcus faecium*, *Salmonella* Choleraesuis subsp., *V. parahaemolyticus*, *L. monocytogenes*, and various other spoilage bacteria (Kim and others 2003; Kühn and others 2003; Li and others 2009; Sung and others 2013). Lipid peroxidation of polyunsaturated fatty acids located in cell membranes due to ROS attack is considered to be the most likely cause for cell death, followed by other causes such as peptidoglycan damage, enzyme and coenzyme inactivation, and nucleic acid destruction (Dalrymple and others 2010). UVA radiation at 365 nm is commonly utilized in the process of photocatalytic oxidation. The efficacy of combining UVA light with photoactive nanoparticles is greater than UVA light alone (Chawengkijwanich and Hayata 2008; Othman and others 2014). However, Long and others (2014) reported negligible inactivation of *S.* Typhimurium using nano-TiO_2 and UVA lamp after 180 min when the initial population was above 7 log CFU g^{-1}, which indicates that a very high microbial load reduces the effectiveness of photocatalytic inactivation. Several studies have investigated the effect of photocatalytic inactivation through food packaging materials on food properties using conventional UVA sources. A UV lamp with an irradiance of 1 mW cm^{-2} caused the *E. coli* population inoculated onto lettuce wrapped in a TiO_2-coated packaging to decrease from 6.4 to 4.9 log CFU g^{-1} (Chawengkijwanich and Hayata 2008). Similarly, *E. coli* O157:H7 populations were reduced from around 9.4 to 6.3 log CFU g^{-1} after 3 d when enclosed in TiO_2-coated low-density polyethylene film and exposed to UV or fluorescent light (Othman and others 2014). Furthermore, TiO_2 paste was used to inactivate *L. monocytogenes* biofilms on stainless steel and glass materials using UVA lamps (Chorianopoulos and others 2011).

However, there are fewer studies using UVA LEDs as a source of irradiation, and studies using this technology continue to focus on water purification (Izadifard and others 2013). For example, continuous irradiation of UVA LED radiation on TiO_2 film with an irradiance of 8 mW cm^{-2} could effectively reduce an especially UV-resistant strain of *E. coli* by 4 log cycles after 180 min of treatment time (Xiong and Hu 2013). UVA LED and TiO_2-coated surfaces were effective in reducing the content of micropollutants typically found in potable water such as metaldehyde (Autin and others 2013). As there is existing evidence that UVA radiation is generally effective when used in conjunction with food packaging incorporating suitable photoactive nano-particles, there is great potential for the application of UVA LEDs in ensuring food safety through photocatalytic oxidation. Hence, more in-depth research should be conducted using UVA LEDs.

Pulsing of UV-light via UV LEDs

The ability to create quick pulses is an advantage that LEDs possess, which may further enhance efficacy of UV radiation delivery. Pulsed UVC radiation produced by a non-LED pulsed polychromatic UV system emitting radiation above 200 nm every 10 s was reported to be more effective than mercury lamps in inactivating *E. coli* in water in a model benchtop water purification system (Bohrerova and others 2008). Despite UVA's limited efficacy without nanoparticles, pulsed UVA LED at 0.28 mW cm^{-2} and a frequency of 100 Hz for 60 min reduced biofilm populations of *E. coli* by 99% (Li and others 2010).

An important advantage of pulsing is energy savings. A study by Wengraitis and others (2013) demonstrated the energy efficiency of using pulsed lighting. *E. coli* was exposed to pulsed light from a UVC LED and the log reduction from treatments with varying

duty cycles and repetition rate frequencies was observed. The results suggested that the most energy-efficient pulsed-light settings were within the range of 0.5 to 50 Hz at 10% duty cycle, with a power consumption of 204 mW, which showed that in terms of log reduction per energy drawn, it was approximately twice as efficient compared with continuous irradiation, and 20 times more efficient compared with pulsed Xenon light.

Evaluation of LEDs in food safety

To sum up, the light-mediated techniques of PDI, photocatalytic oxidation, and direct UV inactivation using LEDs are still maturing fields. LEDs have been shown to be very effective in several *in vitro* studies, with several studies focusing on practical applications such as in packaging and surface sterilization. There is scope for application of LEDs via PDI, UV LEDs, or photocatalytic inactivation on beverages, although it is recognized that there are still limitations to the effectiveness of these methods due to the optical density of the beverages. There is a lack of data on the effect of ROS production from PDI or photocatalytic inactivation on the quality and organoleptic acceptability of food products.

As the mechanisms of inactivation are well understood, the inactivation kinetics of the above methods of inactivation, together with other critical process factors, such as temperature, photosensitizer concentration, and irradiation time, should be systematically studied. For endogenous PDI, Ghate and others (2013) studied the effect of wavelength, temperature, and dosage of LED treatment on the inactivation, decimal reduction values and sublethal injury of selected pathogens, while Kumar and others (2015) modeled the inactivation of selected pathogens at different temperatures, wavelengths, and dosages of LED treatment. Aponiene and others (2015) found the Logistic model was suitable for describing inactivation curves of *B. cereus* incubated with hypericin and exposed to a green LED ($R^2 > 0.97$). Model parameters, representing "number of resistant cells," "shoulder parameter," and "population reduction suddenness," were compared for different treatment conditions, including concentrations of hypericin used, as well as dark incubation time of sample with hypericin. As such, few studies on inactivation kinetics have been conducted on *in vitro* systems for foodborne pathogens of significance, or on spoilage organisms. It is also worth studying the sublethal injury of the above methods. The determination of sublethal injury is useful in ensuring that the efficacy of a treatment is not overestimated, and in preventing sublethally injured cells from recovering when suitable conditions return, regaining its virulence and causing illness (Garcia-Gonzalez and others 2007). However, a higher rate of sublethal injury is an indication that an intervention technology can be enhanced by applying another technology such as high salt or low pH conditions, which will eventually kill injured cells (Ghate and others 2013).

However, it is apparent that the usage of LED light has a major shortfall, that being the very low penetration depth into food, which might limit decontamination to only the surfaces of vegetables, fruits and some meats, or clear liquid food products. Yet, LEDs present several advantages that justify its adoption, including the prevention of resistant strains forming, the absence of toxic mercury and the ability to downsize the source of radiation, compared with conventional and bulky low-pressure mercury lamps. Pulsing UV LEDs can also bring about energy savings. LEDs can therefore possibly be used as a hurdle technology strategy to maintain the safety of foods as they are being distributed in the food supply chain.

Conclusions

Because of the rate at which LED technology has been improving and is expected to improve, there is great potential for its application in the food industry. LEDs have longer life expectancies. They are of comparable, or of higher photon efficiency to conventional lighting, and are more durable. Moreover, their monochromatic nature allows for the exclusion of wavelengths that are not wanted, especially IR radiation which causes surface heating. This saves energy and prevents thermal degradation of food quality in the process. LED chips can also be seamlessly integrated into electronic systems, and the quick on-off feature allows for quick pulsing, dimming, and further energy savings. Therefore, the most notable benefit of adopting LED technology is the prospects of cutting down on energy consumption. Furthermore, the lack of toxic heavy metals makes it an environmentally friendly technology and reduces the need for special disposal. Hence, LEDs can be economically and environmentally beneficial. At present, it has been shown that in small growing facilities which utilize only LEDs, energy consumption has been successfully reduced while producing nutritious food (Poulet and others 2014). LEDs are therefore suitable for small-scale growing facilities such as in space stations. However, their application on a larger scale is still difficult because of the initial installation costs (Mitchell and others 2012; Nelson and Bugbee 2014), and uncertainty over the effectiveness of using LEDs as supplementary lighting (Trouwborst and others 2010; Samuolienė and others 2013). However, costs are expected to further reduce in the near future, while LED performance continues to improve. Establishing Best Management Practices and Standards will also assist in providing a framework for providing guidance in designing, installing, performing economic analysis and adopting LED technology (Mitchell and others 2012).

The monochromatic nature of light produced by LEDs is one of the most unique properties of electroluminescence, and is important in adjusting the spectral composition of light received by plants being grown, or stored after harvesting. Since such flexibility in controlling the spectral composition of light was not possible with conventional lighting, LEDs can be utilized to give us better understanding and control over how food is produced and preserved with relation to spectral composition of light. This is especially so since it is known that increasing the proportion of light in certain wavelengths improves the nutritional quality of foods as they are being grown or while in postharvest storage, and that low levels of light from LEDs (broad spectrum or monochromatic) has been shown to reduce senescence in plants and vegetables stored in postharvest conditions, and even control the rate of ripening in certain fruits. As different species of plants and food crops have different requirements in terms of both light quality and quantity, the wide flexibility that LEDs offer in terms of the output spectral composition, and their ability to be controlled through electronic systems, could be exploited to accelerate our understanding of the response of plants during growth and cultivation, and also in postharvest stages.

The role of LEDs in food safety is also noteworthy. High dosages of monochromatic light are necessary for inactivating foodborne pathogens, as photosensitizing or photocatalytic agents or materials produce ROS at specific wavelengths. Similarly, the lack of radiant heat allows LEDs to be used as a nonthermal means of inactivating foodborne pathogens. UV LEDs can also be used in decontaminating food. *In vitro* studies have shown the effectiveness of LEDs inactivating a variety of significant foodborne pathogens, with minimal heating effect. Therefore, LEDs can be

used in conjunction with cold storage methods, as it is found in general that bacteria can be inactivated more effectively at low temperatures (Ghate and others 2013; Kumar and others 2015). Pathogens can be inactivated using LEDs in the blue region without any additives, although the addition of exogenous photosensitizers is usually more effective. Photosensitizers and photocatalytic material can also be incorporated into coatings or packaging materials so that quick sterilization of such surfaces can be carried out using LEDs. Given the versatility of these techniques, more research is being committed to understanding inactivation kinetics of these treatments in order to optimize the lethality of the processes. However, most research has been restricted to *in vitro* studies, and more work needs to be done on actual food matrices. Another limitation is the low penetration depth of LED light, which limits the treatment to surfaces or liquids of low optical densities. Yet, the nonthermal nature of LED lighting will be suitable for foods that are sensitive to thermal treatment, such as fruits and vegetables, ready-to-eat salads, and others. In addition, LEDs provide an alternative to the use of chemical sanitizers in ascertaining food microbiological safety, as well an additional means of decontamination, as microbial resistance becomes a more urgent problem.

Although the effectiveness of LEDs has been shown to generally improve or retain the quality of foods, few studies have rigorously evaluated the impact of LED treatments on the acceptability of food to consumers. This is especially crucial for postharvest preservation and microbiological decontamination, whose goals are to provide nutritious and safe food which is acceptable to the consumer. This would require more in-depth quantitative and instrumental analysis on food quality parameters such as color, texture, flavor, and other organoleptic qualities. Also, having trained sensory panels evaluating the foods would give valuable insight into the impact of LED treatment on the above quality parameters.

With further progress in LED technology, there may be scope for utilizing LEDs in developing countries where food production, as well as safe and hygienic storage and distribution of food are critical issues. Currently, the integration of LEDs and photovoltaics into a viable system for providing safe drinking water is seen as a plausible combination, whereby energy from the sun is converted into electrical energy for usage by LEDs (Lui and others 2014). Therefore, it is plausible that this technology can be transferred to food-related applications as well. LEDs can harness energy from the sun to provide supplementary light for growth. More importantly, photovoltaic-powered LEDs would be applicable to postharvest operations and in maintaining sanitation of foods, areas in which much food wastage occurs. In conclusion, LEDs have come a long way since they were invented, and their usefulness in the food industry is becoming increasingly evident. Because of the differences in technology compared with current lighting technologies, LED technology brings unprecedented benefits to the full food supply chain, from the production of food, to the postharvest stage, and during the insuring of food safety prior to human consumption. Their further development will be of great benefit to the food industry and society.

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