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Applications of Light-Emitting Diodes (LEDs) in Food Processing and Water Treatment

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Abstract

Light-emitting diode (LED) technology is an emerging nonthermal food processing technique that utilizes light energy with wavelengths ranging from 200 to 780 nm. Inactivation of bacteria, viruses, and fungi in water by LED treatment has been studied extensively. LED technology has also shown antimicrobial efficacy in food systems. This review provides an overview of recent studies of LED decontamination of water and food. LEDs produce an antibacterial effect by photodynamic inactivation due to photosensitization of light absorbing compounds in the presence of oxygen and DNA damage; however, such inactivation is dependent on the wavelength of light energy used. Commercial applications of LED treatment include air ventilation systems in office spaces, curing, medical applications, water treatment, and algaculture. As low penetration depth and high-intensity usage can challenge optimal LED treatment, optimization studies are required to select the right light wavelength for the application and to standardize measurements of light energy dosage.

Keywords Light-emitting diodes · Antimicrobial efficacy · Antimicrobial mechanisms · Food processing · Water treatment

Introduction

Artificial light treatments using light energy with different wavelengths have been used in agriculture and the food industry to disinfect water and food and to improve plant health and growth [63, 74, 118]. Conventional approaches, such as UV light emitted by mercury vapor lamps or pulsed light produced in xenon lamps, have been used to inactivate microorganisms such as bacteria, yeasts, viruses, and fungi. Disadvantages of these treatments include the possibility of contamination by mercury residues, and a short life span of equipment. Light-emitting diodes (LED) made of semiconductor materials and producing monochromatic light have been used in agriculture and the food industry, as they have several advantages over conventional sources. For example, harmful microorganisms in food and water can be eliminated by light with specific wavelengths and pulsed or continuous modes of operation, making LEDs effective. LEDs are nonhazardous (no mercury), and their compact size makes them easy to incorporate into existing food processing applications. LEDs offer high performance, robustness, a long lifetime (> 10,000 h), low power use, and cost effectiveness, making them a promising option for effective disinfection and for plant growth applications [119]. This review explains the fundamentals of LED applications to microbial inactivation in different food products and water. It describes the potential quality changes in recipients of LED treatment, the mechanisms of microbial inactivation during treatments using light of different wavelengths, and the challenges and future opportunities for LED technology in the food processing sector.

LED Fundamentals

An LED is a semiconductor that emits light when electricity passes through it. LEDs work on the principle of electroluminescence, that is, they produce light upon application of an electric or a magnetic field. In an electric or a magnetic field, excited electrons reach lower energy states by emitting light and releasing energy in the form of electromagnetic radiation. LED is a semiconductor material doped with impurities that create a boundary or interface (known as a p-n junction) between two types of semiconductor materials, one type (the positive or p-type) having an excess of holes and the other type (the negative or n-type) having an excess of electrons. The color and the wavelength of the light emitted depends on

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the semiconductors and the impurities used in the LED formation (Table 1). LEDs are similar to conventional diodes, with the p-side called the anode and the n-side called the cathode. Additionally, the diode consists of a nonconducting region between the p and n sides, known as the depletion region [41].

LEDs consist of a chip of semiconductor material doped with certain impurities that enable it to emit light of a particular color and wavelength. A p-type semiconductor can be formed by impregnating a group II element such as magnesium (Mg) into a group III element substrate to provide extra holes in the substrate. An n-type semiconductor is formed by doping a group IV element into a group III element substrate to provide extra free electrons in the substrate. The extra holes on the p-side and the free electrons on the n-side fuse together at the p-n junction to form a nonconducting, depletion region [12]. A radiative recombination of free electrons and holes is an important event in the LED system. On the passage of electric current through the LED, the higher energy electrons in the conduction band (the n-side) combine with the holes in the p-side forming electron-hole pairs, and move to the valence band of the p-type semiconductor where the energy is lower (compared to the n band with its free electrons) (Fig. 1). This bandgap can either be direct, where momentum is conserved, or indirect, where momentum is not conserved and the transition is lower. The transition can be improved by the addition of isoelectronic traps [25]. The difference between the energy of the free electrons and the energy of the electron-hole pairs (i.e., the band gap energy) is emitted as photons, carriers of electromagnetic radiation of certain color and wavelength (Fig. 1). Highly efficient LEDs are based on group III–V semiconductors and are formed by direct band gap alloys. Varying the chemical compositions of these alloys can vary the band gap energy and hence the wavelength of the

Table 1 The semiconductors and applications of LEDs emitting light of different wavelengths [41]

Semiconductor	Voltage drop (ΔV)	Wavelength (nm)	Color	Applications
Gallium arsenide (GaAs), aluminum gallium arsenide (AlGaAs)	< 1.9	> 760	Infrared	Home-entertainment remotes, night-vision cameras, security systems, wound healing
Aluminum gallium arsenide (AlGaAs), gallium arsenide phosphide (GaAsP), aluminum gallium indium phosphide (AlGaInP), gallium phosphide (GaP)	1.6–2.0	610–760	Red	Traffic light systems, wound healing, dental implants, algaculture
Gallium arsenide phosphide (GaAsP), aluminum gallium indium phosphide (AlGaInP), gallium phosphide (GaP)	2–2.1	590–610	Orange/amber	Cell phone screens
Gallium arsenide phosphide (GaAsP), aluminum gallium indium phosphide (AlGaInP), gallium phosphide (GaP)	2.1–2.2	570–590	Yellow	Traffic light systems
Gallium phosphide (GaP), aluminum gallium indium phosphide (AlGaInP), aluminum gallium phosphide (AlGaP)	1.9–4.0	500–570	Green	Traffic light systems, lipid production in microalgae, wound healing, dental whitening
Indium gallium nitride (InGaN), silicon carbide (SiC)	2.5–3.7	450–500	Blue	Telecommunications, message boards, traffic control devices, algaculture, wound healing, dental care
Indium gallium nitride (InGaN)	2.8–4.0	400–450	Violet	Adhesive curing, tooth bleaching
Aluminum nitride (AlN), aluminum gallium nitride (AlGaN), aluminum gallium indium nitride (AlGaInN), diamond (C)	3.1–4.4	< 400	Ultraviolet	Sterilization and air disinfection system, adhesive curing, 3D printing

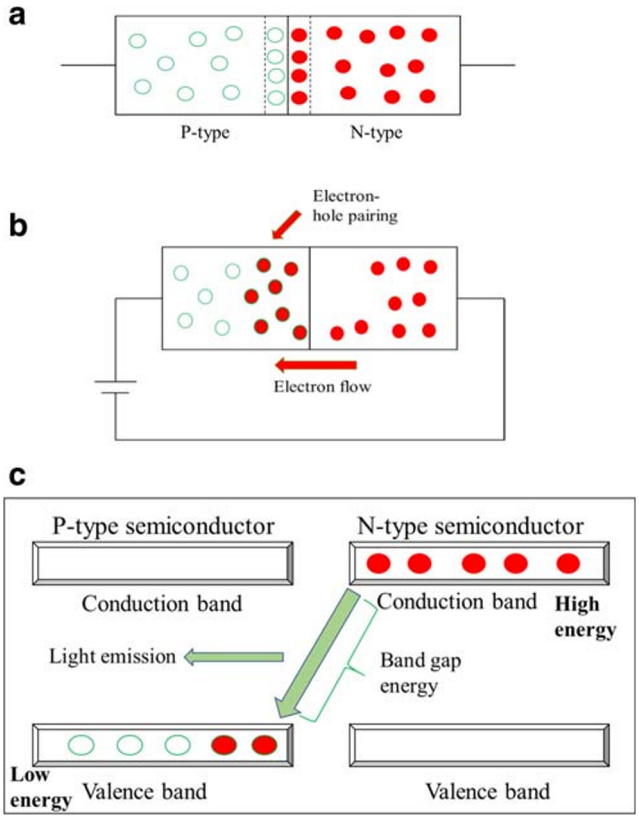

Fig. 1 The electrons on the n-type semiconductor and holes in the p-type semiconductor forms a depletion region at the p-n junction without external current (**a**). Forward-biased diode resulting in the recombination of electrons and holes (**b**). Light emission with energy equivalent to the band gap energy (**c**) [41]

light emitted. On applying the law of conservation of energy with an assumption that the thermal energy produced is much less than photon energy produced, the energy produced in the form of light will be equal to the bandgap of the diodes [117]:

$$E_c - E_v \approx E_g \tag{1}$$

where E_c is the energy of electrons in the conduction band, E_v is the energy of the holes in the valence band, and E_g is the energy in the bandgap of diodes, and signifies the total energy generated during the electroluminescence.

According to the conservation of energy, if the thermal energy is much less than E_g,

$$hv = E_c - E_v \approx E_g \tag{2}$$

where hv describes the energy of a photon emitted, h is Planck's constant, and v is the frequency of the photon of light and is inversely proportional to the wavelength of the light. Equations 1 and 2 clearly satisfy the fact that material with the higher conduction band is needed to emit a smaller wavelength of light and vice versa. For instance, AlGaN has a larger bandgap than GaN and InGaN, so it is preferred over the others to produce deep UV light (wavelengths shorter than 365 nm) or near UV light (320–400 nm) [6, 16].

Packaging of a LED chip can affect the efficiency of a LED system. For example, if the packaging film absorbs most of the light emitted by a LED source due to total internal reflection, the amount of light perceived by the human eye is affected, thus varying the overall luminous efficiency. Overall luminous efficiency provides the efficiency of a light source to convert the electrical energy into the optical power perceived by a human eye in standard conditions. The voltage and current requirements of a LED varies based on the semiconductor material used in the diode and the wavelength of the light emitted; usually the voltage ranges from 1.5 to 3 V and the current ranges from 10 to 30 mA [41]. Regulation of the electric current and the duty ratio (proportion of time operated) helps to regulate the light intensity and the spectral output of the LED.

The irradiance (I) of the LED is an important parameter determining the process effectiveness. The irradiance is the radiant power exposed to unit surface area of the sample. Radiometers can be used for the measurement of irradiance of LEDs emitting light of different wavelengths at specific distance from the source and checked periodically during the lifespan of the source to monitor the source power [27, 36, 52, 102, 104]. The radiant energy exposure (the energy dose) of a sample to light at a constant height and exposure time, is equal to the product of the irradiance and the exposure time, as expressed in equation

$$E = I \times t$$

where E represents the energy dose of the LED light per unit area (mJ/cm^2), I is the irradiance of the LED light (mW/cm^2), and t represents the duration of the exposure of the LED light (in seconds) [36].

Another important parameter is the photon fluence, which is the quotient of dN by dA.

$$\varnothing = \frac{dN}{dA}$$

where $\varnothing$ is the photon fluence (cm^{-2}), dN is the number of photons incident on an imaginary sphere, and dA is the cross-sectional area of this imaginary sphere [101, 112]. The dN can be determined as the ratio of total photon energy incident on the surface to the energy of one photon ($\frac{hc}{\lambda}$), where h is the Plank's constant (6.626×10^{-34} J s), c is the speed of light (3×10^8 m/s), and λ is the wavelength of light (m).

LED Technology for Antimicrobial Applications

LEDs have been applied to air disinfection, water treatment, surface decontamination, and curing [63]. Light with

wavelengths in the range of 200–280 nm (UV-C), 280–320 nm (UV-B), 320–400 nm (UV-A and near UV-visible, NUV-Vis), and 400–470 nm (blue light) have been studied to understand their antimicrobial efficacy. Longer wavelengths, i.e., infrared and red (630–1000 nm) are used for applications such as phototherapy, dying, and curing of coatings, and ink curing [75]. The antimicrobial effectiveness of light energy emitted by lamps, especially in the UV-C range, has been well documented [109, 125, 128]. Most LED studies have focused on the application of UV-C LEDs for water disinfection [17, 118, 129]. However, the application of LEDs that emit light at wavelengths such as 365 nm, 395 nm, and 455 nm is emerging in food processing [40, 47] and water treatment.

LED Treatment of Solid Foods

The efficacy of LED treatments of solid foods depends on the type and nature of the food products and components, the water activity (a_w), and the food surface morphology. Parameters such as light wavelength, treatment duration, dose, illumination temperature, relative humidity, and microbiological parameters are also important. Ready-to-eat fresh cut fruits have a high market demand. These products are stored in refrigerators, but they are susceptible to resistant microorganisms, although the growth of such organisms is limited at low temperatures. LEDs have shown promising antibacterial effectiveness in such products, although their antibacterial efficacy is affected by many product and process parameters, including type of product, composition, treatment temperature, and environmental conditions. LEDs emitting light at 405 nm induced a reduction of 1–1.2 log CFU/cm^2 (colony forming units per cm^2) in fresh-cut papaya inoculated with *Salmonella*. The papaya was treated with a total dose of 1.7 kJ/cm^2 at a set temperature of 4 °C for 48 h [58]. The antibacterial effectiveness of 405 nm LEDs was supported by another study on fresh-cut mango by Kim et al. [59], where the cell counts in a three strain cocktail of *E. coli* O157:H7, three serotypes of *L. monocytogenes*, and five serotypes of *Salmonella* spp. were reduced to less than 1.6 log CFU/cm^2 with a total dose of 2.6–3.5 kJ/cm^2 for 36–48 h. The *E. coli* O157:H7 and *Salmonella* in the cocktail culture were reduced to below the detection limit with 36 h of treatment at 4 °C and at 10 °C, indicating that the antibacterial efficacy of the LED is dependent on the type of bacteria. The sterilization effects of visible light LED treatment on fresh-cut fruits has also been studied. Ghate et al. [36] tested the antibacterial effects of a 460 nm LED at different illumination temperatures and irradiances on fresh-cut pineapples infected with a cocktail of *S. enterica*. A maximum reduction of 1.72 log CFU/g was achieved with 92 mW/cm^2 irradiance at 16 °C illumination temperature. Varying the irradiances had insignificant effects on the inactivation. High energy doses used for long times with small reductions in target pathogens may limit the practical applications of LED treatment unless the antimicrobial efficacy is improved.

Seafoods like molluscs and crabs are rich sources of protein and other nutritional components and are prone to microbial contamination by many sources, either due to pollution or by pre- or post-processing sources. LEDs, an emerging nonthermal antibacterial technology, have been tested on contaminated seafoods. In a study by Josewin et al. [47], the efficacy of a blue LED (460 nm) with a riboflavin photosensitizer was studied on smoked salmon inoculated with a 4-strain cocktail of *L. monocytogenes*. The synergistic effects of an LED (15 mW/cm^2) and riboflavin (100 μM) produced reductions of 1.2 and 1.1 log CFU/cm^2 at surrounding temperatures of 4 °C and 12 °C, respectively. The LED treatment of seafoods might render it susceptible to a subsequent acidic condition. This was reported in a study of ready-to-eat salmon inoculated with *L. monocytogenes* and *Salmonella* spp. cocktail. A 405 nm LED treatment for 8 h with a total dose of 460.8 J/cm^2, produced a reduction of 0.4 and 0.3 log CFU/cm^2 in cell counts of *L. monocytogenes* and a 0.5 log reduction of *Salmonella* spp. at 4 °C and at 12 °C. Although the inactivation was low, both bacteria had a reduced D-values (time required to reduce 90% of the population in simulated gastric fluid) compared to untreated samples, and the treated samples were more sensitive to simulated gastric fluid. However, this effect varied for both strains, as *Salmonella* spp. (gram-negative) showed more susceptibility than *L. monocytogenes* (gram-positive), indicating that the treatment inactivated gram-positive and gram-negative bacteria differentially [73].

Owing to a high water content, ready-to-eat meat products are highly susceptible to contamination by foodborne pathogens. As cooking meat kills pathogens but also decreases the meat's nutritional value, it is a challenge to choose an optimal cooking time and an optimal cooking temperature. Kim et al. [57] measured the effect on *S.* Enteritidis inoculated on cooked with a pulsed LED emitting light at 405 nm. A total dose of 3.8 kJ/cm^2 at 4 °C produced a reduction of 0.8–0.9 log CFU/cm^2. A similar experiment at room temperature produced a smaller reduction in *S.* Enteritidis. LED systems can be designed to produce either continuous or pulsed treatments, according to the objective requirements, but treatment efficiencies can vary based on the design. This aspect was reported in recent research conducted on white mushrooms and commercial ready-to-eat sausages. Pulsed UV-C LED treatment with 20 Hz frequency and a duty ratio of 50% showed better antibacterial efficacy than continuous UV-C LED treatment against three-strain cocktails containing *E. coli* O157:H7, *S.* Typhimurium, and *L. monocytogenes*. Continuous treatment resulted in 2, 1.5, and 2 log reductions, whereas pulsed LED at a 5 J/cm^2 dosage resulted in 3, 4, and 4 log reductions in *E. coli*, *Salmonella*, and *Listeria*, respectively, in ready-to-eat sausage. In white mushrooms, continuous

irradiation resulted in 2, 1, and 1 log reductions and pulsed LED produced 2, 1.5, and 1.8 log reductions, in *E. coli*, *Salmonella*, and *Listeria*, respectively [50]. LEDs emitting light in the visible spectrum need further evaluation.

There have been many reported cases of illness in North America caused by the bacterial contamination of cheese. The presence of high moisture in cheese products supports the growth and survival of foodborne pathogens. Pulsed LED treatments have the potential to decontaminate these products. In a recent study conducted on sliced camembert cheese, a UVC LED emitting light of wavelength 266 nm produced 4.88, 4.72, and 3.52 log reductions in camembert cheese containing cocktails of *E. coli* O157:H7, *S.* Typhimurium, and *L. monocytogenes*, respectively. Also, higher wavelength UVC LED treatments (266–279 nm) showed 4–5 log reductions in *E. coli* O157:H7 and *Salmonella* spp., while a 3–4 log reduction in *Listeria* spp. in sliced camembert cheese was achieved with a treatment of 3 mJ/cm^2 [56].

Contamination of low water activity (a_w) foods such as dry nuts, cereals, and pet foods ($a_w < 0.85$) is a global concern, as thriving microorganisms eventually develop resistance to decontamination efforts. Foodborne pathogens can survive for long periods in a dormant state and become active on exposure to a favorable environment. There have been limited studies on the antibacterial efficacy of LED treatments in low a_w foods, but the studies conducted have shown promising results. Lacombe et al. [66] treated shelled almonds with a 405 nm LED and achieved maximum reductions of 2.44, 0.96, 1.86, and 0.7 log CFU/g in *E. coli* O157:H7, *S.* Typhimurium, *E. coli* K12, and *S.* Enteritidis, respectively. Further research is needed to improve the antimicrobial efficacy of LED treatments of foods with low water activity using different wavelengths (275, 365, 395, and 455 nm) of light energy. Results of LED treatments of solid foods are listed in Table 2.

Surface characteristics of food influence the inactivation efficacy of LED treatment. The variable effects of UV-C LED on white mushrooms and sausages was likely due to the limited penetration of light into the food matrix [50]. However, it is unclear why the elimination of gram-positive bacteria required a higher LED dose than the elimination of gram-negative bacteria. The bacterial inactivation improved with an increase in the duty ratio as well [41, 50, 102]. In the visible range, a 461 nm LED deployed better bacterial inactivation efficacy than 521 nm and 642 nm LEDs [33]. The illumination temperature of the treatment influenced the efficacy of the LED based on and the wavelength of the LED used in the treatment [36, 65].

LED Treatment of Liquid Foods

Liquid foods such as beverages are vulnerable targets for pathogenic contamination because of their high a_w and carbohydrate composition. Commonly, chemical preservatives are added into liquid foods to extend their shelf life and reduce microbial growth. However, due to the growing demand for foods with no additives and consumers' increasing concerns about safe food ingredients, treatments such as ultraviolet light as a physical means to reduce pathogens have been extensively studied in liquid foods. The disinfection effects of UV treatment using a wide range of wavelengths produced from different sources (e.g., mercury lamps, excimer lamps, microwave lamps) on liquid foods, such as, apple cider, juices, beer, and milk have been studied [62]. The studies have covered common foodborne pathogens, such as *E. coli*, *C. parvum oocyst*, *S. cerevisiae*, *L. innocua*, yeasts, and molds. LEDs can emit light in a broad wavelength range including visible, UVA, UVB, and UVC, therefore, its antimicrobial activity has been applied on several liquid foods.

Studies of the antimicrobial effects in liquid foods of LED treatments have mainly focused on apple juice, orange juice, and milk. Compared to water, liquid foods are complex systems containing pigments, fibers, and insoluble particles, and the turbidity and color of liquid foods can affect the antimicrobial efficacy of LED treatments. Lian et al. [74] used a UVA-LED to evaluate its disinfection activity in both colored solutions and orange juice inoculated with *E. coli* DH5α. Different food colors, carotenoids, the flavonoid carthamus yellow, and mixed food colorants of melon color-L, and grape color RCG were prepared at different concentrations from 0.001 to 0.1% with *E. coli* DH5α, and UVA-LED light of 126 J/cm^2 was used to treat the solutions [74]. This amount of energy used was huge however, technically possible, especially with 365, 395 and 455 nm LEDs. The authors used UV-A LEDs with 70 mW/cm^2 intensity for 30 min. There are a number of studies reported, showing huge energy dose of UV-A and blue light pulses emitted from LEDs, used for microbial inactivation in various solid/liquid food matrices [57–59, 73]. However, the reported energy doses of UV-C LEDs were significantly lower as mentioned in this and previous sections, compared to other wavelengths. Lower antimicrobial activity after LED treatment was obtained at higher concentrations of colored solutions and the log reductions in cell counts in different colored solutions were diverse. A maximum log reduction of 1.75 log CFU/ml was achieved in the 0.001% β-carotene colored solution which was still far lower than the 2.5 log reduction in the control phosphate buffered saline (PBS) solution. Similar results were obtained in orange juice, in which the log reduction was much lower than that of the transparent control solution after treatment. Pigments and other suspended particles in liquid foods may reflect and scatter the light, reducing the LED efficiency of bacteria elimination. Since reactive oxygen species (ROS) induced by ultraviolet A (UVA, 320–400 nm) light are central to the bactericidal effect, the antioxidant activity of food colors such as carotenoids in liquid foods can be reduced, resulting in oxidation and quality change.

Table 2 The antimicrobial efficacy of LED in solid foods

Tested food product	LED used	Tested microorganisms	Quality and mode of action	Major findings	References
Sliced camembert cheese	UV emitting peak wavelengths 266, 270, 275, and 279 nm; dose, 1, 2, and 3 mJ/cm^2, respectively; radiation intensity, about 4 W/cm^2	*E. coli* O157:H7, *S.* Typhimurium and *L. monocytogenes*		The 3 mJ/cm^2 dose resulted in 4 to 5 log reduction in *E. coli*, *S.* Typhimurium and *L. monocytogenes*	Kim et al. [56],
Shelled almonds	405 nm MBL LED lights; working distance, 7 cm; treatment time, 0, 1, 2, 4, 6, 8, and 10 min	Pathogenic *E. coli* O157:H7, non-pathogenic *E. coli* K12, pathogenic *S.* Enteritidis (PT30, Stanley and Anatum) and non-pathogenic *S.* Typhimurium strain Chi3985 with 8 or 5 CFU/g inoculum levels		Following log reductions for higher and lower inoculum levels, respectively: *E. coli* O157:H7, 2.44 and 1.44 log CFU/g *E. coli* K12, 1.85 and 1.63 log CFU/g *S.* Enteritidis, 0.7 and 0.55 log CFU/g *S.* Typhimurium, 0.54 and 0.97 log CFU/g	Lacombe et al. [66]
Fresh-cut papaya	405 ± 5 nm LED treatment with 0.9–1.7 kJ/cm^2 (24–28 h), 10 ± 1 mW/cm^2; working distance 4.5 cm in the temperature-controlled incubator (4, 10, or 20 °C)	*S.* Agona, *S.* Newport, *S.* Saintpaul and *S.* Typhimurium	No significant cellular lipid oxidation, significant DNA oxidation, no significant color change and antioxidant capacity, 1.5–1.9 times higher total flavonoid content, no significant change in the ascorbic acid, β-carotene and lycopene content	0.3–1.3 log CFU/cm^2 reduction in *Salmonella* cells at 1.3–1.7 kJ/cm^2 dose	Kim et al. [58]
Fresh-cut mango	405 ± 5 nm LED; irradiance, 20 ± 2 mW/cm^2; at 4, 10, or 20 °C illumination temperature; treatment times, 24–48 h; total dose, 1.7–3.5 kJ/cm^2 in a temperature-controlled incubator	Three strains of *E. coli* O157:H7, 3 serotypes of *L. monocytogenes* and 5 serotypes of *Salmonella*	No significant changes in the color, antioxidant capacity, total flavonoid content, ascorbic acid content, and β-carotene of the LED treated mangoes	2.6–3.5 kJ/cm^2 of LED light resulted in 1–1.6 log CFU/cm^2 at 4 and 10 °C in all the bacterial species and; 1.2 log CFU/cm^2 reduction in *Salmonella* at 20 °C with 1.7 kJ/cm^2 dose	Kim et al. [59]
Fresh-cut pineapples	460 nm LED with irradiance of 92.0, 147.7 or 254.7 mW/cm^2, corresponding to the working distances (4.5, 3.5 and 2.5 cm, respectively); illumination times (24, 13.91 and 8.66 h) to produce the same dose of 7950 J/cm^2 to the slices.	A cocktail of five serovars of *Salmonella enterica* Gaminara, Montevideo, Newport, Saintpaul, and Typhimurium	Discolouration of treated pineapple slices	Significant effect of illumination temperature on the antibacterial efficacy; inactivation ranged from 0.61 to 1.72 log CFU/g	Ghate et al. [36]
Satsuma mandarin fruits	465 nm blue LEDs with low (8 μmol/m^2/s) and high (80 μmol/m^2/s) fluency	*Penicillium italicum*		Radial growth of sporulation zone was found to be 0.3 and 3 mm/day for high and low fluency, respectively. LED-80 produced suppression of sporulation till day 6 after inoculation	Yamaga et al. [132]
Blueberries	Green, red, blue, and white LEDs; working distance, 30 cm	*Bacillus amyloliquefaciens* and *Lactobacillus brevis* for fermentation and *Propionibacterium acnes* and *Staphylococcus*	Green and white LED increased the total phenolic content and total flavonoid content in	White and green LED effective in improved fermentation for 72 h and improved antibacterial activity	Jeong et al. [46]

Table 2 (continued)

Tested food product	LED used	Tested microorganisms	Quality and mode of action	Major findings	References
		epidermis for antimicrobial study	fermented blueberry extract		
White mushrooms and commercial ready-to--eat (fully cooked) sausages	Three UV-C LEDs (280 nm) were combined; working distance-3 cm; varied duty cycle; irradiance, 1 to 5 J/cm^2, continuous and pulsed irradiation	*E. coli* O157:H7 (ATCC 35150, ATCC 43889, and ATCC 43890), *Salmonella enterica* serovar Typhimurium (ATCC 19585, ATCC 43971 and DT 104), and *Listeria monocytogenes* (ATCC 19111, ATCC 19115, and ATCC 15313)	LED treatment reduced formazan formation levels in *E. coli* and *Listeria*; pulsed LED produced more ROS and membrane lipid peroxidation compared to continuous irradiation; no significant effect on membrane damage but effect on membrane potential of *E. coli* and *Listeria*	Continuous and pulsed irradiation resulted in the following inactivation, respectively: *White mushrooms:* *E. coli*, 2 and 2 log CFU/g; *Salmonella*, 1 and 1.5 log CFU/g; *Listeria*- 1 and 1.8 log CFU/g *RTE sausages:* *E. coli*, 2 and 3 log CFU/g; *Salmonella*, 1.5 and 4 log CFU/g; *Listeria*, 2 and 4 log CFU/g	Kim and Kang [50]
Cooked chicken	405 ± 5 nm LED; working distance, 3 cm; surface intensity on cooked chicken 22.0 ± 1.1 mW/cm^2; dose, 1.58-3.80 kJ/cm^2; treatment times, 20-48 h; illumination temperature, 4, 10, and 20 °C	*Salmonella enterica* Enteritidis (124, 125, and 130)	*Salmonella* cells incapable of cellular repair at 4 °C	0.8–0.9 log CFU/cm^2 reduction on cooked chicken in all *Salmonella* spp. with 3.8 kJ/cm^2 dose at 4 °C; growth delays observed at 10 and 20 °C	Kim et al. [57]
Smoked salmon	460 nm LEDs; working distance, 9 cm (intensity of 15 mW/cm^2) to 5.4 cm (intensity of 58 mW/cm^2); dose maintained at 2400 J/cm^2	Four serotypes of *Listeria monocytogenes*		0.7–1.2 log CFU/cm^2 reduction with LED treatment in combination with riboflavin (25, 50, and 100 mM)	Josewin et al. [47]
Ready-to-eat fresh Salmon	405 nm LEDs; radiation intensity, 26 ± 2 mW/cm^2; working distance- 4.5 cm	*Listeria monocytogenes* inoculated on salmon exudates	LED treatments effective in reduction of *Listeria* during the biofilm formation	LED treatment produced 2–2.8 log reduction in planktonic cells on stainless steel or acrylic coupons in salmon exudates during 8 h storage	Li et al. [72]
	405 nm LED; intensity, 16 ± 2 mW/cm^2; treatment time, 8 h; illumination temperature, 4 and 12 °C; working distance −7.9 cm	*Listeria monocytogenes* and *Salmonella enterica* serotype Enteritidis, Typhimurium and Newport	LED treatment produced insignificant color change; it improved the sensitivity of the bacteria to simulated gastric fluid	Reduction of 0.4 and 0.3 log CFU/cm^2 in *L. monocytogenes*; reduction of 0.5 and 0.4 log CFU/cm^2 in *Salmonella* at 4 and 12 °C, respectively	Li et al. [73]

LEDs emitting blue light (400 nm–480 nm) were tested for their ability to destroy pathogens in orange juice and milk [35, 120]. A 2 to 5 log reduction of *Salmonella* was observed in pasteurized orange juice inoculated with a cocktail of *Salmonella* and treated with a 460 nm LED at different irradiance and temperature combinations [35]. Conditions that produced the highest *Salmonella* inactivation were 92 mW/cm^2 with very long treatment time of 13.6 h at a huge energy dosage of 4500 J/cm^2 at 12 °C. Authors maintained the irradiance of 92, 147.7 and 254.7 mW/cm^2 by adjusting the distance of the sample from the 460 nm LED and used a total dosage of 4500 J/cm^2 for the treatment by regulating the treatment times corresponding to 13.6, 8.46 and 4.91 h, respectively. The long treatment time and the enormous energy used on products during LED treatments need to be justified if this technology using UV-A and blue light pulses should be developed for commercial disinfection of food products. One approach would be exploring the use of this technology for other applications (e.g., heating or drying, as huge energy used will heat and remove water from products) along with microbial inactivation, simultaneously.

Srimagal et al. [120] compared the inactivation of *E. coli in milk* using blue LEDs at 405, 433, and 460 nm at 5, 10, and 15 °C and treatment times of 0 to 90 min. Microbial inactivation was highest at elevated temperatures and lower wavelengths, with a maximum of 5.27 log CFU/ml reduction of *E. coli* O157:H7 after 60 min irradiation at 405 nm. The 460 nm LED resulted in a 2 to 5 log reduction, with a stronger effect on bacterial inactivation at higher temperatures, similar to the findings reported in Ghate et al. [35]. Both these studies noticed significant changes in food product colors (orange juice and milk) after exposure to blue LEDs, suggesting that the blue LED altered the quality of the liquid foods. LED lights in the blue range lower bacterial activity mainly through photodynamic inactivation (PDI) of the microorganisms. The photons produced with the LED light can be absorbed by endogenous photosensitizers (e.g., porphyrins, cytochromes, flavins) and NADH in bacteria, which are sensitized after being illuminated [29, 77] as described in the "LED Fundamentals" section. Srimagal et al. [120] reported an optimum condition (405 nm, 13.8 °C, for 37.83 min) under which treated milk was pasteurized with no change in physicochemical properties in comparison to untreated milk. Also, when refrigerated, the shelf-life of the treated milk increased significantly to almost twice of that of untreated milk.

A recent study published by Akgün and Ünlütürk [2] examined the *E. coli* K12 inactivation by UVC-LED at 254 (0.3 mW/cm^2) and 280 nm (0.3 mW/cm^2), and UVC-LED coupled with 365 (0.8 mW/cm^2) and 405 nm (0.4 mW/cm^2) (UVA-LED) in both cloudy and clear apple juice. The combinations of emission wavelengths included 280 nm/365 nm, 280 nm/405 nm, 254 nm/365 nm, 254 nm/405 nm, and 254 nm/280 nm/365 nm/405 nm. The highest antimicrobial activity was achieved when the cloudy apple juice was treated with 280 nm alone and a 280 nm/365 nm combination, with log reductions of 2.0 ± 0.1 and 2.0 ± 0.4 log CFU/mL, respectively, on LED treatment of 40 min. A significantly greater inactivation was observed in the clear apple juice than in the cloudy apple juice. The highest log reduction was obtained at 4.4 log CFU/mL in the clear apple juice treated solely with 280 nm (771.6 mJ/cm^2, 40 min). The hybrid system treated with 280 and 365 nm UV-LEDs resulted in log reductions of 3.9 ± 0.2 log CFU/mL, similar to the 280 nm treatment of cloudy apple juice for the same treatment time (40 min). It was also demonstrated that these hybrid LED treatments showed better inactivation effects on polyphenol oxidase. Even though the fully pasteurized state (~ 5 log reductions) could not be accomplished in apple juice by the combined UVA and UVC LEDs, this study suggests that UVA and UVC LEDs have a synergistic potential for disinfection, with a potential to preserve food colors. An additional disinfection effect might be obtained by increasing the dosage of the UVA and UVC LEDs. The higher efficiency of the UV LED combination and their low energy consumption make them more advantageous than traditional mercury lamps for polyphenol oxidase inactivation. Studies on the inactivation effect of LEDs on liquid systems are listed in Table 3.

Blue light and UVC combined with UVA-LEDs has shown synergistic effects in terms of bacterial inactivation and the preservation of food quality. The nature of liquid foods (particle size, turbidity, and color), the dosage, the time irradiated, and the temperature should be optimized when performing LED decontamination of liquid foods. LEDs combined with other nonthermal technologies, or with mild thermal treatments, should be explored to improve decontamination efficacy.

LED Treatment of Water

Safe drinking water is of global importance, particularly in countries with limited resources. Around 1.2 billion people do not have access to uncontaminated drinking water [104]. Millions of people die every year from waterborne diseases [12]. Waterborne microorganisms cause intestinal infections such as diarrhea, typhoid, cholera, dysentery, amebiasis, salmonellosis, shigellosis, and hepatitis A [38]. Conventional approaches to treat wastewater involve the application of chemicals and considerable energy, which makes them expensive and inaccessible for many societies. Advanced water treatments in developed countries are also costly, involving thermal treatments, chemical disinfections (chlorination, ozone, chlorine dioxide, chloramination), and metals ions (Ag and Cu) to reduce the microbial content [10, 11, 20, 53, 80, 124]. Besides being expensive, conventional methods of water disinfection are often ineffective and unsustainable. Thus, efficient, economical, and robust technologies that have minimal detrimental effects on the environment continue to be investigated for their application to water disinfection and decontamination [12].

More than 7000 municipal UV disinfection systems have been installed worldwide [118], and small disinfection systems are available for domestic use [13]. Water disinfection using UV light has several advantages over conventional disinfection approaches. UV light has antimicrobial efficacy, produces minimal residue and by-products, has low environmental impact, and is compatible with current industrial processes [5, 19, 22, 26, 82]. Unlike chemical water treatments, UV water treatment does not produce drug resistant bacteria [85]. Disadvantages of conventional UV sources include easy breakage and a need for careful disposal, as the mercury lamp can pollute the environment.

Song et al. [119] reported the inactivation of microorganisms such as *E. coli* and coliphage MS2 in laboratory water, and *E. coli* and total coliform in wastewater, with continuous and pulsed 265 nm LED treatments. The inactivation levels of

Table 3 The antimicrobial efficacy of LED in liquid system

Tested food product	LED used	Tested microorganisms	Quality and mode of action	Major findings	References
Suspension in suitable buffers	UV-A LED (365 nm); working distance, 20 mm	*E. coli* DH5α, Enteropathogenic *E. coli*, *Vibrio parahaemolyticus*, *Staphylococcus aureus*, and *Salmonella enterica* serovar Enteritidis		3.9 log reduction in *E. coli* DH5α with 54 J/cm^2 dose; the inactivation was higher at the illumination temperature of 20 °C and pH 8 and varied for different bacterial species	Mori et al. [85]
Suspension in PBS	UV-A LED (365 nm); maximum current of one diode was 0.5 A, the voltage was 4.5 V; intensity was 70 mW/cm^2, working distance, 2 cm	*E. coli* DH5α, Enteropathogenic *E. coli*, *Vibrio parahaemolyticus*, *Staphylococcus aureus* and *Salmonella enterica* serovar Enteritidis	Oxidative DNA damage observed (2.6 folds higher 8-OHdG formation); involvement of ROS like OH^- and H_2O_2 observed in the LED inactivation effect	*E. coli* DH5α, Enteropathogenic *E. coli*, *Vibrio parahaemolyticus*, *Staphylococcus aureus* were reduced by > 5 log CFU/ml by 75 min treatment with 315 J/cm^2 dose; *Salmonella* was reduced by > 4 log CFU/ml with 672 J/cm^2 dose for 160 min with UV-A LED	Hamamoto et al. [39]
Ultrapure water, nutrient water and nutrient water with humic acids	UV LEDs (269 and 276 nm); sample volume 25 ml with stirring	*E. coli* K12		3 to 4 log CFU/cm^3 reduction observed; presence of humic acids and turbidity affected the UV irradiation and inactivation caused; 269 nm LED was more effective	Vilhunen, Särkkä and Sillanpää [126]
Bacterial suspension in PBS	265 nm LEDs; placed over a 6.5 mm wide aluminum channel 1 mm above the water surface; water depth, 7 mm; treatment dose, 0 to 20 mJ/cm^2	*E. coli* K12		> 3 log CFU/ml reduction with 20 mJ/cm^2 dose of UV LED treatment	Chatterley and Linden [17]
Bacterial suspension in appropriate buffers	255, 280, 365, and 405 nm LEDs; pH tested, 6 and 8; treatment times, 60, 120 and 180 s	3 strains of *E. coli* and 2 strains of *E. faecalis*	pH did not show any significant effect	280/365 and 280/405 nm combination of LED treatment were most effective for bactericidal effect; 20 h after the UV irradiation all the tested samples showed 7 log reduction in all treated strains	Chevremont et al. [21]
Bacterial suspension in deionized water	269 and 282 nm LEDs	*Bacillus subtilis*		269 nm LED produced better germicidal effect than 282 nm LED treatment	Rtele et al. [129]
Water samples from tertiary effluent from the City of Regina wastewater treatment plant (WWTP) and bacterial suspension in suitable broth	260 nm UV LEDs	*E. coli* ATCC 25922		High turbidity of WWTP resulted in inconsistent effect; 1–2.5 log reduction obtained with 20 and 50 min treatment in a time dependent manner	Nelson et al. [91]
Bacterial suspension in PBS	UV LEDs emitting wavelengths 265, 280 and 310 nm; 0.7, 1.3	*E. coli* K12		310 nm LED showed least antibacterial effect in batch system; 265 and	Oguma et al. [92]

Table 3 (continued)

Tested food product	LED used	Tested microorganisms	Quality and mode of action	Major findings	References
	and 1.1 mW output power, respectively; used for treatment individually and in combinations			280 nm LEDs produced ~4 log reduction in both batch and flow-through system with dose of 10.8 and 13.8, and 16.4 and 25.5 mJ/cm^2, respectively	
Bacterial suspension in 0.9% saline solution	UV-C LED (281.8 nm); Glass tube (quartz) and soda lime glass; 9 ml of bacterial suspension; treatment times, 10, 40, and 90 s; doses, 8.64, 34.59, and 77.82 mJ/cm^2	*Escherichia coli* DSM 498 *and Bacillus subtilis* DSM 402		Quartz glass had better transmittance of light; *B. subtilis* was reduced by 1.04 (soda lime glass) and 1.79 log CFU/ml (quartz glass) and, *E. coli* was reduced by 1.85 (soda lime glass) and 2.8 log CFU/ml (quartz glass) with 90s treatment; mixing of the samples improved the inactivation	Gross et al. [37]
Bacterial suspension in appropriate buffer	260 nm (UV) LEDs and low pressure UV lamp	*Escherichia coli* B, a non-enveloped virus (MS-2), and a bacterial spore *Bacillus atrophaeus*		Comparable inactivation efficacy for *E. coli* B and MS-2; LED produced better inactivation for *Bacillus atrophaeus*; dose required for 4 log reductions for UV LEDs were as follows: *E. coli* B, 6.2 mJ/cm^2; MS-2, 58 mJ/cm^2, and *B. atrophaeus*, 18.7 mJ/cm^2	Sholtes et al. [114]
Bacterial suspension in 0.05 M NaCl	Semi-commercial LED arrays (270–740 nm); treatment time, 6 h	*Escherichia coli* K12 ATCC W3110 and *Enterococcus faecalis* ATCC 19433		270, 365, 385, and 405 nm arrays produced > 5 $\log_{10}$ reduction; 430 and 455 nm LED arrays resulted in ≈4.2 and 2.3-$\log_{10}$ reduction in *E. coli* and *E. faecalis* cell counts; 310 nm produced insufficient disinfection doe commercial application; 525, 590, 623, 660, and 740 nm arrays produced insignificant disinfection	Lui et al. [76]
	Four UV-LED units emitting wavelengths 265, 280 nm, the combination of 265/280 (50%), and 265/280 (75%)	*E. coli*	Photoreactivation and dark repair decreased in case of 280 nm LED treatment	265 nm LED resulted in the maximum inactivation	Li et al. [70]
Microbes in appropriate buffers	UV-C LED emitting 260 and 280 nm LED and 260/280 nm combination used for treatment	*Escherichia coli*, MS2 coliphage, human adenovirus type 2 (HAdV2), and	DNA and RNA damage observed for individual LED treatments	Over 3 log reduction observed in *E. coli* with all UV LEDs; 260 nm LED was most effective in the inactivation of	Beck et al. [9]

Table 3 (continued)

Tested food product	LED used	Tested microorganisms	Quality and mode of action	Major findings	References
		Bacillus pumilus spores		MS2 coliphage; A dose of 122, 89, and 105 mJ/cm^2 of 260, 280, and 260/280 nm LEDs required for 4-log reduction; 260 and 260/280 nm LED more effective for *B. pumilis* inactivation	
Real wastewater samples and suspension in laboratory water	UV LED (265 nm); sample volume, 50 ml; frequency tested, 0.1, 1, 10, 100, 1 kHz; duty rate-10, 25, 50, 75, 90%	*E. coli* ATCC 11229, coliphage MS2 ATCC 15597-B1		No significant difference in the microbial inactivation observed between continuous and pulsed LED treatments	Song, Taghipour and Mohseni [119]
Dechlorinated tap water	UV LED (285 nm)	Heterotrophic plate count (HPC)		UV LED treatment showed decreased HPC for 5 days storage; *Methylobacterium* species was UV resistant	Oguma et al. [94]
Bacterial suspension in sterile distilled water	UV-A (365 nm) and UV-C (265 nm) LEDs; treatment times, 20 or 30 min (UV-A) and 5–16 min (UV-C); sample volume, 15 ml	*E. coli* (ATCC 25922, ATCC 700891, ATCC 15597, and ATCC 700891)	UVA pre-radiation showed: Insignificant effect in photo repair of bacteria; suppressed dark repair; no role of hydroxyl radical in the inactivation; improved CPD formation only in *E. coli* ATCC 15597	Synergistic effect of UV-A and UV-C was effective for *E. coli* (ATCC 11229, ATCC 15597, and ATCC 700891)	Xiao et al. [131]
Microbes in appropriate buffers	UV LEDs (265, 280, and 300 nm)	*Pseudomonas aeruginosa* and *Legionella pneumophila*, *E. coli*, *Bacillus subtilis* spores, and bacteriophage Qb		Energy consumption was least for 280 nm LED for 3 log reduction; linear curve observed for *L. pneumophila* and bacteriophage Qb; sigmoidal curve observed for *E. coli*, *P. aeruginosa*, and *B. subtilis* spores	Rattanakul and Oguma [107]
UHT skim milk (< 0.5% fat)	405 (NUV-Vis), 433 and 460 nm (blue) LEDs; illumination temperature, 5–15 °C; treatment time, 0–90 min	*E. coli* ATCC 25922	No significant effect on physicochemical properties of the LED treated milk	Highest inactivation at higher temperature and lower wavelengths; 406 nm LED treatment at 13.8 °C for 37.83 min can yield 5 log reduction with minimal color change	Srimagal, Ramesh and Sahu [120]
Clear and cloudy apple juice	Four UV LEDs emitting wavelengths 254, 280, 365 and 405 nm; working distance, 1 cm; sample volume, 3 ml	*E. coli* K12 (ATCC 25253)	Highest inactivation of PPO enzyme obtained by 280/365 and 280/405 nm LED treatment; lowest color difference observed with 280/365 nm LED combination	UV LEDs most effective in clear apple juice; highest inactivation in cloudy apple was ~2 log CFU/ml by 280 nm and 280/365 nm LEDs; 280 nm LED produced 4.4 log reduction in clear apple juice	Akgün and Ünlütürk [2]
Colored beverages and two different commercially	UV-A LED (365 nm); intensity, 70 mW/cm^2; coloring pigment concentrations, 0.001,	*E. coli* DH5α	Increasing the concentration of coloring agents	Maximum log reduction was 1.75 log CFU/ml in the beverage containing 0.001% β carotene;	Lian et al. [74]

Table 3 (continued)

Tested food product	LED used	Tested microorganisms	Quality and mode of action	Major findings	References
available orange juices (A and B)	0.01, 0.1, and 1.0%; treatment time, 30 min; dose, 126 J/cm^2		decreased the antibacterial effect	orange juices (A and B) showed 0.35 and 1.58 log reduction, respectively	
Orange juice	Blue (460 nm) LED; irradiances used, 92, 147.7, and 254.7 mW/cm^2; illumination temperatures, 4, 12, and 20 °C	Cocktail of *Salmonella enterica* serovars Gaminara, Montevideo, Newport, Typhimurium, and Saintpaul	Significant color changes observed	2–5 log reduction observed in *Salmonella* cocktail; best treatment conditions obtained was an irradiance of 92 mW/cm^2 for 13.58 h corresponding to dose of 4500 J/cm^2 at 12 °C	Ghate et al. [35]

all microorganisms were similar for both continuous and pulsed LED treatments at different pulse patterns under equivalent UV energy dosage. The pulsed LED treatments inactivated microorganisms as effectively as pulses produced by conventional xenon lamps, providing high output thermal management for water disinfection. Inactivation of pathogenic bacteria (*Legionella pneumophila*, *Pseudomonas aeruginosa*) and surrogate species (*Bacillus subtilis* spores, bacteriophage Qβ, *E. coli*) was reported with UV-LEDs emitting light of different wavelengths (265, 280, and 300 nm) and compared with bacterial inactivation with a conventional low pressure UV (LPUV) lamp emitting light at 254 nm. The kinetics of microorganism inactivation were determined mathematically with the help of LED energy response curves at different wavelengths using a multitarget model. The inactivation profile of each species showed either a linear or sigmoidal survival curve. LED treatments were more efficient than LPUV treatment for the inactivation of *P. aeruginosa*, *L. pneumophila*, and surrogate microorganisms in water. The 265 nm LED exhibited the most effective energy efficacy based on the inactivation rate constant of all the tested microorganisms except for *E. coli*. The 280 nm LED treatment consumed the least electrical energy to obtain a 3 log reduction of the microorganisms tested (0.15–1.11 kWh/m^3) compared to 265 and 300 nm LEDs (0.24–17.4 kWh/m^3) [107].

Li et al. [70] evaluated the inactivation of *E. coli* with 265 and 280 nm LED treatments, individually and in 265, 280 (50%) nm and 265, 280 (75%) nm combinations. A comparative study of *E. coli* photoreactivation and dark repair was also quantitatively conducted with LEDs and LPUV. The results showed that a 265, 280 nm LED combination did not have any synergistic effect on *E. coli* inactivation. Reactivation of the 265 nm LED treated bacteria was comparable to the LPUV-treated bacteria. *E. coli* treated with 280 nm LEDs at 6.9 mJ/cm^2 showed the lowest percentage of photoreactivation and dark repair. This study concluded that, in water, the 280 nm LED inactivated *E. coli* more efficiently than the 265 nm LED due to the additional output power of the former and its better inhibition of bacterial reactivation. The synergistic antimicrobial efficacy of 260 nm and the 280 nm LEDs was evaluated against *E. coli*, *B. pumilus* spores, MS2 coliphage, and human adenovirus type 2 (HAdV2), and its efficacy was compared with mercury vapor lamps at low and medium pressures. The 260 nm LED was the most suitable for the inactivation of MS2 coliphage, whereas a medium pressure UV lamp inactivated HAdV2 and *B. pumilus* more efficiently than other UV sources [8]. Similar observations were made in a study by Sholtes et al. [114], where the inactivation of *E. coli* B, *B. atrophaeus*, and MS2 were subjected to a 260 nm LED and low pressure UV lamps. *E. coli* B and MS-2 inactivation kinetics were similar with LED and LPUV treatments. For all UV radiation sources, the doses required for a 4 log reduction in microorganisms were higher for *B. atrophaeus* and MS2 than for *E. coli* B. Chatterley and Linden [17] treated *E. coli* in water with a 265 nm LED and conventional LPUV. The LED provided a higher antimicrobial efficacy than LPUV lamps but resulted in a higher disinfection cost. Gross et al. [37] reported water disinfection using a 280 nm LED to inactivate *E. coli* and *B. subtilis* with two different glass (soda lime and quartz) guided lights to increase the disinfection efficiency. Almost all the radiated light was guided to the samples due to total reflection. The rate and efficiency of disinfection of *B. subtilis* and *E. coli* were improved by this light-guided method.

E. coli inactivation was tested with respect to exposure time and LED fluence between batch and flow-through reactors at peak emissions of 265, 280, and 310 nm. Light wavelength combinations (265/310, 265/280/310, 280/310, and 265/280 nm) were tested for their inactivation efficacy [92]. The time-dependent inactivation efficacy was a maximum with 280 nm LEDs, while 265 nm LEDs exhibited the highest fluence dependent efficiency. In the batch system, 265 and 280 nm LEDs required a dose of 10.8 and 13.8 mJ/cm^2 for achieving 4 log reduction in *E. coli*. The 310 nm LED required

56.9 mJ/cm^2 dose for just 0.6 log inactivation. Lower inactivation efficacy and decreased output power were observed with combined emissions at 265/280, 265/310, 280/310, and 265/280/310 nm in a flow-through reactor. The 265 nm LED treatment efficiency in water disinfection was also time dependent [91]. The results indicated that the sample turbidity influenced the bacterial inactivation, and better efficiency was achieved in less turbid water samples. These results suggest that particle accumulation in liquids can protect microorganisms from UV light exposure.

Hamamoto et al. [38] disinfected water with UV-A LEDs (365 nm) and a low pressure UV-C lamp (254 nm). Inactivation of *Staphylococcus aureus*, *Vibrio parahaemolyticus*, enteropathogenic *E. coli*, and *E. coli* DH5α was greater than 3 log CFU/ml after 80 min of high energy UV-A LED treatment. This observation was supported in a study by Mori et al. [85], in which a 365 nm (UV-A) LED showed antimicrobial effects against *E. coli* DH5α, Enteropathogenic *E. coli*, *Vibrio parahaemolyticus*, *Staphylococcus aureus*, and *Salmonella* Enteritidis. Vilhunen et al. [126] observed the effect of 269 and 276 nm on *E. coli* inactivation in two photolytic batch reactors differing in the wavelength emitted with different test mediums, including ultrapure water, nutrient and water, and nutrient and water with humic acids. The LEDs were efficient for *E. coli* destruction even at low optical power. The study showed that the LED wavelengths were effective for *E. coli* inactivation, but the test medium did not have much impact on the inactivation.

Several studies have shown that UV LED can substitute for conventional treatment methods of water disinfection and that it provides benefits absent in conventional treatments. The most studied UV spectrum region for water disinfection is between 200 and 300 nm, with a wavelength of 265 nm the most commonly used wavelength and *E. coli* the most studied microorganism. Water disinfection with a single wavelength was compared with water disinfection using a combination of two wavelengths. However, the data were not consistent, so there was no conclusion made. The fact that different microorganisms respond differently to light energy of same wavelength can be ascribed to the UV light source, the fluence rate, the UV dose, and the exposure time. There is a need to develop a standard operating method to determine the dosage required for microbial inactivation in water [118], and to determine the mechanism of LED microbial inactivation.

Food Quality Changes During LED Treatment

Bacterial disinfection using LEDs in the UV or blue light range is a new nonthermal method for food processing. Most of the research has focused on microbial inactivation, with less emphasis on food quality and structural changes in food components. LED light produces reactive oxygen species (ROS) by photosensitizing light-absorbing molecules in the bacteria, which causes damage to lipids, proteins, cell membranes, and DNA, and results in cell injury and death [78]. However, ROS generated by LED light can modify the structure of food molecules, affecting their nutritional and sensory properties.

Kim et al. [59] evaluated the quality changes on the surface of fresh-cut mango treated with a 405 nm LED to test its antibacterial effects against *E. coli*, *Listeria monocytogenes*, and *Salmonella*. There was no significant difference observed between treated and untreated mango in terms of color, antioxidant capacity, ascorbic acid content, β-carotene, and flavonoids, regardless of the storage temperature. Likewise, there was no significant difference in the physicochemical properties of untreated milk and milk treated with a 406 nm LED (13.8 °C, 37.8 min). However, color changes in the treated milk were observed [120]. Ghate et al. [35] noted variations in orange juice color after exposure to a 460 nm LED. The authors ascribed the color change to the oxidative degradation of carotenoids, which have an absorption spectrum between 400 and 500 nm. Akgün and Ünlütürk [2] showed that UV LED treatment of apple juice led to microbial and enzymatic inactivation. The study also noticed apple juice color changes during LED treatment, with the lowest total color change being observed when 280 and 365 nm LEDs were combined in a single treatment.

A pulsed UV light energy dosage of more than 2.1 J/cm^2 produced a deterioration in the sensory quality of meat products [42]. LED light induced unfavorable flavor development in milk samples due to its reaction with photosensitive compounds [15]. Research of functional and structural changes in food after LED decontamination treatments are scarce, and more investigation of food quality changes after LED illumination are needed.

Mechanisms of Inactivation

LEDs emitting visible light can excite light-sensitive compounds, e.g., porphyrins, present in the bacterial cell wall (Fig. 2). These excited compounds collide with, and transfer energy to, oxygen molecules, producing reactive oxygen species (ROS) such as hydroxyl radicals, hydrogen peroxide, and singlet oxygen. ROS further react with cellular components causing cell death [33, 34, 79].

Light energy in the 320–400 nm range can produce oxidative stress, protein damage, and inhibition or delay of growth without killing the microorganisms irradiated [136]. For instance, a 405 nm LED showed antibacterial activity against the gram-positive bacteria *Listeria monocytogenes*, *Bacillus*

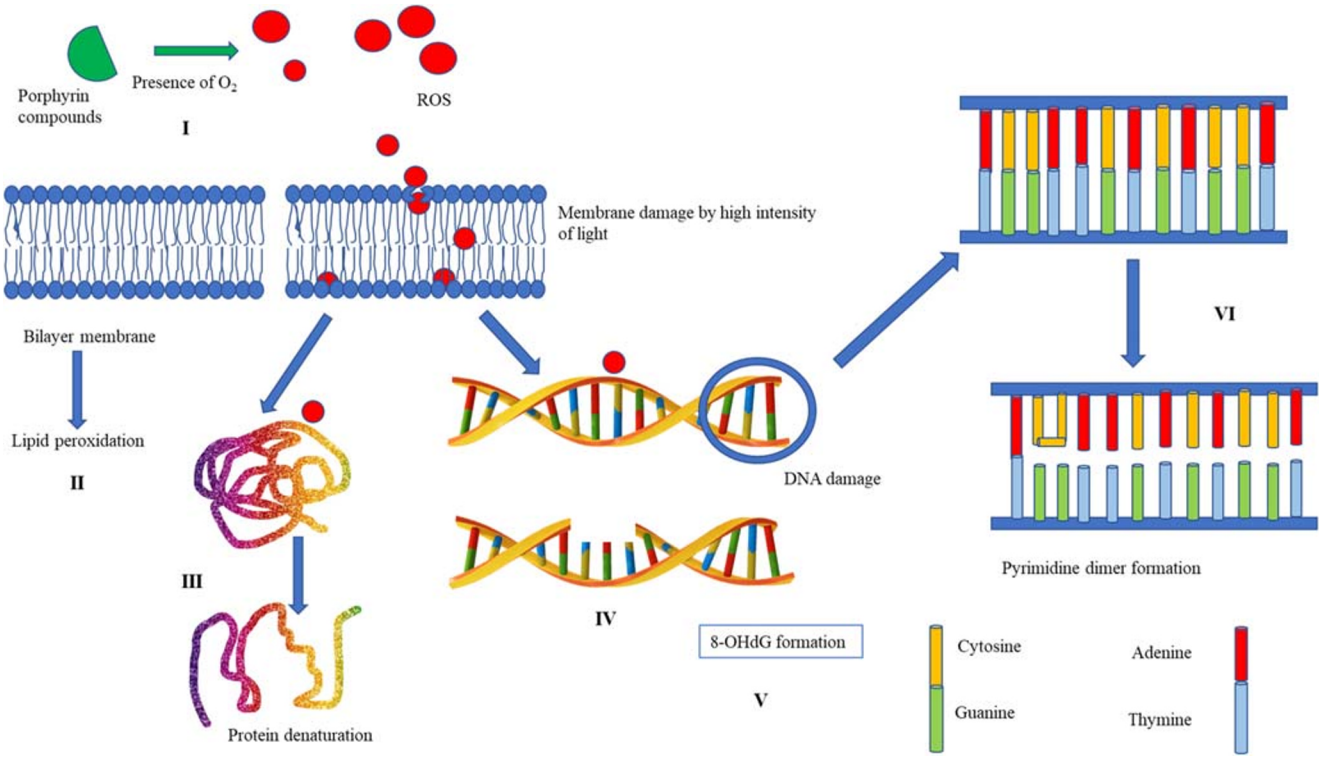

Fig. 2 Effect of LED treatments on bacteria, (I) porphyrin compounds in the bacterial cell wall absorb light and undergo photosensitization producing reactive oxygen species (ROS) in the presence of oxygen; ROS leads to (II) lipid peroxidation in the bacteria; (III) protein denaturation; (IV) DNA damage; (V) the ROS can oxidize the guanine bases leading to the production of 8-hydroxy-2′-deoxyguanosine (8-OHdG) indicating oxidative stress produced by LED treatment; and (VI) UV-C light can lead to the formation of pyrimidine dimers which can lead to inhibition of DNA replication

cereus, and *Staphylococcus aureus*, damaging the bacterial membrane, although the bacterial DNA was not damaged by the oxidative stress [54]. Kim et al. [55] also reported no DNA degradation in gram-positive and gram-negative bacteria after treatment of *L. monocytogenes, E. coli* O157:H7, *Salmonella* Typhimurium, and *Shigella* sonnei with a 405 nm LED. However, DNA oxidation and damages to efflux pump activity and the glucose uptake system due to ROS production were observed after LED treatment of *Salmonella* spp. with 405 nm LED at refrigerated conditions. In similar studies, refrigerated bacteria showed membrane damage, apart from the damage caused by the LED treatment [52]. ROS produced by LED illumination is believed to oxidize the guanine bases in DNA and peroxidate lipids in the cell membrane. However, no significant lipid peroxidation was observed, whereas DNA oxidation was observed, when fresh-cut papaya infected with *Salmonella* was subjected to a 405 nm LED; in the same experiment, the LED did not produce any significant effect on the organoleptic properties of fruit at refrigeration temperature [58]. Kim and Kang [50] observed no significant loss in the membrane integrity of gram-negative bacteria *E. coli* O157:H7 and gram-positive bacteria *L. monocytogenes* pulsed with a UV-C LED emitting light of wavelength 280 nm, whereas the membrane potential values were significantly changed. Moreover, a high membrane lipid peroxidation was observed in both the strains, but it was higher in *L. monocytogenes*. The LED treatments might reduce the activity of succinate-coenzyme Q, an electron transport chain enzyme involved in the production of energy and cell proliferation in bacterial cells [50]. This possibility was supported by LED illumination of *Pseudomonas aerugenosa* with wavelengths of 464 nm (blue), 528 nm (green), and 636 nm (red). The red and green LEDs did not inactivate the bacteria. A catalase A (enzyme that detoxifies hydrogen peroxide) mutant strain showed more sensitivity than the wild strain to the blue LED treatment, and overexpression of catalase A increased the sensitivity of the wild strain to the irradiation, indicating that hydrogen peroxide was a major ROS during the LED treatment [96]. Addition of the hydroxyl radical scavenger mannitol did not affect the inactivation of *E. coli* DH5α when treated with UV-A followed by UV-C LED, indicating that the hydroxyl radical might not have any role in the inactivation. On the contrary, it was observed that production of the hydroxyl radical and hydrogen peroxide had a major role in UV-A LED inactivation, as the reduction of *E. coli* DHα decreased with the addition of mannitol [39]. The cytotoxic response of bacteria to 405 nm LED treatment was further studied in *S. epidermidis*, where the antimicrobial effect of the LED was significantly decreased in the presence of sodium pyruvate (hydrogen peroxide scavenger), but a decrease was not observed in the presence of dimethyl thiourea (hydroxyl

scavenger). This suggests that hydrogen peroxide played a greater role than the hydroxyl radical in the microbial inactivation [106]. HPLC analysis by reversed-phase chromatography of *P. aeruginosa* samples showed expressed coproporphyrin III, suggesting the production of endogenous porphyrins in the bacteria, which would explain the photodynamic inactivation (PDI) effect of blue light [3].

Bacteria use defense mechanisms, such as DNA, photoreactivation, dark repair, biofilm formation, to respond to damage inducing UV LEDs. For instance, cyclobutene pyrimidine dimer (CPD) formation was enhanced in *E. coli* ATCC15597 due to a 265 and 280 nm LED hybrid irradiation. Also, the recA protein, a core protein in the repair of the cell after an SOS response, was overexpressed [131]. CPD generation in *E. coli* DHα was more pronounced with UV-C irradiation than with UV-A irradiation, which produced minimal *E. coli* DHα CPD, indicating that UV-A treatment induced less damage than UV-C treatment to *E. coli* DHα DNA [39]. LED treatment with 280 nm light inhibited the photoreactivation and dark repair compared to the more germicidal 265 nm light in normal conditions and these LED treatments further resisted the compromised DNA repair mechanisms in the bacteria [70]. These results are supported by an earlier study on the oxidative stress by NUV light on *S.* Typhimurium, where long exposure to low-intensity NUV light resulted in bacterial demise, probably due to oxidative stress and inhibition of the oxyR regulon, which plays a major role in triggering bacteria defense against stress. Long exposure to low-intensity NUV light also rendered the cells sensitive to further sterilization techniques [64].

Synergistic antimicrobial effects of sequential treatments with LEDs emitting light at different wavelengths have also been reported. Pre-treatment of different strains of *E. coli* with a UV-A (365 nm) LED UV-C (265 nm) LED treatment increased the level of UV-C inactivation [131]. Although the photoreactivation ability was not influenced by the pretreatments, the dark repair was inhibited. The hybrid 260/280 nm LED treatment caused no significant DNA or RNA damage and did not inactivate *E. coli* K12, MS2 coliphage, human adenovirus type-2, or *Bacillus pumilus* spores [9].

Visible light (400–700 nm) sensitized with curcumin and toluidine blue increased the inactivation of *Streptococcus mutans* more than light treatment or photosensitizers alone [98]. Red and blue LED treatment at 24 J/cm^2 sensitized with 0.75 mM and 25 μM curcumin/toluidine blue mixtures resulted in almost complete inactivation of *S. mutans* [99]. Red and blue visible light produced more ROS when photosensitizers were added, supporting the higher inactivation observed [14]. Similarly, the addition of ultrasound to UV-LED (254 nm) treatment enhanced the inactivation of *E. coli* ATCC15997 and also reduced the photoreactivation of the microorganisms tested [135].

The antimicrobial effects of LED varied with the bacteria treated. Gram-negative bacteria are encased in a thin peptidoglycan layer sandwiched between an inner and relatively impermeable outer membrane, which maintains the rigidity of the cytoplasmic membrane, whereas a thick peptidoglycan layer and a single membrane encase gram-positive bacteria [88, 113]. At high pH, the cytoplasmic membranes of gram-negative bacteria leaked, while gram-positive bacteria were resistant [83]. Ghate et al. [34] found that the gram-negative bacteria *Salmonella* and *E. coli* were sensitive to 461 nm LED treatment in alkaline pH, while the gram-positive bacteria *L. monocytogenes* were sensitive to 461 nm LED treatment in acidic conditions. *E. coli* O157:H7, *S.* Typhimurium, and *Shigella sonnei* were sensitive to bile salts after 405 nm LED treatment due to the loss of membrane integrity. The lack of an outer membrane probably made the gram-positive bacteria sensitive to acidic conditions and the solubilization of the outer membrane of the gram-negative bacteria made it more sensitive to the alkaline pH [34, 55]. *S. enterica* Enteritidis that contaminated cooked chicken were subjected to 405 nm LED on agar plates supplemented with antibiotics specific to cell wall, protein, DNA, and RNA. The 405 nm LED made these sites more sensitive to the antibiotics and the *S. enterica* Enteritidis were metabolically inhibited by 32.5, 24.2, 30.1, 44.1%, suggesting that the antibacterial efficacy was linked to cellular damage [57]. The inactivation of *E. coli* and the production of 8-hydroxy-2′-deoxyguanosine (8-OHdG) after UV-A (365 nm) LED treatment indicated that the presence of oxygen played a major role in the DNA damage, as the DNA damage was reduced significantly when the same experiment was performed under anaerobic conditions [39].

Possibly, light inactivates bacteria by activating prophages (bacteriophages in a dormant state) present in the bacterial genome. In methicillin-resistant *S. aureus*, 460 nm LED treatment induced upregulation of phage-related genes, activating prophages into phages and thus causing cell lysis [133]. Adenovirus, a resistant waterborne pathogen residing in both treated and wastewater systems, consists of core proteins that play a major role in the adenovirus infection of a host [110]. Possibly, UV light produces its antimicrobial effects by damaging viral proteins. This hypothesis was supported when UV light of less than 240 nm from a germicidal UV spectrum lamp damaged viral proteins, inducing protein aggregation in adenovirus 2 [9]. The maximum reductions were observed in hexon and penton proteins. Proteins tend to absorb light of lower wavelengths, whereas nucleic acids tend to absorb light of higher wavelengths. Bacteriophage MS2 was more sensitive than Adenovirus type 41 to UV treatment. Adenovirus type 41 was resistant to UV light at 254 nm and its inactivation required a much higher dose, 225 mJ/cm^2 [61]. The addition of titanium dioxide (TiO_2) as a photocatalyst to UV-A light increased its antimicrobial efficacy against the murine norovirus, a surrogate of the human norovirus, while UV-B alone was effective in inactivating murine norovirus activity. Although a reduction in infectious viral particles was observed, there were no significant changes observed in viral

nucleic acids, indicating that the effect on other components, including proteins, in such viruses [67]. Although UV-LEDs emitting 285 nm light showed promising viral inactivation [93] more extensive research at different wavelengths is needed.

Both dormant and germinating stages of fungi show involvement of ROS and a requirement for the presence of oxygen, as the sensitivity of these fungi to 405 nm LED was reduced in the absence of oxygen and in the presence of ROS scavengers. All three fungi—*Saccharomyces cerevisiae*, *Candida albicans*, and *Aspergillus niger* (conidia)—showed the presence of intracellular porphyrin, indicating the involvement of photodynamic inactivation (PDI) in fungi. *S. cerevisiae* showed inactivation even in anaerobic conditions in the presence of ROS scavengers and showed significantly higher inactivation in aerobic conditions, suggesting the involvement of components other than porphyrins in *S. cerevisiae* inactivation [87]. Synergistic use of UV-A (365 nm) light and riboflavin produced phenotypic changes in the fungi *C. albicans* and *Fusarium solani*, such as a lower growth of biofilm and color variations, where biofilm formation is a synergistic microorganism response to any stress [48].

LED light of different wavelengths inactivates microorganisms, mainly by activating the production of ROS and inhibiting microorganism defense mechanisms. The extent of LED damage depends on the microorganism targeted, the wavelength and dose of the light, and surrounding conditions. More research on the inactivation mechanisms of LEDs at different wavelengths is required.

Other Applications of LED Technology

UV-C Treatment

LEDs emitting light in the UV-C range, 210–270 nm, have been developed since 2010 [134], and have been applied in air disinfection systems to inactivate nebulized viruses, bacteria, and fungi [51]. Ultraviolet germicidal irradiation lamps reduced viable microorganisms and endotoxins in the central ventilation system of an office [84]. A UV-C LED in the 275–285 nm range showed antimicrobial efficacy against *E. coli* W3110, *P. aeruginosa* PAO001, *S. marcescens* NBRC 3046, *S. aureus* NBRC 12732, and *C. albicans* IFM 40009, microorganisms that frequently contaminate solutions used for intravenous infusions [95]. Longer treatment times are required when UV-C LEDs are used in low dosage; however, the development of higher power UV-C LEDs will lead to their wider use in the disinfection of water and food products.

UV-B Treatment

UV-B LEDs (280–320 nm) are applied in the phototherapy of psoriasis, a common skin disease. UV-B light has also reduced the powdery mildew in cucumber due to the pathogen *Podosphaera xanthii* [123].

UV-A Treatment

LEDs emitting light at 365 nm (UV-A) have been used to disinfect air. Two stable currents of UV-A LED (1.2 mW/cm^2, 0.5 A, or 0.2 mW/cm^2, 1.0 A) applied for 75 min resulted in a 3 log reduction of *E. coli* DH5α in air [32]. UV-A LED light sources are also being developed for suitable therapeutic applications in human skin [100]. UV-A LEDs have found applications in curing polymers, in medicine, and in air disinfection. UV-A LED light at 380–420 nm emits low heat, an advantage in curing applications.

Near-UV-Visible LED Treatment

UV light near the visible region (~ 395–405 nm) (NUV-Vis) has several applications. NUV-Vis LEDs emitting light at 405 nm have been used for tooth bleaching [60]. LEDs in the NUV range are being developed for curing, as an alternative to mercury lamps [81]. Their curing ability has also found use in 3D printing and adhesive curing.

Visible LED Treatment

LEDs emitting light in the visible range have been evaluated in dental implantations, wound healing, and algaculture. Titanium dioxide (TiO_2) is generally used as a photocatalyst in dental applications when UV light is used [97, 105]. TiO_2 was codoped with nitrogen and bismuth to increase its antimicrobial activity when the LED was used in the visible range of 420 to 690 nm. TiO_2 doped with Bi showed promising antimicrobial effects on the biofilm-producing bacteria *Streptococcus sanguinis* and *Actinomyces neaslundii* on the surface of dental implants [89].

Visible LEDs have been shown to improve algaculture. Increases in biomass production of *Pichoclorum atomus* were the highest when irradiated with red, followed by blue, yellow, purple, and green LEDs, while the green LED produced the maximum lipid content from the algal species [43]. Blue, green, red, and white LEDs increased the biomass production of a *Spirulina* sp. LEB 18 culture (food supplement) [103]. The ability of green LED treatment to yield high lipid content in microalgae cultures has been reported extensively [105, 116]. A red LED increased the biomass and a blue LED enhanced oil formation in a mixed culture of *Chlorella* sp. and *S. cerevisiae* [115]. The ability of visible LEDs to enhance algaculture makes them suitable for biodiesel production. Particular applications of visible LEDs are discussed in "Blue LED Treatment," "Red LED Treatment," and "Coupling Different LEDs" sections.

Blue LED Treatment

LEDs made of indium gallium nitride (InGaN) and gallium nitride (GaN) emit blue light of 450–500 nm. Blue LEDs are used to treat water with or without photocatalysts [19] and to disinfect medical instruments. A blue LED emitting light of 455 ± 30 nm enhanced the antimicrobial effect of curcumin in the oral cavity [69]. An LED emitting blue light showed antimicrobial effects against the periodontopathic species *Porphyromonas gingivalis* and its biofilm when used in combination with 0.1% riboflavin as a photosensitizer. However, this antimicrobial effect was significantly less than that of a red LED [7]. Blue LEDs with a color intensity of 96.8 μmol photon/m^2/s facilitated maximum biomass production from *Chlorella vulgaris* microalgae [31]. Blue LEDs improved biomass production in *Synechococcus nidulans* LEB 115 cultures by 80% and improved lipid production in *Chlorella fusca* LEB 111. Chlorophyll pigments and carotenoid accumulation in the latter increased with an increase in light intensity [28]. *Chlorella vulgaris* showed maximums in specific growth rate and lipid production when treated with at 200 μmol/m^2/s with a blue LED and a 12:12 h L/D photoperiod [4]. A blue LED fostered the highest specific growth in *Nanochloropsis* spp. followed by white, green, and red LEDs [24]. The potential of blue LEDs in medical applications needs to be supported by data regarding their mode of action. However, they have proven to be effective in enhancing the specific growth of microalgae, which can be used for biofuel production.

Red LED Treatment

Red light from 610 to 760 nm is emitted by LEDs with aluminum gallium arsenide semiconductors. The germicidal effect of red LEDs has been found to accelerate the wound healing process in mice, and is used to disinfect appliances [108, 127]. A red LED (660 nm) in combination with toluidine blue O (TBO) reduced *Streptococcus oralis* in dental plaques in a dose-dependent manner [45]. After treatment with 0.25% hydrogen peroxide, *Porphyromonas gingivalis* biofilms (associated with periodontitis) were reduced by LED light in the red spectrum (625–635 nm) [30]. As an algaculture application, a red LED (660 nm) was more effective than blue and white LEDs in improving the specific growth rate and increasing the cell concentration of *Chlorella* sp. [23].

Coupling Different LEDs

The synergistic effect of LEDs emitting light of different wavelengths has been tested in biodiesel production and algaculture. Abomohra et al. [1] combined blue and red LEDs to enhance biodiesel production and lipid productivity in the microalga *Scenedesmus obliquus*. *Isochrysis galbana* is food for several bivalve larvae and has been studied for biomass and lipid production in a two-phase system by Che et al. [18]. The authors used a 50:50 ratio of blue (465 nm) and red (640 nm) LEDs in the first phase for biomass culture and a green (520 nm) LED in the second phase for lipid production. Maximum biomass and lipid content were obtained at a light intensity of 400 μmol/m^2/s and a photoperiod of 18.6 h L/D (light/dark) cycle. Hun et al. [44] also observed that a combination of blue and red LEDs improved biomass production and photosynthetic pigments and that a green LED improved lipid production in four microalgae (*Phaeodactylum tricornutum*, *Isochrysis galbana*, *Nannochloropsis salina*, and *Nannochloropsis oceanica*). In a three phase culture study of *Nannochloropsis oceanica*, a blue LED (465 nm) was used in the first phase to study the microalgal growth parameters, a green LED (550 nm) was used in the second phase for lipid production, and temperature stress was used in the third phase to increase the production of mono and polyunsaturated fatty acids [116]. The synergistic effects of combined blue and red LEDs for biomass production, and combined blue, red, and green LEDs for lipid production have been established. However, the antimicrobial efficacy of combining multiple wavelengths in areas other than food and water disinfection needs more attention. LEDs emitting light in the UV range are replacing mercury lamps in curing applications, while red, blue, and green LEDs are frequently applied in biodiesel production and algaculture.

Challenges and Opportunities

LEDs are mercury-free and their consistent light irradiance and high efficiency is an improvement on the performance of the traditional UV lamp. Efficient UV-A, NUV, and visible LEDs are available for research and industrial work, but UV-C LEDs need to be improved with respect to output degradation of sticking resin and adhesive die, and reduced reflection of reflectors [86]. The heat generated within LED devices during operation can cause device damage and wavelength shift. Continuous irradiation results in an increase in the LED temperature, necessitating a large heat sink to control temperature. A pulsed irradiance (1 to 20 pulses per second) can significantly reduce the rate of temperature rise [119]. Radiant energy supplied in pulses can be changed based on need.

Since, LED is a surface treatment, the shadowing effect of multiple layers of bacteria in a treated material can result in a lower bacteria inactivation rate. Thus, proper exposure of a bacterial sample to the LED light during treatment must be ensured [68]. The penetration depth of UV light is only few millimeters and depends on the surface and optical properties of the target. Therefore, the experimental design must consider the LED antimicrobial efficacy, particularly when targeting solid/liquid foods. The design of UV-A LED food/liquid

treatments must also consider the high capability of microorganisms to regenerate after treatment [76].

The high LED doses required to kill microorganisms in food can have a detrimental effect on the quality of the treated products. A dosage of more than 2.1 J/cm^2 of pulsed UV light energy resulted in sensory quality deterioration in meat products [42]. As light reacts with photosensitive compounds, and a high-intensity light source can cause a temperature rise in the target, unfavorable flavors in target foods can develop during UV LED treatments; this is frequently observed in the treatment of milk [15].

UV-C LEDs provided nonthermal food treatments that resulted in few changes in color, flavor, and vitamins during treatments of fruit juices [49, 111]. Apart from providing microbial decontamination, subjecting foods to blue LEDs improved the chlorophyll levels in pea seedlings, and red LEDs were observed to increase β-carotene in the leaves and stems of pea seedlings [130]. The use of a combination of LEDs emitting light at different wavelengths can improve the antimicrobial effect. For instance, UV-C induces pyrimidine dimer formation and UV-A delays the DNA repair mechanism of microorganisms, and can also kill microorganisms by inflicting oxidative damage [21, 74]. The use of chlorine with a UV-LED improved the inactivation rate of *B. subtilis* spores by approximately two-fold compared to the use of the UV-LED alone [71]. Thus, other decontamination methods and photosensitizers can be used in combination with UV-LEDs to improve the inactivation of microorganisms and spores.

LEDs require further research to improve their ability to disinfect water. UV-C LEDs are the most commonly utilized to disinfect water, but their low power output, low energy conversion efficiency, and high cost has hindered a large-scale adoption of UV-C LEDs. In the conversion of electrical energy to light energy, a high proportion of UV-C LED electrical energy is converted to heat, which must be immediately removed to cool down the LED junction. The heat production of LEDs during operation wears out system components and subjects the targets to damaging heat. Therefore, durable, heat resistant, cost effective LED components need to be carefully selected, and the LED system must be designed to release heat efficiently to avoid operational failure.

Previous research has focused on LED treatments of stagnant water. LED treatments of large volumes of flowing water would be more useful for real life conditions. Water depth plays a major role in decontamination. Longer wavelengths can penetrate deeper to achieve microbial inactivation. The turbidity of the targeted sample plays a major role in the overall efficiency of the LED treatment. Inorganic matter in a water sample absorbs the light, reducing the light available for disinfection. The particles that constitute the turbidity also shield the microorganism targets of the LED. Such factors are familiar to LED researchers and optimization studies are ongoing. The light wavelength used must provide enough energy to eliminate the LED target in spite of being inhibited by turbidity and the absorption of light by nontargeted components in the medium.

Concluding Remarks

Light-emitting diodes (LEDs) are an emerging technology for various applications in food processing, including disinfection of solid and liquid food products and water; this technology offer several benefits to food processors including, no toxic waste generation, durability, robustness, monochromatic light production, customization depending on the final application, compared to conventional sources of light. UV-C LEDs are mainly used to kill microorganisms in water, and UV-C LED units for portable applications such as water sterilization bottles, disinfection of medical equipment, are available in the marketplace. The selection of LEDs for economical water disinfection is based on microorganism inactivation efficacy and low electrical energy consumption. Simultaneous and sequential LED treatments, utilizing different combinations of LEDs, are used to achieve maximum disinfection levels in water and foods. Microorganism species respond differently to light at different wavelengths, and more research is needed to understand this differential response, and to select the LED treatment that fits the conditions at hand. Changes in food macromolecules during LED treatments are also under continued investigation. While, LEDs could be added as an additional treatment for microbial inactivation in food products and water in the future, the important factors influencing the disinfection efficacy of LEDs emitting light with different wavelengths and the mechanisms involved need further investigation.

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