Review

Pulsed light processing of foods for microbial safety

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Abstract

The demand for processed foods and the awareness about food quality and safety are increasing rapidly. The consumers’ demand for minimally processed foods and growing competition in the market have made the processors to adopt newer non-thermal technologies that preserve nutrients and sensory properties of the products. Conventionally, heat processing of foods is carried out to convert raw material into value-added product, reduce or eliminate microbial load to improve safety, and extend shelf life. Some of the limitations of thermal processing techniques can be overcome by employing non-thermal processes. High hydrostatic pressure, pulsed electric field, ultrasound, cold plasma, dense phase carbon dioxide, ozone, and pulsed light (PL) processing are gaining popularity in food processing. PL technology is a non-thermal technology, where sterilization and decontamination are achieved by impinging high-intensity light pulses of short durations on surfaces of foods and high-transmission liquids. Although a few reports on the PL technology are available, in-depth studies on this are needed to adopt at a commercial level. The present review provides an overview of light-based processing of foods and covers important aspects such as different PL systems used for processing of foods, mode of action of PL on microbes, the effect of PL on liquid foods, surface decontamination of foods and parameters that affect PL efficacy, combination processing with PL. With the growing demand in non-thermal processing for the technological advancement in the area of generation of light, light-based processing will be a promising technology for microbial load reduction.

Key words: Pulsed light; Food safety; Non-thermal processing; Minimally processed; Microbial load.

Introduction

As the human evolution progressed, the way food being consumed and their priorities have also been evolved. The consumption of processed foods is on the rise due to change in lifestyle, particularly in urban areas. Traditional thermal-based food-processing methods such as appertization, pasteurization, and canning have been dependent on high temperature, to ensure prolonged shelf life and food safety. Although thermal processes are efficient tools for microbial inactivation, they also contribute to undesirable changes in food matrix such as structural alteration of proteins and polysaccharides, production of free radicals, affecting the functionality of food and flavour, textural softening, and destruction of colours and vitamins (Devlieghere et al., 2004). High-temperature short-time processes, electromagnetic radiation-based microwave, radio frequency heating, and ohmic heating techniques have gained focus in the recent past as alternative and rapid heating techniques to minimize the severity of heat treatment and thereby enhance product quality.

Over the past few years, consumer demand for fresh, natural, and minimally processed foods with better quality has increased. To address this, researchers are working on developing alternative techniques that not only meet the consumer demand but also energy-efficient, cost-effective, and rapid. Many novel technologies that do not involve heat processing have been developed to inactivate...
microorganisms. The novel non-thermal technologies such as high hydrostatic pressure (HHP), pulsed electric field (PEF), ultrasound (US), cold plasma, dense phase carbon dioxide, ozone, and pulsed light (PL) processing are gaining popularity in food processing. These technologies hold several promises by preserving the delicate sensory and nutritional qualities of food and hence used for minimal processing of food products (Ortega-Rivas and Salmerón-Ochoa, 2014). These technologies offer several advantages compared to thermal processing by minimizing the effect of heat on food and minimization of flavour loss (Norton and Sun, 2008; Soliva-Fortuny et al., 2009; Chawla et al., 2011; Misra et al., 2011; Rastogi, 2011; Thirumadas et al., 2015; Wang et al., 2016). Among the non-thermal technologies, one of the emerging technologies is light-based processing. The present review deals with the usage of this technology for microbial load reduction in foods.

**PL Processing**

PL technology is a non-thermal technology, where decontamination of foods such as fruit juices, meat products, vegetables, and fruits is achieved by using high-intensity light pulses for a short duration of time. The PL includes a wide wavelength range of 200–1100 nm, which includes ultraviolet (UV): 200–400 nm, visible (VIS): 400–700 nm, and near-infrared region (IR): 700–1100 nm (Elmnasser et al., 2007; Palgan et al., 2011). The term pulsed light is known since 1980 and was first adopted by the US Food and Drug Administration (FDA) for food processing in 1996 (FDA, 1996). To increase the safety of fruit and vegetable juices, US FDA regulations have implemented 5-log pathogen reduction process (US FDA, 2004). Significant microbial reduction in very short treatment time, low environmental impact, and its high flexibility are some of the major benefits of PL (Uesugi and Moraru, 2009; Oms-Oliu et al., 2011). Xenon flash lamps are more environment-friendly than continuous-wave UV lamps as they do not use mercury (Gomez-Lopez et al., 2007). One of the big advantages of PL over static UV treatment is that the fact that the energy is delivered in a very short time (Sauer and Moraru, 2009; Chaine et al., 2012). PL systems have relatively low operation costs and generate only reduced amounts of solids wastes (Pereira and Vicente, 2010). The benefits include reduced risk from foodborne pathogens on public health, extended the shelf life of the product, and improved economics during food distribution (Ozer and Demirci, 2006). PL has potential applications in food processing that requires a rapid disinfection where overheating and a reflecting cylinder. Paskeviciute et al. (2011) and Luksiene et al. (2012) constructed high-power PL device in their laboratory having a chamber, a reflector with a flash lamp, and a power supply for chicken, vegetable, and fruits decontamination, respectively. Sharma and Demirci (2003) and Ozer and Demirci (2006) conducted the experiment to decontaminate the alfalfa seeds and fish fillets, respectively, using a PL sterilization chamber containing treatment chamber, UV strobe, tray, and a control module. Similarly, Bialka and Demirci (2007) used a laboratory scale, batch PL system for decontamination of blueberries with slight modification in the set-up having a quartz window and a cooling blower. PUV treatment was carried out in the continuous flow-through system for inactivating *Staphylococcus aureus* in milk. The system included a UV chamber, UV lamp, pump with variable flow rate, and V-groove reflector (Krishnamurthy et al., 2007).

Choi et al. (2010) designed a laboratory-scale PL system for non-thermal sterilization of infant foods. They used water bath as a cooling device to dissipate the heat generated during the discharge by quartz lamp and oscilloscope to view the exponential decay pulse. Cheigh et al. (2013) designed a laboratory-scale PL system consisting a xenon lamp used to produce intense pulsed light (IPL) with an emission spectrum in the range of 200–1100 nm for inactivating *Listeria monocytogenes* on solid medium and seafoods (Figure 1). Hwang et al. (2015) designed an IPL treatment unit for microbial inactivation of various liquid samples, which had a pulse generator and a spectroradiometer to determine the irradiance of xenon lamp, cooling system (fans) on either sides of the lamp to dissipate the generated heat. Similarly, Yi et al. (2017) also self-designed a laboratory-scale IPL for describing the IPL inactivation curves of *Pseudomonas aeruginosa* under different pulse conditions. Hwang et al. (2017) constructed a pilot-scale IPL device by upgrading the xenon lamp and power supply. Sesame seeds inoculated with per the literature reports available, the three major commercial companies producing disinfection systems based on PL are SteriBeam Systems from Germany, Xenon Corporation from USA, and Claranor from France. Experiments conducted by Hierro et al. (2011), Lasagabaster et al. (2011), Ramos-Villarroel et al. (2014), Maftei et al. (2014), Koh et al. (2016a),Moreira et al. (2017), and Valdivia-Najar et al. (2017) are associated with SteriBeam, whereas results reported by Keklik et al. (2010), Wambura and Verghese (2011), Pataro et al. (2011), Muñoz et al. (2011), Gómez et al. (2012a,b), Xu et al. (2013), and Huang and Chen (2014) were obtained with a Xenon Corporation device, mainly the model SteriPulse™.XL 3000. Artiguez et al. (2011), Levy et al. (2012), Nicorescu et al. (2013), Manzocco et al. (2014), Ignat et al. (2014), Fernández et al. (2016), and Rajkovic et al. (2017) carried out the experiment with the PL system from Clarmonar with multiple xenon lamps. MacGregor et al. (1998) used a PL generator including rectangular PVC housing, pulse generator, and a control circuit for bacterial inactivation. This bench-top experimental facility had two inoculated Petri dishes inclined at 45° received equivalent doses. Takeshita et al. (2003) studied the damage caused by PL on *Saccharomyces cerevisiae* using the system similar to that designed by Dunn et al. (1995) having power supply unit and a flash lamp that produce PL consisting of intense flashes of broad-spectrum white light (200–1000 nm). Fine and Gervais (2004) used One-Shot EN2/2143-1 unit, a 3-fluidized bed as a PUV system having adjustable air nozzles and compressed air that allows tangential blowing for fluidization of the food powders; flash lamp surrounded by a quartz jacket with water circulation to limit lamp overheating and a reflecting cylinder. Paskeviciute et al. (2011) and Luksiene et al. (2012) constructed high-power PL device in their laboratory having a chamber, a reflector with a flash lamp, and a power supply for chicken, vegetable, and fruits decontamination, respectively. Sharma and Demirci (2003) and Ozer and Demirci (2006) conducted the experiment to decontaminate the alfalfa seeds and fish fillets, respectively, using a PL sterilization chamber containing treatment chamber, UV strobe, tray, and a control module. Similarly, Bialka and Demirci (2007) used a laboratory scale, batch PL system for decontamination of blueberries with slight modification in the set-up having a quartz window and a cooling blower. PUV treatment was carried out in the continuous flow-through system for inactivating *Staphylococcus aureus* in milk. The system included a UV chamber, UV lamp, pump with variable flow rate, and V-groove reflector (Krishnamurthy et al., 2007).

**PL Treatment Systems for Microbial Load Reduction**

The pioneer company producing PL equipment for application in water purification systems and virus inactivation systems for biopharmaceutical manufacturers is Purepulse Technologies Inc. (San Diego, California), a subsidiary of Xenon Corp., which commercialized the PureBright™ system (Dunn et al., 1995). As
bacteria, moulds, and yeast were treated using this PL system. Pataro et al. (2011) carried out microbial-inactivation experiments using a laboratory-scale continuous-flow PL apparatus which consisted of a linear Xenon flash lamp, power/control module, sterilization chamber, photoelectric detector module, and cooling system (Figure 2). Ferrario and Guerrero (2016) performed PL treatment in apple juice with the help of a continuous flow-through PL system. Caminiti et al. (2011b), Muñoz et al. (2012), and Chaine et al. (2012) also used a continuous flow-through PL system for processing liquids like fruit juices and sugar syrup.

**Mode of Action of PL on Microbes**

UV was the only agent responsible for the inactivation of pathogens and no antibacterial effect attributed to IR or VIS light was found (Paškevičiūtė and Lukšienė, 2009; Ramos-Villarroel et al., 2014; Kramer et al., 2015). In addition, it has been shown that both the VIS and IR regions of PL in combination with its high peak power also contribute to the destructive effect on microorganisms (Elmnasser et al., 2007). The antimicrobial properties of UV light on bacteria are attributed to absorption of radiation by conjugated carbon–carbon double bonds in nucleic acids and proteins, and subsequent DNA structural changes (Ramos-Villarroel et al., 2012). Cheigh et al. (2013) identified the cell damage on the foodborne pathogen, *L. monocytogenes* treated with UV-C and IPL with the help of transmission electron microscopy (TEM). UV-C–treated *L. monocytogenes* cells were similar in structure to that of untreated cells except for a blurry and indistinct cell wall (Figure 3). In contrast, IPL-treated cells showed the destruction of cell wall structures, cytoplasm shrinkage, and rupture of the internal organization leading to leakage of cytoplasmic content and ultimately to cell death (Cheigh et al., 2012). But, conversely, Krishnamurthy et al. (2010) concluded that *S. aureus* treated with PUV had cell wall damage, disintegration, cellular content leakage, cytoplasmic membrane shrinkage, and also found that internal cellular structures were collapsing. Cheigh et al. (2012) also indicated that the IPL treatment was effective in reducing the bacterial population in *L. monocytogenes* and *Escherichia coli* O157:H7 than continuous UV-C irradiation. However, despite a high energy density and broad spectrum (with wavelengths including the UV-C region), IPL treatment exerted milder photochemical effects on the cells (e.g. the formation of double-strand breaks) than did UV-C irradiation. Levy et al. (2012) mentioned that PL had a better effect than continuous UV treatment for *Aspergillus niger* spores. Similarly, Orlowska et al. (2013) also found 5-log reduction of *E. coli* in water at 10 mJ/cm² for continuous mercury lamps and at 5 mJ/cm² for pulsed lamps. Nicorescu et al. (2013) studied the effect of PL on the structural differences in *Bacillus subtilis* inoculated on powdered spices with the help of scanning electron microscopy (SEM). The cell membrane was disrupted clearly forming deep craters in the cell wall after PL treatment, whereas it was contrary in the case of *B. subtilis* treated in suspension (Figure 4). The cell wall disruption may be due to photothermal stress and germicidal action caused by the PL having a UV component. It altered the DNA structure by decreasing supercoiling of DNA and then breaking into a single strand that in turn leads to cell death (Nicorescu et al., 2013). Xu and Wu (2016) studied the structural difference in *E. coli* treated with PL and confirmed that the structural changes in membrane integrity of *E. coli*, leading to flattening of cells, can be due to heating of intracellular fluid, and UV light absorption by bacteria.

**Figure 1.** Schematic diagram of the intense pulsed light (IPL) system (Cheigh et al. 2013).

**Figure 2.** Schematic diagram of the continuous flow PL system (Pataro et al., 2011).
health status. Inactivation of these pathogens on liquid food complexes are mentioned in Table 1. PL processing is influenced by various factors that dictate its efficiency on microbial inactivation, retention of quality, and other properties of the product. Important factors that determine the effectiveness of PL is the fluence level applied on the sample, the amount of energy (dose or number of pulses) and wavelength of light/composition of the spectrum (Ramos-Villarroel et al., 2012). Inactivation of microbes is higher for PL treatment with higher pulse number and higher intensity (MacGregor et al., 1998; Maftei et al., 2014; Ramos-Villarroel et al., 2014). It is indicated that when the spectral range of the PL treatments, particularly the UV component, is altered by using filters, the inactivation of *E. coli* and *Listeria innocua* is lower (Ramos-Villarroel et al., 2012). And among the sub-divisions of UV, UV-C–containing spectrum was more effective in inactivating *B. subtilis* and *A. niger* spores (Levy et al., 2012). Absorption of light, particularly in the UV region, and shielding of microbes by suspended matter are significant limiting factors in PL treatment of microbes in liquid substrates (Sauer and Moraru, 2009). PL has very limited penetration depth in opaque media and is capable of targeting the surface microorganisms. *Penicillium expansum* inactivation efficiency of PL treatment dramatically decreased from 3.21 to 1.58 log colony forming units (CFU)/ml when the depth of apple juice was increased from 6 to 10 mm (Maftei et al., 2014). Inactivating effect of PL treatments against *P. expansum* was greatly depended on the microbial load that is 1.30 and 3.2 log reduction for 3 × 10⁴ and 2.3 × 10⁴ CFU/ml, respectively, for inoculated juice samples (Maftei et al., 2014).

The susceptibility trend is reported to be Gram-negative bacteria > Gram-positive bacteria > bacterial spores > fungal spores (Rowan et al., 1999; Anderson et al., 2000; Levy et al., 2012). *S. cerevisiae* was found to be the most resistant strain to PL treatment than *L. innocua*, *E. coli*, and *Salmonella enteritidis* in PL-treated apple juice system (Ferrario et al., 2015b). In contrast, Nicorescu et al. (2013) have reported that bacteria is more resistant than yeast for PL treatment, whereas viruses are more resistant to PL treatment compared to bacteria (Huang et al., 2017). Gram-negative bacteria, *E. coli,* is more susceptible to PL when compared to Gram-positive bacteria, *L. innocua,* which may be due to the presence of distinguishing structural/compositional variation in the cell walls of these bacteria (MacGregor et al., 1998; Otaki et al., 2003; Ramos-Villarroel et al., 2011; Ramos-Villarroel et al., 2012). *E. coli* is more sensitive to UV-C treatment than *L. monocytogenes* as the Weibull model parameters also confirms, which is a better fit compared to the linear model for evaluation the microbial inactivation (Bialka and Demirci, 2008; Bialka et al., 2008; Chun et al., 2010). *Bacillus* is more susceptible than mesophilic bacteria, and *L. innocua* is more resistant than *Pseudomonas fluorescens* to PL at low temperature and low fluence levels (Luksiene et al., 2012; Hilton et al., 2017). Hilton et al. (2017) indicated that PL treatment effectiveness is independent of temperature for *E. coli* and *P. fluorescens* in clear liquid substrates within the temperature range of 5–40°C. However, in the case of *L. innocua*, the effect of temperature and PL was observed at 50°C. Higher PL resistance shown by *Listeria* spp. compared to *Pseudomonas phosphoreum* and *Serratia liquefaciens* could be related to the presence of photoreactive substances and protective compounds that contribute to the antimicrobial effectiveness of PL (Lasagabaster and De Maranon, 2012). Ramos-Villarroel et al. (2011) mentioned that IPL sensitivity by microorganisms may be related to differences in bacterial cell wall composition due to their protective and repair mechanisms against the damage. PL induced

**Figure 3.** TEM of *L. monocytogenes*: (A) untreated, (B) treated with 150 pulses (30 s), (C) treated with 900 pulses (180 s) with IPL at a fluence of 1.75 mJ/cm² per pulse, and (D) treated for 1000 s with UV-C at 254 nm (Cheigh et al., 2013).

can be attributed to overheating, intercellular water vapourization, and subsequent membrane disruption. PL processing is a multi-target process in which both photothermal/photophysical and photochemical effects are caused, thus alteration in cell membrane disruption/leakage of cell content and chromosomal DNA damage occurs, respectively (Cheigh et al., 2012; Ramos-Villarroel et al., 2012; Nicorescu et al., 2013).

**Effect of PL on Liquid Foods**

PL processing is being applied on various liquid products for decontaminating the foodborne pathogens that affect the human
sublethal injury of \textit{S. cerevisiae} cells at low doses up to 12 J/cm\textsuperscript{2} (Ferrario \textit{et al.}, 2014). PL treatment causes sublethal damages which make cells more sensitive to stress in subsequent stages such as storage at low temperature (Lasagabaster and de Marañón, 2014).

In contrast, PL did not cause any sublethal damage to the bacterial cells such as \textit{E. coli}, \textit{L. monocytogenes}, \textit{S. Typhimurium}, and \textit{V. parahaemolyticus} (Hierro \textit{et al.}, 2012). \textit{Listeria} and \textit{Salmonella} were not found to have the ability to repair the cell damage induced by

| Table 1. The effect of PL treatment on microbial inactivation in liquid foods. |
|---------------------------------|---------------------------------|------------------|-----------------|-----------------|
| **Food product** | **Microorganism** | **Treatment** | **Log reduction** | **Reference** |
| Milk | \textit{S. aureus} | 3 pulses/s and 1.27 J/cm\textsuperscript{2}/pulse; distance from the UV light strobe 5–11 cm; flow rate 20–40 ml/min | 0.55–7.23 log CFU/ml | Krishnamurthy \textit{et al.} (2007) |
| Apple juice | \textit{E. coli} ATCC 25922 | Frequency 3 pulses/s and pulse width 360 µs: fluence 12.6 J/cm\textsuperscript{2} | 2.66 log CFU/ml | Sauer and Moraru (2009) |
| Apple cider | \textit{E. coli} O157: H7 | Frequency 3 pulses/s and pulse width 360 µs: fluence 12.6 J/cm\textsuperscript{2} | 2.52 log CFU/ml | |
| Apple juice | \textit{L. innocua} | Frequency 3 pulses/s (pulse width 360 µs) of 100–1100 nm width, approximately, 1.21 J/cm\textsuperscript{2}/pulse; PL fluence of 4 J/cm\textsuperscript{2} | 4 log CFU/ml | Pataro \textit{et al.} (2011) |
| Orange juice | \textit{E. coli} | Fluence of 6 J/cm\textsuperscript{2} | 2.9 log CFU/ml | |
| Orange juice | \textit{L. innocua} | Fluence of 6 J/cm\textsuperscript{2} | 0.93 log CFU/ml | |
| Sugar syrup | \textit{B. subtilis} spores | Pulses (250 µs); fluence 1.5 J/cm\textsuperscript{2} | 4.2 log CFU/ml | Chaine \textit{et al.} (2012) |
| Sugar syrup | \textit{S. cerevisiae} | Fluence 1.23 J/cm\textsuperscript{2} | 5.4 log CFU/ml | |
| Sugar syrup | \textit{G. stearothermophilus} spores | Fluence 1.86 J/cm\textsuperscript{2} | >4 log CFU/ml | |
| Sugar syrup | \textit{A. acidoterrestris} spores | Fluence 1.2 J/cm\textsuperscript{2} | 3 log CFU/ml | |
| Sugar syrup | \textit{A. niger} | Fluence 1.2 J/cm\textsuperscript{2} | 1.3 log CFU/ml | |
| Infant food | \textit{L. monocytogenes} | Width 1.5 µs; operating time 0–600 s; 2300 µs treatment | 1 log CFU/g | Choi \textit{et al.} (2010) |
| Infant food | | 4700 µs of treatment | 2 log CFU/g | |
| Infant food | | 9500 µs of treatment | 3 log CFU/g | |
| Milk | \textit{E. coli} | 200–1100 nm, 3 Hz and 360 µs, 1.17 J/cm\textsuperscript{2}/pulse at a distance of 2.5 cm: 7–28 J/cm\textsuperscript{2} | 0.61–1.06 log CFU/ml | Palgan \textit{et al.} (2011) |
| Milk | \textit{L. innocua} | 200–1100 nm, 3 Hz and 360 µs, 1.17 J/cm\textsuperscript{2}/pulse at a distance of 2.5 cm: 7–28 J/cm\textsuperscript{2} | 0.51–0.84 log CFU/ml | |
| Milk | \textit{S. Typhimurium} | 200–1100 nm, 3 Hz and 360 µs, 1.17 J/cm\textsuperscript{2}/pulse at a distance of 2.5 cm: 7–28 J/cm\textsuperscript{2} | 0.51–1.73 log CFU/cm\textsuperscript{2} | |
PL through photoreactivation mechanism (Paskeviciute et al., 2011). Sublethal damage of bacteria cells by PL treatment confirmed that membrane damage is one of the important causes for bacterial inactivation, apart from microbial DNA damage, depending on the energy dose and sensitivity of light pulses (Pataro et al., 2011).

Additionally, distance of the sample from the light source, treatment time, volume of the sample, geometry of the treatment chamber, orientation, and design of lamps are also the critical factors that are to be optimized in order to accomplish maximum effectiveness of the PL treatment (Gomez-Lopez et al., 2007; Krishnamurthy et al., 2007; Ignat et al., 2014; Xu and Wu, 2016). Inactivation effects of IPL treatment on L. monocytogenes showed significant inactivation compared to UV-C treatment due to higher penetration depth and emission power of IPL (Cheigh et al., 2013). Food parameters that influence PL effectiveness for microbial inactivation are reflection coefficient, intrinsic transparency and surface condition of the item, thickness, colour, viscosity, moisture content, turbidity, light transmissivity, the presence of particulate material, and flow conditions of the product (Choi et al., 2010; Artiguez et al., 2011; Ferrario and Guerrero, 2016). Indeed, physicochemical factors such as chemical composition, total soluble compounds, pH and light absorbance (especially due to compounds as carotenoids) could potentially protect the microorganisms from the PL treatments, and thus different microbial inactivation levels are achieved (Valdivia-Najar et al., 2017). As the total solids in reconstituted milk increased, reduction levels of E. coli decreased by 2.0, 0.62, and 0.45 log CFU for 9.8%, 25%, and 45% total solids, respectively. The effect of optical properties of beverages on P. aeruginosa inactivation by IPL has been reported (Miller et al., 2012; Hwang et al., 2015). They found that beverages with higher transparency like apple juice, carbonated drink, and plum juice showed 7 log reductions with 12.17–24.35 J/cm², whereas grape juice, milk, and coffee showed a lower reduction value of 1–1.9 log CFU/ml with a fluence of 29.21 J/cm². Similarly, due to differences in transparency of the medium (1 mm thickness), lower inactivation levels of E. coli and L. innocua were also reported by Palgan et al. (2011) in milk (1275.2) and orange juice (79.7) when compared to apple juice (5.81) and maximum recovery diluent (0.74) with lower e.

PL was more efficient in the apple juice system with lower turbidity compared to orange and strawberry juices suggesting that higher turbidity of juices diminishes the PL efficiency (Ferrario et al., 2015a). Chaine et al. (2012) also observed lower inactivation of B. subtilis spores in sugar syrup (3 log reduction than in distilled water—4.6 log reduction) after exposure to 1.8 J/cm², PL under static conditions. They suggested that these differences in the light transmission in the UV-C region as the absorption coefficient of clear syrup at 254 nm resulted in 200-fold higher than that corresponding to distilled water. Ferrario et al. (2013) concluded that PL effectiveness is negatively influenced by the higher absorbance values of liquids in the UV-C region. Properties of food surface have an impact on decontamination efficiency (Kramer et al., 2017). Choi et al. (2010) found that inactivation of L. monocytogenes at 15 kV in infant meal (dark-coloured viscous product with 14% carbohydrates and 85.98% water) was effective (3 log reduction at 4800 µs) but lower than light-coloured, thin, infant beverage (5 log reduction at 3500 µs) which is due to the product characteristics. PL treatment efficiency was hindered by the presence of milk fat due to scattering of light by fat globules (Miller et al., 2012). Increasing levels of oil and protein reduced the killing efficiency of IPL since proteins have high absorption at about 288 nm and above of the UV region, lipids also absorb UV, decreasing the effective radiation dose on microbes. Hence, foods with high carbohydrates but poor in fats and proteins, such as fruits and vegetables, seem to be more appropriate for IPL processing (Gomez-Lopez et al., 2005).

Continuous flow-through PL of apple juice was more effective in inactivating microbes than batch mode PL (Muñoz et al., 2012; Ferrario et al., 2013; Ferrario and Guerrero, 2016). Chaine et al. (2012) mentioned that PL requires shorter residence time for microbial inactivation and subsequently higher flows of liquid foods could be treated using various parallel modules of PL treatment. In apple juice, a maximum reduction of 7.29 log CFU/ml was achieved for E. coli with high turbulence (3000 rpm) compared to 4.46 and 2.66 log CFU/ml for the treatment with low turbulence (500 rpm) and static treatment, respectively. For the same high turbulence treatment, inactivation levels of E. coli in apple cider of up to 5.49 log CFU/ml greater than low turbulence and about 3.2 log CFU/ml higher than static treatment was observed by Sauer and Moraru (2009). The use of turbulence enhanced the inactivation of E. coli in reconstituted milk by PL treatment (Miller et al., 2012). Thus, turbulence can significantly enhance the effectiveness of PL treatment, presumably by maximizing exposure of microbial cells to the incident light and could also disintegrate the clusters/clumps of microbial cells that lead to increasing microbial inactivation.

A high fluence of 26.25 J/cm² resulted in 3.2 log reduction in the total microbial count, and concomitantly, milk temperature was increased to 55°C, which indicated a combined effect of photochemical and photothermal damage of natural microflora by PL in raw milk (Innocente et al., 2014). E. coli and L. innocua counts were decreased by 24.7 and 1.93 log CFU/ml in apple juice treated with PL at 28 J/cm², and subsequent recovery of the cell was not observed even after 48 h (Palgan et al., 2011). Similarly, exposure of 17.5 kJ/m² fluence, PL found to decrease L. brevis population in apple juice by 3 log cycle (Ignat et al., 2014). PL did not affect pH, Brix, and non-enzymatic browning index, whereas it did slightly affect the colour of apple juice (Muñoz et al., 2012). Similarly, no change in colour, soluble substances, and pH of the product was reported until 53.3 J/g PL treatment in apple juice (Maftei et al., 2014). The results of the sensory studies conducted by Palgan et al. (2011) on reconstituted apple juice exposed to PL at 28 J/cm² fluence showed that there was no significant difference in terms of colour, sweetness, odour, or acidity of apple juice, but lowest score was observed for flavour compared to either control or samples treated with PL for a shorter time.

**Effect of PL for Surface Decontamination of Foods**

Various solid food products are being decontaminated by PL processing for producing safe food, which increases the shelf life of the products. Few of the examples are listed in Table 2. Log reduction values of E. coli and L. innocua reported by Ramos-Villarroel et al. (2014) showed that fresh-cut avocado treated at 305–1100 nm (2.74 and 1.35 log CFU/g, respectively) were higher than those of samples treated at 400 to 1100 nm (0.83 and 0.68 log CFU/g, respectively), indicating the antibacterial effect of UV component. Efficacy of PL treatment depends on the type of microbe, inoculum size, and inoculation site (Huang and Chen, 2014). Manzocco et al. (2014) studied the effect of inoculation site by inoculating Salmonella enterica in the pasta dough before rolling into sheet and after sheeting. They observed that log reduction was lower in the case of S. enterica inoculated in the dough before sheeting (0.8 log reduction) when compared to that of inoculated...
### Table 2. The effect of PL treatment on surface decontamination of foods.

| Food product                      | Microorganism                   | Treatment                                                                 | Log reduction | Reference                    |
|----------------------------------|---------------------------------|---------------------------------------------------------------------------|---------------|------------------------------|
| Fresh-cut melon                  | Enterobacteriaceae              | UV-C irradiance on melon cubes was 20 W/m² up to 10 min; fluence—1200 J/m²   | 2.61 log CFU/g| Manzocco et al. (2011)       |
|                                  |                                 | Fluence—6000 J/m²                                                         | 2.32 log CFU/g|                             |
|                                  |                                 | Fluence—12,000 J/m²                                                       | 2.14 log CFU/g|                             |
| Fresh-cut mushrooms              | E. coli                         | Full spectrum (λ = 180–1100 nm); total fluence of 12 J/cm²               | 3.03 log CFU/g| Ramos-Vallarroel et al. (2012)|
|                                  | L. innocua                      | Fluence of 6 J/cm²                                                        | 2.66 log CFU/g|                             |
|                                  | E. coli                         |                                                                           | 2.02 log CFU/g|                             |
|                                  | L. innocua                      |                                                                           | 1.77 log CFU/g|                             |
| Plum                             | B. cereus                       | Illumination spectrum was broad (200–1000 nm) and had maximal emission at | 1.4 log CFU/g | Luksiene et al. (2012)       |
| Tomato                           |                                 | 260 nm; duration of light pulse was 112 µs, frequency 5 Hz; UV light dose 5.4 J/cm² | 1.5 log CFU/g |                             |
| Cauliflower                      |                                 |                                                                           | 1.3 log CFU/g |                             |
| Sweet pepper                     |                                 |                                                                           | 1.8 log CFU/g |                             |
| Strawberry                       |                                 |                                                                           | 1.5 log CFU/g |                             |
| Ground caraway                   | B. subtilis                     | 200 to 1100 nm with pulse duration of 300 µs; treatment of 10 J/cm² (1 J/cm² × 10 flashes) | 0.8 log CFU/ml| Nicorescu et al. (2013)     |
| Ground black pepper              |                                 |                                                                           | 1 log CFU/ml  |                             |
| Ground red pepper                |                                 |                                                                           | 3.8–6.7 log CFU/g | Huang and Chen (2014)      |
| Blueberries                      | E. coli O157:H7                 | Wavelength of 180–1100 nm with pulse rate of 3 pulses and pulse width of 360 µs for 5–60 s: FL fluence of 5–56.1 J/cm² | 4.8–5.7 log CFU/g |                             |
| Spinach                          | L. innocua                      | 180 to 1100 nm with 17% of UV light, duration—0.3 µs and fluence—8 J/cm² | 1.85 log CFU/g| Aguero et al. (2016)        |
|                                  | E. coli                         |                                                                           | 1.72 log CFU/g|                             |
| Egg shells                       | S. enterica subsp.              | 200 to 1100 nm, with 20% of UV-C, 8% in UV-B and 12% in UV-A; treatments fluence of 2.1 J/cm² | 5 log CFU/egg shell | Lasagabaster et al. (2011) |
|                                  | enterica serovar Typhimurium    |                                                                           |                             |
| Beef carpaccio                   | E. coli                         | Duration of the pulse is 250 µs, 30% UV light, 30% infrared radiation and 40% visible light: fluencies of 0.7–11.9 J/cm² | 0.6–1.2 log CFU/ cm² | Hierro et al. (2012)        |
|                                  | S. Typhimurium                  |                                                                           | 0.3–1.0 log CFU/ cm² |                             |
|                                  | L. monocytogenes                |                                                                           | 0.3–0.9 log CFU/ cm² |                             |
| Tuna carpaccio                   | V. parahaemolyticus             |                                                                           | 0.2–1.0 log CFU/ cm² |                             |
|                                  | L. monocytogenes                |                                                                           | 0.2–0.7 log CFU/ cm² |                             |
| Fish products                    | P. phosphoreum                  | High-intensity pulses of 325 µs duration and wavelengths from 200 to 1100 nm, with about 20% of UV-C, 8% of UV-B, and 12% of UV-A region: one pulse fluence of 0.053 J/cm² | 5 log CFU/cm² | Lasagabaster and De Marañón (2012) |
|                                  | S. liquefaciens                 |                                                                           | 3.9 log CFU/cm² |                             |
|                                  | S. putrefaciens                 |                                                                           | 2.1 log CFU/cm² |                             |
|                                  | B. thermosphacta                |                                                                           | <1 log CFU/cm²  |                             |
|                                  | Pseudomonas                     |                                                                           |                             |
|                                  | L. innocua                      |                                                                           |                             |
| RTE meat products                | L. monocytogenes                | Pulse is delivered in 250 µs that correspond to a fluence of 0.7 J/cm²: total fluence applied 0.7–11.9 J/cm² | 1.01–1.61 log CFU/ cm² | Ganan et al. (2013)         |
| dry-cured loin                   | S. Typhimurium                  |                                                                           | 0.51–1.73 log CFU/ cm² |                             |
| Shrimp fillets                   | L. monocytogenes                |                                                                           | 0.89–1.81 log CFU/ cm² |                             |
| Salmon fillets                   | S. Typhimurium                  |                                                                           | 0.26–1.48 log CFU/ cm² |                             |
| Flatfish fillets                 | L. monocytogenes                | 1.75 ml/cm²/pulse; pulse duration-1.5 µs; frequency-5 Hz; fluence—6.3 to 12.1 J/cm² | 2.2–2.4 log CFU/g | Cheigh et al., (2013)       |
|                                  |                                 |                                                                           | 1.9–2.1 log CFU/g |                             |
|                                  |                                 |                                                                           | 1.7–1.9 log CFU/g |                             |

on the surface of egg pasta after sheeting (2.5 log reduction). Dip-inoculated produce was harder to be decontaminated than spot-inoculated ones due to infiltration of E. coli into the open surface structures of the produce (Xu et al., 2013). In contrary, at 8000 J/m² dose of UV-C irradiation, 2.16 log reduction was achieved in E. coli on ready-to-eat (RTE) salad surface, where it was 2.57 log cycle for L. monocytogenes (Chun et al., 2010). PL treatment did not show any significant difference in susceptibility of pathogen and mesophilic. At 5.4 J/cm² fluence of UV light, reduction by 2 and 2.4 log CFU/ml was observed for Listeria and Salmonella, respectively, on the chicken surface (Paskevičiute et al., 2011). Contrarily, Chun et al. (2009) reported that at 8000 J/m² dose of UV-C irradiation, 2.74 log reduction was achieved in L. monocytogenes on RTE ham, whereas it was only 2.02 and 1.72 log cycle for S. Typhimurium and Campylobacter jejuni, respectively. Whereas, one log reduction of E. coli and L. monocytogenes was achieved at the 60-s treatment of UV light at 8-cm distance in raw salmon fillets (Ozer and Demirci, 2006). Paskevičiūtė and Lukšienė (2009) concluded that the reduction of bacterial viability on the surface of chicken was a function of the light dose when the distance from the light source,
impulse repetition rate, and the voltage were constant. Only 0.99 log reduction of \textit{P. aeruginosa} was observed on sesame seeds when IPL treatment was applied, whereas 7 log reduction was observed in \textit{P. aeruginosa} inoculated mineral water. This large difference in reduction is mainly due to the matrix type; while all sides of sesame seeds could not be exposed to IPL because of shielding effect. The irregular surface of sesame seeds protected the hidden microorganisms from IPL so that microbial reduction would not increase regardless of the fluence applied (Hwang et al., 2017). Likewise, Moreaua et al. (2011) noticed the reduced effectiveness of PL in the case of peppercorn decontamination with \textit{B. subtilis} compared to that of decontamination on glass marbles that could be attributed to the non-uniform surface of the spice, which caused an insufficient microbial reduction. The surface topology plays a major role in PL treatment, as microbes can lodge on irregular surfaces and thus reducing that effect of PL in the target organism (Sauer and Moraru, 2009). PL treated at 5.4 J/cm² for raspberry and strawberry inactivated \textit{E. coli} by 3.0 and 2.3 log CFU/g and \textit{Salmonella} by 3.4 and 3.9 log CFU/g, respectively. Variation in the reduction of microbes on the surface of raspberry and strawberry can be attributed to shadowing/shielding effect (Bialka and Demirci, 2008). Due to shadowing/shielding effect, microbes on rough surface structures have the chance of being protected by PL, thus by hiding in the sub-surface structures (Nicorescu et al., 2013; Maftei et al., 2014). \textit{Salmonella} and \textit{E. coli} showed a higher reduction in blueberry (4.2 and 5.7 log reduction, respectively) compared to that on strawberry (2.1 and 1.9 log reduction, respectively) at 22.5 J/cm² due to the different topographical surface of the berries. The presence of achenes on strawberry could potentially shadow microorganisms from highly directional coherent PL beam from reaching its target leading to partial decontamination compared to the smooth skin of blueberries (Huang et al., 2017). Cauliflower being the most irregular surfaced vegetable was less decontaminated by PL than other fruits and vegetables, which is said to be due to the shielding effect of PL and thus the antimicrobial efficiency of PL exhibited clear dependence on surface irregularity (Luksiene et al., 2012). Koh et al. (2016a) studied the effect of cut type on fresh-cut cantaloupe treated with PL. They found that sample surfaces had significantly lesser microbial count compared to cuboid and triangular prism-shaped sample, which is due to area/volume ratio of the sample. Higher the area/volume ratio causes more wounds on the product, thus higher electrolyte leakage leading to increased microbial growth. A higher percentage of microbial inactivation of 50% was observed for sphere-shaped samples compared to the cuboidal or triangular prism, which could also be due to decreased scattering light around the edges of the sphere and lower shielding effect due to lower initial microbial load (Koh et al., 2016a).

Sample temperature was found to increase with an increase in pulses number, treatment time, and sample distance from the lamp (Wambura and Verghese, 2011; Ferrario et al., 2013). Wambura and Verghese (2011) observed 6°C temperature increase for every 10-s PUV treatment. Similarly, Ferrario et al. (2013) also found that temperature of fruit juice treated for 60 s with PL increased between 7.4 and 16.8°C. To dissipate the temperature changes due to sample heating, incorporation of the cooling systems in the equipment, external water-ethylene glycol cooling system can be adopted that limits the heating rate and final temperature of the product (Pataro et al., 2011). Huang and Chen (2014) and Huang et al. (2015) approached to overcome this limitation of PL by using wet PL treatment that is submerging the raspberries and blueberries in agitated water. This process provided the benefits of preserving the quality of fruits by reducing sample heating, uniform PL exposure, and physical removal of bacterial cells due to the agitation of the water. Colour discolouration was coupled with sample heating when blueberries treated with dry PL at 30 and 60 s (Huang and Chen, 2014). Thus, wet PL can be considered as one of the potential non-chemical alternatives to chlorine washing with higher efficacy and environmentally friendly process. To promote the quality of vegetables, and also to avoid shadowing effect of PL, wet PL treatment was carried out by Xu et al. (2013) for fresh produce like green onions. Wet PL treatment showed time-dependent log reduction for spot-inoculated green onions. However, wet PL treatment had no effect on time for dip-inoculated produce (<1.2 log reduction). At 30- and 60-s dry PL treatment on green onions, quality in terms of softer and shrunken tissue, colour, and smell were altered. Dry PL at 5 s was more effective than 60-s wet PL treatment (>4 log reduction) for \textit{E. coli} inactivation in green onions (Xu et al., 2013). Egg decontamination efficacy by PL could also depend on washing process before PL processing (Hierro et al., 2009). Higher \textit{Salmonella} decontamination was obtained in unwashed egg shells than washed ones which can be due to damage of egg cuticle that in turn provide a protective shielding against PL. Washing procedures (washing with soap and warm water followed by immersion in 70% ethanol and posterior eggshell flaming) could cause damage to the cuticle and thus facilitate cell penetration into pores and therefore protect bacteria being affected by light. Hierro et al. (2009) mentioned that there was a 2.49 log reduction of \textit{S. enteritidis} in unwashed egg shells. In contrast, a 5 log reduction in \textit{Salmonella} counts were observed in both washed and unwashed eggshells treated at 2.1 J/cm² fluence. Lasagabaster et al. (2011) used different washing procedure for eggshells (immersion in 70% ethanol) and even concluded that washing had no effect on PL antimicrobial effectiveness on the surface of eggshells and even did not detect any \textit{Salmonella} penetration into egg content. \textit{Salmonella} inoculated on eggshell was found to have photoreactivation mechanism, and hence Hierro et al. (2009) advised to store eggs that are PL treated away from light.

Inactivation efficacy of PL was similar for both total bacterial count (TBC) and total yeast and mould count (TYMC) as reported by Xu and Wu (2016). Whereas at the end of the 10-day storage, TBC and TYMC counts were significantly higher in PL 30 s than those in PL 5 s and PL 15 s, however, which was considerably lower than control. This greater number of microbes on PL 30 s may be because of structural damage of raspberry (softer texture) due to longer PL treatment that benefits microbial growth and a surface structure that affected the attachment of bacterial cells by protecting the pathogenic bacteria (Xu and Wu, 2016). The use of PL had reduced the amount of inoculated yeast cells on carrot slices by about three to four cycles (Kaae and Lyager, 2007), whereas it was 1.6 log cycles in apple discs exposed to PL (Gomez et al., 2012b), due to shielding of microorganisms by rough apple surface and internalization into apple tissue that could have a major influence on the inactivation pattern (Moreira et al., 2017). Similarly, reduction in the native microflora was lower than \textit{L. innocua} and \textit{E. coli} inoculated on spinach when treated with PL due to internalization of endogenous microorganisms. And the initial load of microflora was also significantly reduced, showing high efficiency for coliforms and its development was limited during refrigerated storage (Agiero et al., 2016). PL processing showed its capability to decontaminate and promote higher microbial stability during storage, thus increasing shelf life of the product (Ignat et al., 2014). During the cold storage, the counts of \textit{L. innocua} on fresh-cut tomatoes that

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were subjected to PL treatments did not significantly change through first 12 days of storage, whereas the gradual increase of _L. innocua_
counts on the untreated tomato slices were observed just after 4 days
(Valdivia-Nájar et al., 2017). Application of PL led to significantly
lower mesophilic aerobic count during the 14-day storage period
compared to untreated apple (Moreira et al., 2017). PL treatment
could inactivate microbial growth and hence, extended the shelf life
of treated samples by 8 days, as compared to untreated fresh-cut
cantaloupe (Koh et al., 2016a). Vacuum-packaged and -unpackaged
chicken frankfurters did not have any effect on log reduction of _L.
monocytogenes_ (maximum of 1.9 log CFU/cm²) with UV treatment
for 60 s at 5 cm; however, it caused colour and quality changes
in the samples (Keklik et al., 2009). Decontamination of _L.
monocytogenes_ in vacuum-packaged ham (1.78 log CFU/ cm²)
was higher than bologna (1.11 log CFU/ cm²) at 8.4 J/cm². PL-treated
vacuum-packaged ham extended the shelf life by an additional
30 days compared to the only vacuum-packaged ham, but the shelf
life of bologna was not extended by PL (Hierro et al., 2011).
Apples treated with PL were susceptible to surface browning
when compared to untreated samples (Moreira et al., 2017). PL
induces degradation of biopolymers in cell wall, affects the pectin
present in the cell wall, and cells appeared collapsed with ruptured
membranes and thus causing a rupture and folding of cell walls. This
membrane damage would increase in enzymatic browning reactions
like polyphenol oxidase activity due to greater tissue damage and
loss of functional cell compartmentalization (Gómez et al., 2012b).
Gómez et al. (2012a) also found changes in total profile analysis,
dynamic, and creep behaviour on apple surface due to PL treatment
and storage period. The use of PL at high fluences (28 J/cm²)
dramatically affects the final quality of fresh-cut mushrooms, and
thermal damage due to high PL doses seems to cause dehydration
and major textural modification. Enzymatic inactivation in PL-treated
samples flashed at that high dosage was also observed by
Oms-Oliu et al. (2010a). Similarly, Koh et al. (2016b) noticed that a
decrease in the pH and an increase in acidity were more pronounced
for untreated samples compared to PL-treated fresh-cut cantaloupes,
throughout the storage. Even, Koh et al. (2016a.b) found that there
was no effect on total soluble solids of fresh-cut cantaloupe at 4 ± 1°C
due to decreased respiration rate in chilled storage. Colour
was not negatively affected by PL treatment for fruits and vegetables
(Luksiene et al., 2012; Ignat et al., 2014; Agüero et al., 2016; Koh et
al., 2016a). However, change in colour of the endive salad and fresh-
cut avocados was more pronounced as the fluence applied intensified
(Kramer et al., 2015). Browning products and in turn increase the oxidative stability of
egg pasta (Manzocco et al., 2014). Paskevičiūte et al. (2011) and
Paskevičiūte and Luksiene (2009) mentioned that sensory properties
of treated chicken depend on the process parameters and showed
UV dose of 5.1 J/cm² at 38°C had no changes on raw meat flavour
and taste. PUV light treatment affected the tissue structure of ham
which could be due to the destruction of the network and changes
in myofibrillar proteins (Wambura and Verghese, 2011). Sensory
evaluation of PL-treated ham showed that there was no alteration
in colour, flavour, appearance, and odour, whereas, for bologna,
differences for odour and flavour were observed at higher fluences
than 4.2 J/cm² (Hierro et al., 2011). Similarly, Tomašević (2015) also
found that there was no alteration in appearance and total score
values of beef samples treated with IPL. In contrary, Hierro et al.
(2012) conducted the sensory analysis and found that PL fluences of
8.4 and 4.2 J/cm² or lower did not affect the raw attributes such as
odour and colour of beef, and tuna carpaccio, respectively. However,
during shelf-life studies, beef and tuna carpaccio showed significant,
remarkable difference in colour and odour when treated with PL at
4.2 J/cm² and above. Changes in a* and b* values were observed
for RTE loin samples compared to _Salchichon_ along the 28 days
storage when PL of 11.9 J/cm² was applied. Colour parameters were
not dramatically modified by PL treatment in these RTE dry-cured
products, which may be attributed to the greater stability of the
cured pigments in comparison to those of fresh meat (Ganan et
al., 2013).

Ultraviolet light is known to induce a range of adverse effects
in food products due to the generation of free radicals through a
wide variety of photochemical reactions, which can damage vita-
mins, antioxidants, while also inducing lipid oxidation and colour
changes (Kouchma, 2009). One of the disadvantages of continuous
UV light is the induction of oxidation processes in meat, which after-
ward changes its sensorial properties (Paskevičiūtė and Luksiene,
2009; Paskevičiute et al., 2011). Wambura and Verghese (2011) also
reported that PUV light treatment induced oxidation process, thus
making sample rancid during the storage time. The extent of lipid
peroxidation was found to be higher for vacuum-packaged chicken
frankfurters than unpackaged ones when treated at mild (5 s at
13 cm) and moderate (30 s at 8 cm) UV treatment conditions (Keklik
et al., 2009). A slight increase in lipid peroxidation was observed in
the chicken meat after high-power PL treatment, whereas organo-
leptic properties such as smell, odour, flavour, taste, or colour
changes had no effect under non-thermal treatment conditions. At
higher exposure dose (>5.4 J/cm²), thermal effects were induced
and also changes in organoleptic properties of chicken breast meat
was noticed (Paskevičiute et al., 2011). Lipid peroxidation in dry-
fermented salami was not noticed immediately after PL treatment,
whereas in chicken breast meat, it was found immediately (Rajkovic
et al., 2017). Off-odour in PL-treated samples remained over the
14-day storage period due to photophysical changes occurred on
fresh-cut apples, and overall quality of the PL-treated apple was
lower than that of untreated ones (Moreira et al., 2017). Similarly,
fresh-cut melon submitted to UV-C light had a lesser degree of off-
flavour perception than that of the control during 14-day storage
time (Manzocco et al., 2011). Slight flavour changes were noted by
Ignat et al. (2014) in apple slice exposed to a fluence of 17.5 kJ/cm²
which was similar to those detected during 7-day storage of untreated
ones. Lasagabaster et al. (2011) found that there was no significant
effect on rheological properties of egg and a slight burnt odour in
the egg shell was noticed as a sensory parameter, which was also
not significant. Even, PUV treatment had no effect on egg quality
in terms of albumen height, eggshell strength, and the presence of
cuticle (Keklik et al., 2010). High doses of PL (>8.75 J/cm²) reduced
_Salmonella_ as a result of egg pasta heating or sample heating rather
than the germicidal effect of UV component of light and sensory assessors observed that the intensity of sulphur odour increased in samples exposed at 1.75 J/cm² (Manzocco et al., 2014). In cheddar cheese, PL did not affect the colour and lipid peroxidation during refrigerated condition, but panelists scored the PL-treated samples lower than the untreated ones for the sensory attributes such as overall liking, flavour, and appearance. However, a dose of 9.22 J/cm² had an adverse effect on organoleptic properties of cheese (Proulx et al., 2017). Similarly, a significant difference in odour and flavour in the cheese slices treated with 4.2 and 8.4 J/cm² shows the presence of sulphur notes and the difference in deamination magnitude between types of cheese which could be explained by their different topography that is porous nature in Manchego vs smooth in Gouda type of cheeses (Fernández et al., 2016b). Gómez-Lopez et al. (2005) mentioned that the presence of sensory attributes such as off-odours in IPL-flashed minimally processed white cabbage and overall visual quality in Iceberg lettuce limited the shelf life to 7 and 3 days, respectively.

The PL treatment affected the textural properties, firmness of fruit and vegetables (Luksiene et al., 2012; Xu and Wu, 2016; Moreira et al., 2017). Firmness values reported by Ramos-Villarroel et al. (2014) showed that fresh-cut avocado treated at 305–1100 nm were lower than those of samples treated at 400–1100 nm over the entire 15-day storage period, although their differences were not statistically significant. The application of UV-C light on fresh-cut melon had no differences in colour and firmness up to 3 days of storage as the leakage of intercellular liquids from UV-C light-treated samples was significantly lower than the control. Thus, UV-C light treatment appears to be capable of increasing the dehydration of a thin surface layer of melon cubes without affecting its overall firmness and odour. It can be inferred that this phenomenon may cause the formation of a thin dried film hindering juice leakage during the first 3 days of storage (Manzocco et al., 2011). PL treatment maintained the colour, firmness, and carotenoid content of fresh-cut mangoes (Charles et al., 2013). Strawberries treated with PL did not show pronounced softening when compared to untreated samples even after 8 days of storage at 6°C, and cell wall strengthening of the fruit was induced by PL stress (Duarte-Molina et al., 2016). Similarly, firmness retention was also observed on PL-treated fresh-cut cantaloupe compared to untreated samples during the storage, which may be due to the thickness of the sample (~3 cm) as the effect of PL is restricted to the surface of the product (Koh et al., 2016a,b). But contrarily, the adverse effect of single PL treatment at 11.7 J/cm² on tissue structure of fresh-cut cantaloupes under chilled storage was minimized by applying repetitive PL (RPL) treatment at 0.9 J/cm² every 48-h interval leading to increased microbiological quality, retention of firmness, and ascorbic acid content (AAC). Further, more firmness was higher for fresh-cut cantaloupes treated with RPL compared to the untreated fresh-cut cantaloupes throughout storage that may be due to lower CO₂ concentration in treated samples that could otherwise decompartmentalize the enzyme and their substrates which then act on cell walls of fruits tissue leading to rapid deterioration (Koh et al., 2016b).

PL treatment did not have any effect on the antioxidant activity of fruits and vegetables (Luksiene et al., 2012; Moreira et al., 2017). AAC was conserved throughout the storage period when treated at low fluences (2.7 and 7.8 J/cm²) in fresh-cut cantaloupe (Koh et al., 2016a). A slight increase in AAC after RPL treatment was noticed and even maintained throughout the storage, which could be due to abiotic stress exerted by PL irradiation on fresh-cut cantaloupes (Koh et al., 2016b). IPL applied on spinach and RPL on fresh-cut cantaloupes lead to an increase in the total phenolics concentration and the antioxidant capacity, thereby improving the health-related characteristic of the product (Agüero et al., 2016; Koh et al., 2016b). High-power PL treatment did not affect the AAC in fruits and had a negligible effect on total phenolic content (TPC) in fresh fruits and vegetables (Luksiene et al., 2012; Charles et al., 2013; Koh et al., 2016a). TPC was not affected right after the treatment, whereas during 10-day storage it was found to be decreasing significantly and at the end of the storage, PL did not improve nor affect the TPC levels in raspberries (Xu and Wu, 2016). The total anthocyanin content (TAC) of raspberry was not influenced by PL at 5 and 15 s; surprisingly, PL-treated berries showed higher TAC compared to the control at the end of the 10-day storage. However, PL at 30 s increased the TAC by 10.1 mg cyanidin-3-glucoside equivalents/100 g fruit, when compared to 5 s treatment which could be due to stimulation of colour and anthocyanin accumulation by PL (Xu and Wu, 2016).

The respiration rate was increased by the production of CO₂ and O₂ consumption at a higher rate when PL was applied on spinach and fresh-cut cantaloupe (Agüero et al., 2016; Koh et al., 2016a). Similarly, partial pressures of O₂ and CO₂ inside the packages of tomato slices were significantly affected by PL processing (Valdivia-Nájar et al., 2017). These changes could be associated with a physiological stress or even physiological damage caused by the IPL treatment, which in turn could affect the metabolic activity of the vegetable/fruit tissue (Agüero et al., 2016). IPL treatment increased the respiration rate and gas concentration of lettuce and fresh-cut mushroom at the end of the storage, and the O₂ level was <2%, indicating anaerobic respiration of product in turn affecting the sensory/quality/properties of the product (Gómez-Lopez et al., 2005; Ramos-Villarroel et al., 2012). Likewise, during storage conditions, respiration rate of IPL-treated fresh-cut avocados increased and thus caused an undesirable anaerobic condition leading to the fermentation process in the fruit or triggering anaerobic metabolism of the stored product which in turn lead to increase in ethanol production and inhibiting ethylene production (Ramos-Villarroel et al., 2011). In contrast, Oms-Oliu et al. (2010a), Koh et al. (2016b), and Kramer et al. (2015) did not observe any significant effect of CO₂ by PL application in fresh-cut mushrooms, cantaloupe, and mung bean sprouts, respectively.

**Combination Processing With PL**

The limitations of PL processing are uneven exposure, shadowing effect, browning, and sample heating. Many technologies/strategies have been developed to address and challenge the limits of processing, increase the inactivation efficacy, maintain the quality of foods, and finally obtain minimally processed foods (Señorans et al., 2003). Application of an anti-browning dipping treatment in combination with IPL would increase the shelf life of minimally processed vegetables and fruits (Gómez-Lopez et al., 2005). The use of ascorbic acid (AC) at 1% on sliced mushroom before flashing at 4.8 and 12 J/cm² significantly reduced browning during storage (Oms-Oliu et al., 2010). To minimize the browning on PL-irradiated apple surface, AC/calcium chloride solution was used as an anti-browning dipping prior to PL treatment (Gómez et al., 2012a). Further, this combination of AC + PL-treated apples showed greater microbial growth after 7-day refrigerated storage than PL alone which could be due to tissue damage and antioxidant capacity of AC that affect the damage caused by PL on microbes. In a similar study conducted by Moreira et al. (2017), pectin-coated fresh-cut apples that were exposed to PL were found to have the highest reduction in the
microbial count during storage, but the combination was not found to be antagonistic. The combined application of the edible coating [gellan-gum–based (0.5% w/v) coating enriched with apple fibre] and PL (12 J/cm²) treatment retarded the microbiological deterioration of fresh-cut apples, reduced softening, and browning during 14 days of storage at 4°C (Moreira et al., 2015). Dipping of fresh-cut apples in AC/calciocalium chloride solution preceding to pectin coating and followed by PL treatment was more efficient in minimizing browning, retaining antioxidant activity, and even did not have any effect on microbial loads and sensory acceptability of apple cubes. Firmness was also maintained in fresh-cut apples when treated with AC/calciocalium chloride solution that would help in cross-linking the polymer matrix and thus delaying softening of apple surfaces (Moreira et al., 2017). The treatments combining PL (12 J/cm²) and malic acid (MA) of 2% v/v resulted in significantly greater inhibition of L. innocua and E. coli populations than either PL or MA alone, by achieving more than 5 log reductions for fresh produces such as fresh-cut avocado, watermelon, and mushroom throughout the storage period. Even, TEM observations demonstrated that damage, especially to E. coli cells, was caused by PL inactivation due to agglutination of cytoplasmic content and disruption of cell membrane thus leading to microbial death (Ramos-Vilasarrot et al., 2015). The combination of PL and MA dipping of mango slices was found to be additive leading to a maximum reduction of 4.49 log cycle for L. innocua compared to PL alone (2.5 log CFU/g). It is noteworthy that combination of PL, MA, and alginate coating (ALC) lowered the inactivation level at the same time, and ALC acted as an antagonistic factor which limited the effect of MA and PL. Therefore, Salinas-Roca et al. (2016) concluded that PL should be applied before ALC and MA treatment to overcome the interference caused by ALC. And, the highest inactivation of moulds, yeasts, and psychrophilic bacteria was obtained with PL–ALC–MA treatment that showed the best microbial quality of mango slices during the storage, and also ALC helped to maintain the integrity of fruit by reducing the presence of exudates.

Maftei et al. (2014) stated that studies should be aimed at evaluating strategies based on the combination of PL treatments with other minimal processing technologies, e.g. addition of natural preservatives or mild heat treatment, in order to successfully tackle safety issues for clarified juices treated with PL technology. Combined effect of PL + nisin treatment in RTE sausages, resulted in a significantly higher reduction of L. innocua compared with individual treatment (PL alone—1.37 and nisin dip alone—2.35 log CFU), thus suggesting an additive effect of PL and nisin of 4.03 log CFU (Uesugi and Moraru, 2009). Non-thermal PL treatment inactivation tests against L. innocua inoculated on modified chitosan containing a nanoemulsion of mandarin essential oil-coated green beans showed that 1.2 × 10³ J/m² per bean side was able to cause a reduction of about 2 log cycles. However, PL did not show any synergistic antimicrobial effect against L. innocua throughout the storage and colour properties had a slight detrimental impact with browning spots formation on the samples (Donisi et al., 2015). Furthermore, a 6 log cycle in yeast reduction was observed by Ferrario et al. (2015b) when PL was applied prior to US treatment for both commercial and naturally squeezed apple juice. Similarly, Ferrario and Guerrero (2017) also achieved S. cerevisiae KE162 inactivation of 5.8 and 6.4 log reduction in commercial and naturally squeezed apple juice respectively, even though US treatment was applied before PL. Whereas, US applied before PL treatment did not contribute significant inactivation for A. acidonotestris spore in apple juice matrix. These combinations showed an additive effect on inactivation and storage studies revealed that the level of inactivation reached by the application of US and PL was extended throughout storage compared to fresh untreated juice (Ferrario et al., 2015b).

The sequence of high-intense pulsed light (HIPL)/PEF resulted in a slight lowering of E. coli K12 cells in apple juice compared to PEF/PL, and the combination had no effect on quality parameters except for slight colour changes. HIPL/PEF treatment had a significant effect on sensory attributes such as flavour and odour of the non-thermally treated apple juice compared to thermally pasteurized control (Caminiti et al., 2011b). Caminiti et al. (2011a) reported that light-based technology (UV/HiPL) combined with PEF had no effect on colour, flavour, non-enzymatic browning, TCP, and TAC of an apple and cranberry juice blend and received similar sensory score to that of pasteurized samples, whereas combination with nanothermosonation (MTS) adversely affected overall acceptability and product quality. Similarly, Caminiti et al. (2012) found no change in colour, browning, and anthocyanin content of orange and carrot juice blended with either PEF, UV (10.6 J/cm²) or HiPL (3.3 J/cm²), with MTS (400 kPa, 35°C, 1000 W, 20 kHz). Muñoz et al. (2011) concluded that HiPL and thermosonation (TS) in combination irrespective of the sequence applied had an additive effect on E. coli inactivation in orange juices when compared to either of the technology as a stand-alone. US in conjunction with PL treatment exhibited an inactivation equal to the sum of both effects taken separately (6.3, 5.9, and 3.7 log reduction for S. enteritidis, E. coli, and S. cerevisiae, respectively) in commercial apple juice. Delay in mould and yeast recovery was observed due to the additive effect of US + PL during the 10-day storage period and prevented apple juice from turning darker and brownish (Ferrario and Guerrero, 2016). The combination of PL (low fluence—51.5 J/ml) as first hurdle followed by TS led to significantly higher inactivation of E. coli than TS as the first hurdle. The combination of PL and TS showed an additive effect on inactivation of E. coli than any of these hurdles applied individually which could be due to the influence of treatment on different targets that is DNA for PL and cell membrane for TS (Muñoz et al., 2012). Muñoz et al. (2011) reported that there was no evidence of sublethal damage of cells with HiPL and TS applied individually or in combination, but sublethal injury was detected by Muñoz et al. (2012) when PL (low—4.03 J/cm²) was applied as the first hurdle with TS compared to PL (high—5.1 J/cm²) treatment as a first hurdle.

The combination of wet PL and 1% H₂O₂, was found to be the most efficient treatment for inactivating Salmonella on raspberries and blueberries by >5.6 log CFU/g (Huang et al., 2015). Dip-inoculated green onions were treated using PL (60 s), surfactant (sodium dodecyl sulphate, SDS)–sanitizer combination washing (10 ppm chlorine + 1000 ppm SDS and 300 ppm H₂O₂ + 1000 ppm SDS) as well as PL–surfaceactant–sanitizer combination (10 ppm chlorine + 1000 ppm SDS + 60 s PL and 300 ppm H₂O₂ + 1000 ppm SDS + 60 s PL). Different inactivation efficiency has been observed in various structures of green onions (Figure 5). The combination of wet PL treatment with chlorine washing had an additive effect on E. coli inactivation of about 2.4 log reduction when compared to chlorine washing or PL alone. PL combined with SDS; surfactant was better effective compared to PL and chlorine combination showing the synergistic effect of surfactant. Hydrogen peroxide was slightly more efficient in inactivation of E. coli on green onions (0.7 to 2.6 log CFU/g) than thymol and citric acid combined with 60 s PL treatment. PL–surfactant–sanitizer combination had no additive effect when compared to PL plus surfactant combination (Xu et al., 2013). PL is more efficient in reducing microbial loads on a fresh-cut salad than similar treatments in electrolyzed water (400 ppm free
chlorine) or chlorine dioxide (15 ppm). PL may, therefore, be an appropriate measure to reduce the required amount of fresh water in fresh produce processing and to keep microbial loads in the wash water on a low level (Kramer et al., 2017). Therefore, PL in combination with other technologies can be a novel technology for producing minimally processed foods without compromising the nutritional and sensorial quality of foods.

**Conclusion**

PL being one among the novel food-processing techniques has the ability to reduce the deleterious effects that thermal processing and traditional processing methods have on the colour, texture, flavour, and nutritive value of foods. The novel emerging PL technology is finding application in the food industry with a broad scope in improving nutritional and organoleptic properties and also extending shelf life of food. Novel technologies are considered to be a very promising alternative to conventional processing techniques. A distinct advantage of light-based techniques for certain operating parameters is the inactivation of microorganisms with maintaining of the foods’ sensory attributes and minimal quality loss. One of the disadvantages of PL is high investment costs (€300 000–800 000) and PL is an inappropriate technology for cereals, grains, and spices due to their opaque nature, uneven surfaces, crevices, or pores because of the ability of microorganisms to harbour in minor openings, whereas it is an efficient method of decontaminating packaging materials, surface of foods and liquids. Therefore, light-based technology with slight alteration by the addition of cooling systems in order to minimize the thermal effect can be a promising technique to inactivate the microbes in plant-derived foods, including both solid and liquids by retaining the quality of foods and increasing the shelf life of the products. And, light-based processing of animal products with proper packaging material has an application in the food industry by increasing the shelf life and even maintaining the organoleptic properties of food throughout the storage. In future, more research is required for a more comprehensive understanding of inactivation mechanism of Gram-positive and Gram-negative bacteria by PL, how the fluence, type of microbial strain, as well as physical and chemical properties of the liquid foods affects the occurrence of lethal and sublethal effects induced by PL treatment.

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