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Recent advances in the application of pulsed light processing for improving food safety and increasing shelf life

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Abstract

Background: New technologies of non-thermal disinfection such as pulsed light (PL) have emerged lately as an alternative to traditional (thermal and chemical) disinfection and preservation methods. PL can be used to decontaminate a wide variety of foods as well as to decontaminate contact surfaces, thus improving safety in foods and extending their shelf life. Moreover, this technology can prevent or reduce some of the detrimental effects of traditional methods on nutrients and bioactive compounds of food products.

Scope and approach: The combination of PL with other techniques such as ultraviolet light (UV), thermosonication (TS), pulsed electric fields (PEF), manothermosonication (MTS), etc., can improve the effectiveness of the decontamination process. Therefore, in this review, some of the most relevant studies evaluating the potential application of PL treatments to decontaminate food samples, and its impact of nutritional and physicochemical quality parameters will be discussed.

Key findings and conclusions: PL treatments are suitable for microbial decontamination in transparent drinks and for surface contaminated foods without complex microstructures. They also can be used for meat, fish and their by-products However, it is still necessary to evaluate the appropriate treatment conditions (number of light flashed, voltage, distance between sample and flash light, spectral range of light flashes and contamination) for each food and microorganism separately to improve the effectiveness and minimize the appearance of negative attributes reducing the quality of product as, in some cases, PL can have a negative impact on the photosensitive compounds and sensory properties of food products.

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Keywords: microbial inactivation; non-thermal technology; sensory properties; nutritive value; pulsed light

1. Introduction

Pulsed light (PL) is a non-thermal innovative technique used for food preservation among other relevant novel technologies such as high-pressure processing, pulsed electric fields and high electrical voltage discharges (Stoica et al., 2013). It is based on the application of short time light pulses with an intense broad spectrum (Barba *et al.,* 2018). These pulses act inactivating the microorganisms at a surface level of food and the packaging material (Elmnasser *et al.,* 2007). The microbial DNA absorbs UV light which leads physic-chemical changes in its structure, thus resulting in damage of genetic information, impaired replication and gene transcription as well as eventual death of the cell (McDonald *et al.,* 2002).

PL includes the employment of inert gas flash lamps to transform short duration as well as high power electric pulses into short duration and high-power pulses of radiation having similar spectrum to that of the sun (200–1100 nm), including infrared (IR), visible light (VL) and ultraviolet (UV) (Kramer and Muranyi, 2014). Moreover, flashes can be produced for several seconds with the help of xenon flash lamp. At an industrial level, PL is a useful tool to decrease microbial counts in foods, as well as food packaging materials. It can be also used to decrease microbial contamination of food contact surface, equipment and media (e.g. air and water) implicated in the production processes (Sun, 2005).

PL treatment employs 1-20 flashes/second with an energy density ranging from 0.01 to 50 J/cm^2 at the surface and it has potential application in food processes requiring a rapid disinfection. During the last decades, various studies have confirmed the germicidal effect of PL in alfalfa seeds, blueberries, corn meal, carrot, honey, lettuce, milk, fish fillets, spinach, strawberries and food contact surfaces made of stainless steel (Elmnasser et al., 2007; Oms-Oliu et al., 2010). Particularly for food industrial applications, the PL technology has been successfully applied to decontaminate food

packaging materials. Some of the current applications is on caps, cups, bottles, foils and flexible food packages that can be processed in continuous flows at 7,000-90,000 caps and up to 90,000 bottle preforms per hour (CLARANOR, 2018a). Moreover, PL system can be applied to decontaminate beverages in continuous regime before filling stage (bottles and cans, for instance) at pilot scale (XENON, 2016; Pataro et al., 2011).

In this review, some recent studies, conducted over the last years, about the potential of PL and PL together with other technologies for microbial inactivation in both liquid and solid matrices published will be discussed.

2. PL system

Although the first studies about PL in physics dates back to 1960's, its potential use as potential technology for food decontamination is related to more recent investigations when selected pathogenic and spoilage microorganisms such as *Bacillus cereus*, *Escherichia coli*, *Listeria monocytogenes*, *Pseudomonas aeruginosa*, *Saccharomyces cerevisiae*, *Salmonella enteritidis*, and *Staphylococcus aureus* in Petri dishes were exposed to PL (MacGregor et al., 1998; Rowan et al., 1999). These experiments indicate that PL effect is dependent of treatment conditions. UV source, number of pulses and selected microorganism are relevant variables explored in these studies to achieve satisfactory reduction levels. One of the first applications of PL technology to decontaminate food was carried out with bovine milk (Smith et al., 2002).

It is worth mentioning that some patents from this period explored the application of PL technology to decontaminate food. An equipment patented in 1985 is one of the oldest records of the specific use of PL treatment to destruct microorganisms (Hiramoto, 1984). In this apparatus, the application is dedicated to decontaminate surfaces. Likewise, the equipment patented by Dunn et al. (1989) achieved from 1 to 3 $\log_{10}$ reduction of *Pseudomonas* spp. on cottage cheese curds, molds in

white bread, coliform and psychrotrophic bacteria in fresh fish. Moreover, food packaging material was also successfully decontaminated by PL treatment by Dunn's apparatus.

Further experiments evaluated the PL effect on food microorganisms has gained major attention, particularly PL decontamination in food matrix. For instance, *Serratia marcescens* in bovine milk (Smith et al., 2002), *Saccharomyces cerevisiae* in wheat flour and black pepper (Fine and Gervais, 2004) and *Apsergillus niger* spores in corn meal (Jun et al., 2003) were subjected to PL treatment.

In the period of 2000-2010 the number of studies about the use of PL technology to decontaminate food has grown. Moreover, important advances regarding the use of PL technology was dedicated to achieve industrial level, particularly for surface decontamination. The creation of companies exclusively dedicated to manufacture PL equipment and the insertion of existing companies into this new market occurred in this period facilitated the advances in food industry. Decontamination of food packaging materials is one of the main successful industrial applications of PL technology in food industry (CLARANOR, 2018a; XENON, 2016).

Moreover, PL equipment differs according to manufacturer, but a typical PL system consists of a high-voltage power supply, a storage capacitor, a pulse-forming network which establishes the spectrum properties and pulse shape, gas-discharge flash lamp and a trigger that initiates discharging the electrical energy to the flash lamp (John & Ramaswamy, 2018). Some of the most commonly used equipment are steripulse XL 3000c PL sterilization system (Xenon Corporation, MA, USA), covering a spectral range of emission from 200 nm to 1100 nm (Caminiti *et al.*, 2011), and in some cases an automatic laboratory system (Steribeam Xe-Matic-2L-A, Kehl, Germany) equipped with standard clear 18 cm long UVC transparent quartz Xenon lamps (Maftei *et al.*, 2014). A commercial automatic PL unit (CLARANOR S.A., Avignon,

France) equipped with 8 automatic flash xenon lamps placed all around the sample holder was also used to process whole tomatoes (Aguiló-Aguayo *et al.*, 2013). For continuous treatment of liquid samples, a dynamic flow through pilot unit (Maria PUD system, Claranor, Monosque, France) was used (Artiguez *et al.*, 2011). The **Figures 1-2** show some of the different PL equipment models. This scenario illustrates the important advances made in only two decades of constant evolution and application of PL technology to achieve industrial level, which also include the food processing area.

3. Factors determining the effectiveness of the PL process

Several studies published over the last years displayed that the effectiveness of PL treatments on microorganism inactivation depends on several factors such as the number of flashes, the voltage applied, the distance between sample and lamps, the spectral range of light flashes, the time between contamination and treatment, the type of sample treated and the type and amount of microbial contamination (Heinrich *et al.*, 2016).

In this regard, Koch et al. (2019) explore the effect of PL fluence (0.52-19.11 J/cm^2), distance between the lamp and sample (8.3-13.4 cm), and treatment time (1-30 s). In this study pork skin was inoculated with pathogenic bacteria (*Salmonella Typhimurium* and *Yersinia enterocolitica*) and subjected to PL treatment. The authors observe that only by combining the lowest distance, highest PL fluence and the longest treatment time (8.3 cm, 19.11 J/cm^2, and 30 s) induced significant reduction on *Salmonella Typhimurium* (2.97 log CFU/cm^2) and *Yersinia enterocolitica* (4.19 log CFU/cm^2) inoculated on pork skin. Similar results were reported by Cheigh *et al.* (2013) who studied the inactivation of *L. monocytogenes* on seafood such as salmon, shrimp fillets and flatfish using intense PL at different light doses (0.11-1.75 mJ/cm^2 per pulse). They noticed that the application of PL at 1.75 mJ/cm^2 per pulse and 6900 pulses achieved reductions of 1.9, 2.1

and 2.4 log CFU/cm² of *L. monocytogenes* previously inoculated onto flatfish fillets, salmon and shrimp, respectively. Moreover, the fluence of wavelength below 300 nm seems play a central role in the inactivation effect of PL technology. This outcome was observed by Levy et al. (2012) who reported a drastic reduction in the inactivation effect on spores of *Bacillus subtilis* and *Aspergillus niger* exposed to fluences in the range 300-1100 nm. Conversely, exposing both microorganisms to fluences that included wavelengths below 300 nm produced 6 log reduction.

The relationship between contamination time and PL treatment was also studied. In this regard, Rajkovic *et al.* (2010) evaluated the applicability of PL treatments (3 J/cm^2 with an input voltage of 3000 V) in the decontamination of *L. monocytogenes* and *E. coli* O157:H7 found on the surface of a meat-slicing knife at different times between the contamination and the application PL treatment. The best result (6.5 log CFU/side of knife, complete microbial inactivation) was reached when the knife surface was treated by PL treatments quickly (after knife´s contact with meat products of ≤60 s). The average reductions were 5.82, 5.01 and 2.58 $\log_{10}$ N_0/N after 4 min, 15 min and 1 h, respectively (Rajkovic *et al.*, 2010). More recently, Rajkovic *et al.* (2017) assessed the efficacy of pulsed UV light treatments at 3 J/cm^2 (1 pulse) or 15 J/cm^2 (5 pulses) after 1 or 30 min and every pulse was manually started at a rate of a pulse/2 s to reduce *L. monocytogenes*, *E. coli* 0157:H7, *S. typhimurium* and *S. aureus* on the surface of dry fermented salami inoculated with 6.3 log CFU/g. The authors found a significant effect of PL treatment time, observing the best results after 1 min of applying PL (2.18-2.42 log CFU/g reduction), while after 30 min the reduction varied from 1.14 to 1.46 log CFU/g.

Other important factors influencing the process effectively are: i) the type of contamination, ii) the initial concentration of microorganism and iii) the matrix composition. In this line, some authors (Rajkovic *et al.*, 2010; Agüero *et al*., 2016) found that the Gram-negative bacteria displayed higher

resistance at PL treatments than fungal spores and Gram-positive bacteria. In addition, Pataro *et al*. (2011) assessed the influence of PL application on apple and orange juice inoculated with the Gram-positive (*L. innocua* 11288) and Gram-negative (*E. coli* DH5-α) bacteria. Among the studied bacteria, *E. coli* cells presented higher susceptibility to application of PL compared to *L. innocua* cells in both juices. After applying PL treatment at 4 J/cm^2, microbial decreases were of 4.00 and 2.90 log-cycles for *E. coli* and 2.98 and 0.93 log-cycles for *L. innocua*, in apple and orange juices, respectively. In the same way, Rajkovic (2010) demonstrated that ILP treatment was more effective for the inactivation of *E. coli* O157:H7 on the surface of the slicing knife than for *L. monocytogenes*. The difference in the results achieved between both pathogens, was <0.1 $\log_{10}$ N_0/N for *L. monocytogenes* (Gram-positive) and 4.62 $\log_{10}$ N_0/N for *E. coli* O157:H7 (Gram-negative). The decontamination efficacy also decreased at high initial contamination levels; this fact could be due to light attenuation when high population densities are found, thus preventing the pulsed light incidence on microorganism placed in the lower layers (Maftei *et al*., 2014).

The surface characteristics and nutrient composition of sample were also studied as they could be important factors to be considered in the decontamination efficacy after applying PL treatments. In this regard, Koch et al. (2019) inoculated pork loin with *Salmonella Typhimurium* and *Yersinia enterocolitica* and applied PL treatment (Pl fluence of 0.52-19.11 J/cm^2, 8.3-13.4 cm between the lamp and sample, and 1-30 s of treatment time). The authors also did not obtain markable differences on pork loin (reductions in the range 0.4-1.6 and 0.4-1.7 log CFU/cm^2 for *S. Typhimurium* and *Y. enterocolitica*, respectively). According to authors, this effect could be explained by the surface roughness, porosity and hydrophobicity, which may have caused a shading effect and eventual protection against PL exposure.

Palgan *et al.* (2011a) evaluated the feasibility of using high intensity light pulses (HILP) (frequency of 3 Hz/0-8 s) to reduce *E. coli* and *L. innocua* in matrices with differing transparencies (orange juice, apple juice and milk), observing that microbial inactivation dropped with reducing transparency of the medium. For apple juice (the most transparent media), the reduction of *E. coli* and *L. innocua* after 8 s was of 4.7 and 1.93 $\log_{10}$ CFU/mL, respectively, whereas for milk (the opaquest medium) was of 1.06 and 0.84 $\log_{10}$ CFU/mL, respectively. A similar trend was reported by Aguirre *et al.* (2014) when they studied the decontamination of *Listeria innocua* in culture media with different colorations, observing higher microbial resistance for more coloured media. In general, PL process presented a higher effectiveness for inactivating bacterial cells in clear media (Pollock *et al.*, 2017; Aguirre *et al.*, 2014). Take into account this fact, it is of great importance to optimize the PL process prior to improve its efficacy, thus avoiding product impairment and surface heating.

4. Advantages/disadvantages of PL process

Some of the most important advantages of PL compared to other type of treatments are discussed below. For instance, PL is an effective tool against a great variety of pathogenic and contaminating agents due to the inactivation mechanism of PL process, which is ascribed to the UV component of the broad spectrum of the flash and impacts of the high peak power (Oms-Oliu *et al.*, 2010; Rajkovic *et al.*, 2010). Moreover, PL allows the decontamination of food packed and unpacked and contact surfaces and does not generate residual compounds because PL treatments use xenon flash lamps, which are nontoxic due to mercury-free properties, and do not use chemicals disinfectants and/or synthetic preservatives (Ortega-Rivas, 2012; Ferrario, and Guerrero, 2018). In addition, this technology presents low operation cost for each treatment, good consumer´s acceptance, as they prefer fresh and healthy foods and minimally processed

208 with high enhanced of organoleptic quality (Palgan, 2011b) as well as the possibility to operate
209 in continuous or batch mode. Finally, PL involves the use of short processing times and high
210 throughput since PL light is a more efficient and fast method of inactivating microorganisms
211 (due to the instantaneous delivery of more intense energy) than continuous UV light, for the
212 same total energy supplied (Bohrerova *et al.* 2008). It also has an easy integration with other
213 processes such as temperature (Artíguez and Marañon, 2015), ultrasound, (Ferrario *et al.*, 2015),
214 combination with other disinfectants (Kramer *et al.,* 2017) or other technologies such as
215 thermosonication (Muñoz *et al.,* 2011) and the combination of based-coatings with PL (Donsi *et*
216 *al.*, 2015).

217 In addition to these facts, PL technology has been associated with improved decontamination
218 effect in comparison to other approaches commonly applied in food industry, such as the use of
219 chlorine, organic acids and hydrogen peroxide (**Table 1**). According to the experiment carried out by
220 Huang and Chen (2018), the PL treatment achieved higher levels of microbial reduction against
221 inoculated *Salmonella enterica* than chlorine (1.5-2.8 vs 0.63-1.62 $\log_{10}$ CFU/mL, respectively). In a
222 similar way, organic acids are interesting alternatives to chlorine to disinfect food. In this context,
223 Salinas-Roca et al. (2016) evaluated the impact of PL, malic acid, and its binary combination to
224 disinfect mango slices inoculated with *Listeria innocua*. PL and malic acid induce reductions of 2.5
225 and 2.9 $\log_{10}$ CFU/mL, respectively. Interestingly, the binary combination of PL with malic acid
226 induce a 4.5 log reduction. However, combining PL, malic acid and alginate produced reductions in
227 the range 3.0-4.0. The authors argued that combing PL with malic acid is an effective treatment to
228 reduce *Listeria innocua* contamination in mango slices.

229 Finally, the disinfecting effect of PL technology was compared to chlorine (10 and 100 ppm),
230 hydrogen peroxide (H_2O_2, 300 ppm), thymol (0.2 mg/mL), and citric acid (1 mg/mL) on green onion

leaves and stem inoculated with *Escherichia coli* (Xu et al., 2013). Both PL and chlorine treatments induced a reduction in the range of 0.9-0.12 $\log_{10}$ CFU/mL in the leaves and stem. Differently, all the samples treated by H_2O_2, thymol, and citric acid achieve less than 1 $\log_{10}$ CFU/mL. These results support the role of PL technology in disinfection of food due to its similar and even higher disinfection capacities against common pathogenic bacteria in comparison to other compounds with antimicrobial activity.

However, the PL technology also presents some important drawbacks. This technology is a surface decontamination technology, thus opacity and composition of matrix influence in a great manner the process effectiveness. Moreover, it also presents a high investment cost (Palmieri and Cacace, 2005; Heinrich *et al.*, 2016), short life time temporary lamps, changes in pH and color at high fluence and overheating of samples (Heinrich *et al.*, 2016), possible formation of ozone (Koch et al., 2019). In order to reduce the heating of the samples some authors have introduced the water-assisted pulsed light (WPL) technology (Huang and Chen, 2014; Huang and Chen, 2015). It is important to highlight that, in some cases, PL treatment has a negative effect on some compounds that can lead to changes in sensory characteristics of food products, for example, promoting the degradation of some natural pigments, browning, as well as bad flavor and smell. For instance, Ignat et al. (2014) indicated the PL treated apple slices (157.5 kJ/m^2) were associated with anomalous flavor, reduced apple flavor, and more intense brown color in comparison to untreated samples.

5. Food processing applications

Several studies reported the application of PL to reduce microbial counts from different commodities of vegetable and animal origin. Some of the most important findings are discussed below and in **Tables 2-5**.

253 *5.1. Liquid foods*

254 The use of PL as a non-thermal technology for conservation purposes is a new tendency in
255 liquid food processing research. Some of the most recent studies about the use of this technique in
256 beverages are shown in Table 2. Although the application of PL in beverages has been reported to
257 significantly reduce the initial number of microorganisms, this reduction is variable and depends on
258 the transparency of the beverages. For instance, as can be seen in Table 2, transparent beverages such
259 as water (2.96 to 5.0 $\log_{10}$ N_0/N) and apple juice (1.0 and 4.9 $\log_{10}$ N_0/N) presented lower microbial
260 counts after PL treatment than other opaque drinks such as grape, strawberry, and orange juices or
261 milk, independently of the targeted microorganism. Artíguez and Marañón (2015) evaluated the
262 impact of a PL system with continuous flow on the inactivation of *L. innocua* in whey, skimmed
263 whey, diluted whey and distilled water. The authors observed a higher reduction in *L. innocua* when
264 the number of pulses and total fluence were increased. For a similar total fluence, treatments
265 consisting of a greater pulse number but with lower voltage were more effective. In water, for total
266 fluencies of 11 J/cm^2, a decrease of 5 log CFU/mL in the number of initial pathogens was reached.
267 Moreover, the self-life was increased by 7 days at 4 ºC compared with untreated group. The
268 microbial inactivation by PL treatment differed according to the amount of light transmitted through
269 the fluid, which explains the highest inactivation of *L. innocua* cells in diluted whey samples.

270 The efficiency of PL treatment on the inactivation of different microorganism has been studied
271 by several authors. *Salmonella enteritidis, Escherichia coli, Saccharomyces cerevisiae* and *Listeria*
272 *innocua* are the most commonly evaluated microorganism. In general, Gram-negative bacteria (e.g.
273 *E. coli* and *Salmonella enteritidis*) presented higher susceptibility to PL treatment than Gram-positive
274 bacteria (**Table 2**). For instance, Pataro *et al.* (2011) investigated the impact of PL treatment, in the
275 range of 1.8 to 5.5 J/cm², on apple and orange juice inoculated with the Gram-negative (*E. coli* DH5-

α) and Gram-positive (*L. innocua* 11288) bacteria. A laboratory scale continuous flow PL system with xenon flash-lamp emitting high intensity in the range of 100-1100 nm was used (frequency of 3Hz/360 μs). The most important inactivation effect was observed when the highest amount of energy was applied to the juice stream. *E. coli* presented higher susceptibility compared to *L. innocua* cells in both juices (reductions in apple and orange juices were of 4.00 and 2.90 log-cycles for *E. coli* and 2.98 and 0.93 log-cycles for *L. innocua*, respectively) when subjected to PL treatment at 4 J/cm^2.

Maftei *et al*. (2014) assessed the effectiveness of PL applications on the inactivation of *Penicillium expansum* inoculated in apple juice. Several critical processing attributes including number of pulses (5, 10, 15, 20, 30 and 40 flashes), depth of the juice layer (6, 8 and 10 mm), fluence (0.2 and 0.4 J/cm^2 per pulse) and inoculation level (2.3 x 10^4 CFU/mL and 3x 10^5 CFU/mL) were assessed. The lethality caused by PL treatment on *P. expansum* was reported to be dependent on the depth of the juice layer, fluence and mold contamination level. The inactivation of *P. expansum* improved using high intense PL applications, thinner juice layers and lower contamination levels. Microbial inactivation only slightly increased, with log reductions varying between 3.76 and 1.27 log CFU/mL for 32 J/cm^2 (40 flashes per side) and energy fluences of 4 J/cm^2 (5 flashes per side), respectively. The study also indicated a reduced protective effect against enzymatic browning in apple juice using 0.2 and 0.4 J/cm^2. Moreover, the study also indicated that increasing PL treatment intensity amplified color changes.

5.2. Meat, fish and derived products

Table 3 shows the most recent works evaluating PL decontamination of fish, meat and derived products. In general, around 2.0 log CFU/mL reduction of the initial count of microorganisms was achieved after PL treatments, independently of the target microorganism and the matrix. *Listeria monocytogenes* and *Salmonella enterica* were the main studied microorganisms in fish after applying

PL treatments. Overall, similar values of *Listeria monocytogenes* decontamination were found in both meat (0.9-2.24 log CFU/mL) and fish/seafood (0.7-2.4 log CFU/mL), whereas for *Salmonella enterica* the values were ≈ 2.0 log CFU/mL (**Table 3**). However, PL promoted some changes in the sensory characteristics of these products. The study carried out by Koch et al. (2019) with pork skin and loin indicated that the lowest level of PL fluence (0.52 log CFU/cm^2) was the only sensory accepted samples in comparison to more intense treatments (4.96 and 12.81 log CFU/cm^2). Moreover, both pork skin and loin treated with 0.52 log CFU/cm^2 received the same scores of untreated samples for rancid odor. Interestingly, the authors did not associate this effect to lipid peroxidation due to low oxidation level induced by PL treatments on pork skin (<0.12 μg/g). Moreover, Hierro *et al.* (2012) assessed the feasibility of PL treatments (0.7, 2.1, 4.2, 8.4 and 11.9 J/cm²) to enhance the safety of beef and tuna *carpaccio*. The results indicated a significant reduction in the initial microbial count (≈1 log CFU/cm²) of the samples inoculated with *Vibrio parahaemolyticus*, *E. coli*, *L. monocytogenes* and *S. typhimurium* after applying PL treatments (8.4 and 11.9 J/cm^2), and obtained a significant improvement in the food safety of these products. However, PL treatments at high doses (8.4 and 11.9 J/cm^2) resulted in color variation (lower redness and yellowness than untreated sample) and a negative impact on sensorial quality (lower score for color and odor in comparison to untreated samples).

The effectiveness of PL treatments in surfaces in contact with food was also studied. Rajkovic *et al.* (2010) assessed the applicability of PL treatment (3 J/cm^2 with an input voltage of 3000 V) in the inactivation of *L. monocytogenes* and *E. coli* O157:H7 present on the surface of meat slicing knife (meat extract, pork meat and fermented sausage). The inactivation effectiveness differed according to the type of meat product in touch with the treated surface and on the remaining time between the contamination and the application of PL treatment. The best result (6.5 log CFU/side of

knife, complete microbial inactivation) was found when the knife surface was treated with PL treatments quickly (after the knife contacted with meat products ≤60 s) and when the knife surface was in touch with products with lower protein and fat amount (Rajkovic *et al.*, 2010).

Regarding the impact on sensory properties, the study carried out by Koch et al. (2019) indicate associated the most intense PL treatments (4.96 and 12.81 J/cm^2) with unpleasant, ozoneous, pungent, ammoniacal, and off-odor perception in pork skin and loin. Conversely, the samples subjected to 0.52 J/cm^2 were perceived as "less porky" and "slightly chemical", which support the indication that excessive PL treatment reduced the quality of food. Additionally, significant changes on color caused by PL treatment were also indicated particularly for redness.

5.3. Fruits and Vegetables

Over the last years, many studies have been published dealing to the microbial decontamination after applying PL treatments to fruits (blueberries, melon apple, raspberry and strawberry) and vegetables (tomatoes, beans, salad, onions and avocado) (**Table 4**). In most of these studies, the decontamination was assessed on samples of fresh products artificially inoculated or in native microflora. Although complete microbial inactivation was not achieved, reductions of ≈1-6 log CFU/mL were achieved in vegetables and fruits without compromising of the nutritional value of products.

For instance, Aguiló-Aguayo *et al.* (2013) assessed the impact of PL, at fluencies of 2.68 and 5.36 J/cm^2, on the decontamination (natural and inoculated microorganisms) of red-ripe tomatoes. The application of PL at fluence of 4 J/cm^2 decreased tomato total microflora by 1 $\log_{10}$ CFU/mL. On the other hand, treatment at fluencies of 2.2 J/cm^2 and 4 J/cm^2 caused a decrease of 2.3 $\log_{10}$ CFU/mL of *S. cerevisiae* inoculated. In addition, Aguiló-Aguayo *et al.* (2014) assessed the influence of PL (3.6, 6.0 and 14 J/cm^2) on avocado microbial content,

observing reductions in aerobic mesophilic microorganisms (1.20 log CFU/g) after PL treatment of 14 J/cm^2. The growth of molds and yeasts was also delayed during 3 days and the shelf-life was increased to 15 days. In addition, Ignat *et al.* (2014) assessed the impact of different PL fluencies (17.5, 52.5, 105.0 and 157.5 kJ/m^2) against the growth of *L. brevis* and *L. monocytogenes* inoculated on fresh sliced apples during storage at 6 ºC. Independently of the fluence used, the application of PL treatments significantly reduced the total viable counts (1 log CFU/g) and inoculated bacteria (3 log CFU/g) of the samples. Differently, Xu *et al.* (2016) studied the impact of PL application on the inactivation of *Salmonella* spp. and *E. coli* O157:H7 on fresh raspberries stored for 10 days at 4 ºC. In comparison with untreated samples, the fresh raspberries treated with PL during 5-30 s had lower pathogen survival. However, the most efficient treatment was obtained by using PL for 30 s (fluence of 28.2 J/cm^2), which resulted in reductions of 4.5 and 3.9 $\log_{10}$ CFU/g in *Salmonella* spp. and *E. coli* O157:H7 populations, respectively.

In addition to safety related analysis, the physicochemical properties (weight, texture and color, for instance) and nutritional properties of the samples after applying PL treatments were also studied. For example, Aguiló-Aguayo *et al.* (2013) assessed the influence of PL in color, texture, weight and ascorbic acid of tomato stored at 20 °C for 15 days. Regarding nutritional quality, ascorbic acid amounts did not change during storage, while total lycopene, α-carotene and β-carotene amounts and percentage of lycopene isomerization in both tomato tissues and chloroplast were higher in tomatoes treated with high PL dose (30 J/cm^2). In another study, Aguiló-Aguayo *et al.* (2014) evaluated the effect of PL application (3.6, 6.0 and 14 J/cm^2) on lipid oxidation chlorophyll stability and color of avocado after 15 d at 4 ºC. These authors observed that after 15 days, the color was maintained, and the chlorophyll content was increased. The authors argued that enzymatic browning could explain this effect, particularly due to cell

disruption that facilitated the enzyme-substrate contact while cutting the fruits but the PL treatment did not prevent enzymatic browning. Moreover, the lipid fraction exhibited a minimal peroxide formation and the rancidity processes were not increased.

In addition to the positive effect of PL processing in reducing the microbial counts present on fruits and vegetables, some studies reported the negative effect of this technology at high and long pulses on the food appearance and nutritional quality of the foods. In this line, Aguiló-Aguayo *et al.* (2013) noticed that although the microbial counts present in tomatoes after 3 days of storage were reduced, and the appearance (wrinkled skin and softening) and weight loss were also detected in PL treated samples. In addition, Ignat *et al.* (2014) investigated the influence of PL on the appearance of sliced fresh apples during storage at 6 ºC. The use of PL treatment at 17.5 kJ/m2 did not induce any protective effect against enzymatic browning in comparison to untreated samples. Moreover, the use of 157.5 kJ/m2 favored more intense color changes than untreated and PL treated samples at 17.5 kJ/m2. The main reason for this particular effect was related to disruption of apple cell membranes. The authors also observed a high microbial reduction at high fluencies verifying that the high fluencies negatively affected to color and sensorial attributes of apple slices. In a similar way, a study with fresh-cut mangoes indicated that PL treatment (4 pulses at 2.80 J/cm^2) indicated non-significant changes on luminosity but yellow color (b* value) was better preserved during 7 days of storage at 6 °C for up to 7 days (Lopes et al., 2017).

The study carried out by Charles et al. (2013) evaluated the impact of PL (four pulse with a total of 8 J/cm^2) on selected endogenous enzymes (polyphenoloxidase and phenylalanine ammonia lyase) fresh cut fresh-cut mangoes. The results of PL treatment indicated that both Polyphenoloxidase and Phenylalanine ammonia lyase activity were improved during storage of mangoes cuts but a non-significant effect on color was observed between untreated and PL-treated

samples. Likewise, PL treatment (4, 6, and 8 J/cm^2) did not induce important changes in pectin methylesterase and polygalacturonase activity of fresh-cut tomatoes. This outcome was obtained during storage at 5 °C for 20 days (Valdivia-Nájar et al., 2018). Finally, Xu *et al.* (2016) assessed the influence of PL applications on fresh raspberries stored for 10 days at 4 ºC, observing that the PL treatment negatively affected to the color and texture of raspberries. However, no significant changes were observed in total phenolic compounds (TPC) and the total antioxidant capacity (TAC) levels of the treated samples compared to the untreated ones. The initial population of total bacteria, total yeast and mold in raspberries decreased with all PL treatments.

5.4. Salad

Recently, several studies have evaluated the application of washing cycles with PL-treated water for microbial disinfection of salad samples (**Table 4**). Manzocco *et al.* (2015) studied the effectiveness of using recycled water from lamb´s lettuce washing after applying PL treatments (pulse light dose ranges from 0 to 17.5 KJ/m^2). The authors observed a complete inactivation of most of the autochthonous microflora and a significant reduction (5-6 log CFU/g) in inoculated microorganisms (*E. coli*, *L. monocytogenes* and *S. enterica*) using PL doses of 11 KJ/m^2.

Moreover, the influence of increasing the washing cycles in the decontamination process and hygienic quality of washed lamb's lettuce was also investigated. Increasing wash cycles up to 5 did not decrease the effectiveness of decontamination (reduction of ≈4 log CFU/g in native microflora). Moreover, a decrease of 1 log CFU/g in native microflora was reached in the washed salad. Kramer *et al. (*2017) compared the application of PL alone or in combination with the traditional disinfectants (chlorine and chlorine dioxide) on the reduction of microbial counts (*L. innocua*) from bean sprouts and endive salad during a simulated wash process for up to 60 s with PL dose of 320 mJ/cm^2. The best results were obtained using PL wash, where the microbial

414 counts were reduced by up to 2.5 log in endive salad and 0.45 log CFU/g in beans sprouts,
415 demonstrating the efficiency of PL treatments in comparison to other traditional disinfectants
416 (**Table 4**). Therefore, the application of PL is a good alternative to inactivate suspended
417 microorganisms in the washed water. In addition, PL is an economical alternative method, which
418 can be used to reduce the generation of wastewater without losing the efficiency of the
419 disinfection process.

420 **6. PL together with other technologies**

421 In order to enhance the efficiency of the PL applications, some authors proposed the
422 combination of PL with subsequent storage at low temperatures. For instance, Ferrario *et al.*
423 (2013) assessed the inactivation kinetics of *E. coli* ATCC 35218, *Saccharomyces cerevisiae*
424 KE162, *Salmonella enteritidis* MA44 and *L. inocua* ATCC 33090 inoculated in apple,
425 strawberry juices, melon and orange using HIPL. The samples were subjected to irradiation for
426 2-60 s as pre-treatment, corresponding to fluencies between 2.4 and 71.6 J/cm^2. After 60 s at
427 71.6 J/cm^2, microbial reductions in the range 0.3-6.9 log-cycle were observed. These authors
428 showed the potential of using PL processing, for inactivation of some microorganism in different
429 types of fruit juices at low temperature (<20 °C).

430 In a further study, Ferrario *et al.* (2015b) evaluated the impact of PL treatments on the
431 inactivation of native flora and inoculated microorganisms (*S. cerevisiae E. coli, S. enteritidis, L.*
432 *innocua*) in strawberry juices, orange and apple inoculated with these microorganisms. The
433 application of PL treatments at 71.6 J/cm^2 resulted in 0.3–2.6 and 0.1–0.7 log reductions in
434 inoculated microorganisms and in native flora, respectively. The turbidity of the samples and the
435 size of the particles had a negative effect on PL treatment efficiency. These authors also reported

436 that the application of PL was ineffective in reducing the native microorganisms of strawberry
437 juices, orange and apple stored for 10 days under refrigerated conditions.

438 **Table 5** summarizes several studies recently published that display the effect of PL
439 treatments together with other technologies. Moreover, in these studies, apart from obtaining a
440 significant reduction in microbial contamination, minimally processed foods with improved
441 nutritional and sensorial profiles. Ultrasound (Ferrario *et al.,* 2015, 2016 and 2017),
442 thermosonication (Muñoz *et al.,* 2011 and 2012), disinfectant products (Xu *et al.,* 2013),
443 advanced oxidation processes using hydrogen peroxide (Huang *et al.,* 2015; Huang y Chen
444 2015), combination with water (Xu *et al.,* 2013; Huang y Chen 2014 and 2015) and edible
445 coating (Donsi *et al.,* 2015) are the most common and reliable strategies to be used combined
446 with PL treatments.

447 Some authors have proposed several alternatives to PL in order to avoid sample heating
448 and browning effect when this technology is used for sanitization of fresh vegetables and fruits.
449 For instance, water-assisted pulse light (WPL) treatment has been suggested as a useful tool to
450 overcome these limitations. In this regard, Huang and Chen (2014) compared the inactivation of
451 *Salmonella* spp. And *E. coli* O157:H7 in blueberries using dry PL and WPL at different times (5-60
452 s). These authors observed an effective inactivation of both pathogens after all treatments. However,
453 the aspect of blueberries was negatively influenced after applying dry PL treatments. Moreover, in
454 another study, the application of WPL treatments was found to be more effective on inactivating
455 both pathogens than chlorine washing. After WPL treatment for 60 s, the populations of *E. coli*
456 O157:H7 inoculated on skin and calyx of blueberries decreased by >5.8 and 3.0 log CFU/g,
457 respectively. A similar trend was found for *Salmonella* spp., with >5.9 log and 3.6 CFU/g reduction
458 on blueberry skin and calyx, respectively.

On the other hand, the effect of WPL application alone (5-60s) or together with 1% H_2O_2 or 100 ppm sodium dodecyl sulfate (SDS) on the decrease of murine norovirus (MNV-1), *Salmonella* and *E. coli* O157:H7 in raspberries and strawberries was investigated (Huang and Chen, 2015). *E. coli* reduction in strawberries and raspberries differed according to WPL time, observing reduction values of 1.4-2.4 log units and 1.6-4.5 log units, respectively. The inactivation of *Salmonella* spp. and *E. coli* O157:H7 was higher after using the WPL+H_2O_2 combination for 60s in comparison to other treatments (e.g. chlorine, SDS, H_2O_2, WPL and the combination of WPL+H_2O_2 and WPL+SDS). *E. coli* O157:H7 cell number reduction on raspberries and strawberries was of 5.3 and 3.3 log CFU/g, respectively, whereas for *Salmonella* was 4.9 and 2.8 log CFU/g, respectively. Regarding MNV-1, the application of WPL and H_2O_2 did not improve the treatment effectiveness for raspberries, while it was slightly improved in strawberries (WPL: 1.8 log CFU/g and WPL+H_2O_2: 2.2 log CFU/g). The potential of using WPL alone or in combination with H_2O_2 was demonstrated as a good alternative for decontamination of fresh and frozen berries.

More recently, Avalos *et al.* (2016) assessed the influence of PL application with a quality-stabilizing dip (0.5% w/v $CaCl_2$ and 1% w/v N-acetylcysteine) on the microbial count reduction, the quality and antioxidant features of fresh-cut apples during 15 days storage at 5 ºC. A significant reduction of the naturally-occurring microbiota without compromising the quality of apples was achieved. The application of quality-stabilizing pre-treatments inhibited the browning phenomena and oxidation on the cut-tissue surface. Oxidation and browning in PL-treated samples were not promoted. Compared to untreated samples, vitamin C and phenolic compounds were higher in PL-treated fresh-cut apples. Moreover, the quality and antioxidant properties of the samples were better maintained at the doses of 8 and 16 J/cm^2.

The combination of PL processing with edible coatings (e.g. chitosan, pectin, alginate and gellan) is another interesting strategy that has been taken into account and could be employed for improving the safety of vegetables and fruits. Recently, Chen *et al.* (2017) evaluated the use of this technique to increase the shelf-life of fresh-cut cantaloupes. These authors combined alginate and PL (fluence of 0.9 J/cm^2) and observed an increase on shelf-life of fresh-cut cantaloupes up to 28 days. After 28 days, the total viable counts and yeast mold counts were reduced ≈4 log CFU/g.

Donsi *et al.* (2015) investigated the combination of high pressure processing (HPP) and PL with a modified chitosan based-coating containing a nanoemulsion of mandarin essential oil on green beans preservation. Coated and uncoated green bean samples (2.0×10^{-2} to 2.2×10^{-2} kg, respectively) inoculated with *L. innocua*, were exposed to PL treatments at 3×10^4 and 1.2×10^5 J/m^2 energy dose, respectively. No synergistic or additive antimicrobial influence was observed against *L. innocua* in PL-treated and bioactive coated samples during storage. Moreover, no effect was observed in the firmness or coating integrity of the samples treated with the combination of PL processing and bioactive coating during storage.

The use of PL together with other technologies increased the microbial inactivation and shelf-life of food products. For example, Muñoz *et al. (*2011) observed that PL together with thermosonication was more effective to reduce the initial concentration of *E. coli* in orange juice than PL alone. In this regard, reductions of 3.93 log CFU/g were obtained after the application of PL+thermosonication, whereas reductions of 2.92 log CFU/g were found using PL alone. After the application of US+PL, Ferrario *et al.* (2015) observed an increased reduction of *Alicyclobacillus terrestris* and *Sacharomyces cerevisiae* counts in apple juice. The application of PL alone showed a reduction of 4.4 log and 3.0 and CFU/g for *Sacharomyces cerevisiae* and

505 *Alicyclobacillus terrestris,* respectively, whereas the application of US+PL presented a reduction
506 of 5.9 and 6.4 log CFU/g for *Alicyclobacillus terrestris* and *Sacharomyces cerevisiae,*
507 respectively.

508 **7. Industrial relevance of PL technology in food sector**

509 The application of Pl technology in the food industry has been gaining more attention and
510 potential applications, especially in the last 10 years. The use of PL technology to decontaminate
511 food packaging material is the most concrete application, as indicated in previous sections. The
512 safety levels achieved in this sector of food industry are relevant, support the continuous research
513 in the area and also expand to new applications. The small size and design, in order to be
514 implemented on existing processing lines, are also important characteristics available for
515 packaging materials.

516 However, the use of PL technology to decontaminate food still require more efforts to
517 achieve industrial scale of direct food decontamination. At the current level, few pilot scale
518 studies have been carried out and revealed important considerations. The decontamination of
519 sesame seeds carried out by Hwang et al. (2017) achieved 1.46 log reduction operating at 44.46
520 J/cm^2 for 120 s in a pilot scale semi-continuous system (up to 3 kg recirculating in the system).
521 The shadow effect, which can prevent the exposure of microorganisms to PL irradiation and
522 reduce treatment efficiency, remains as the main concern. A possible alternative to increase
523 energy exposure during PL treatment is enhancing the area exposed to PL. A promising outcome
524 was reported by Krishnamurthy et al. (2007) who achieved total inactivation of *Staphylococcus*
525 *aureus* in milk with a continuous system operating at 20 ml/min. This particular apparatus was
526 equipped with a V-groove reflector, which reflected the energy back to the quartz tube where
527 milk was treated.

An important consideration is the development of efficient PL systems for heat liable food and packaging materials. Increasing temperature may cause changes and potential quality decrease. For instance, temperature increase around 20 °C may occur in most intense PL treatments and achieve higher decontamination levels, by combining short distance between lamp and sample and high PL fluence, as indicated by Koch et al. (2019). Either a cooling system or a more efficiency PL fluence approach are necessary to reduce temperature increase when considering scaling up.

The current information disclosed by companies in the area of food package decontamination indicate that operational cost is reduced, considering the same amount of material. For instance, in order to decontaminate 10,000 cups of 28 mm, the total operational cost is estimated in 42 €, whereas the estimated cost to carry out the same decontamination with peracetic acid is around 266 €. Reduced water consumption, particularly for decontamination step, can also be achieved (CLARANOR, 2018b). However, further studies and thorough evaluation of costs associated with starting, operating and maintaining the processing line, which take into account the type of food, microorganism, reduction level, amount of processed food and other variables presented in this review are still necessary.

8. Conclusion

PL treatment is a successful, fast and environmentally friendly decontamination technology with many potential applications in the food industry, especially as a promising non-thermal technology to be used for food safety purposes. It has been found that PL treatments are suitable for microbial decontamination in transparent drinks and for surface contaminated foods that not presenting complex microstructures.

High-power PL increased the shelf life of meat, fish and derivate products as well as on food contact surfaces. However, for other types of food it is still necessary to evaluate the appropriate treatment conditions (number of flashes, voltage, distance between sample and flash light, spectral range of light flashes and contamination) for each food and microorganism separately to improve the effectiveness and minimize the appearance of negative attributes that reduce the quality of product. In this sense, more studies about the effect of PL on the microbial inactivation and food quality characteristics are necessary at laboratory and pilot scale. The process economic evaluation also deserves more attention, few information is available for both researchers and professionals working on this promising food industry area.

To avoid these problems, it is necessary to optimize the treatment conditions and take into account that the effectiveness of the treatments depends on the time among contamination, PL treatment parameters and food matrix. Currently, to avoid these existent limitations some authors have complemented the PL treatments with other techniques, which can keep the food conservation with minimal impact on the food quality. Finally, it is necessary to carry out studies on a large scale in order to introduce this disinfection technique at industrial level.

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References

Agüero, M.V., Jagus, R.J., Martín-Belloso, O., & Soliva-Fortuny, R. (2016). Surface decontamination of spinach by intense pulsed light treatments: Impact on quality attributes. *Postharvest Biology and Technology, 121,* 118-125.

Aguiló-Aguayo, I., Charles, F., Renard, C.M.G.C., Page, D., & Carlin, F. (2013). Pulsed lights effect on surface decontamination, physical qualities and nutritional composition of tomato fruit. *Postharvest Biology and Technology, 86,* 29-36.

Aguiló-Aguayo, I., Oms-Oliu, G, Martín-Belloso, O., & Soliva-Fortuny, R. (2014). Impact of pulsed light treatments on quality characteristics and oxidative stability of fresh-cut avocado. *Food Science and Technology, 59,* 320-326.

Aguirre, J.S., Heirro, E., Fernandez, M., & Garcia de Fernando, G.D. (2014). Modelling the effect of light penetration and matrix colour on the inactivation of *Listeria innocua* by pulsed light. *Innovative Food Science and Emerging Technologies, 26,* 505-510.

Artíguez, M.L., & Martínez de Marañón, I. (2015). Improved process for decontamination of whey by a continuous flow-through pulsed light system. *Food Control, 47,* 559-605.

Avalos, K.R.L, Marsellés-Fontanet, A.R., Martín-Belloso, O., & Soliva-Fortuny, R. (2016). Impact of pulsed light treatments on antioxidant characteristics and quality attributes of fresh-cut apples. *Innovative Food Science and Emerging Technologies, 33,* 206-215.

Barba, F.J., Sant'Ana, A.S., Orlien, V., & Koubaa, M. (2018). Innovative technologies for food preservation: Inactivation of spoilage and pathogenic microorganisms, 1st edn. Academic Press, Elsevier.

Bohrerova, Z., Shemer, H., Lantis, R., Impellitteri, C. A., & Linden, K. G. (2008). Comparative disinfection efficiency of pulsed and continuous-wave UV irradiation technologies. *Water Research, 42,* 2975–2982.

Caminiti, I. M., Noci, F., Muñoz, A., Whyte, P., Morgan, D. J., Cronin, D. A., & Lyng, J. G. (2011). Impact of selected combinations of non - thermal processing technologies on the quality of an apple and cranberry juice blend. *Food Chemistry, 124*(4), 1387-1392.

Cao, X., Huang, R., & Chen, H. (2017) Evaluation of pulsed light treatments on inactivation of Salmonella on blueberries and its impact on shelf-life and quality attributes *International Journal of Food Microbiology, 260*, 17–26

Charles, F., Vidal, V., Olive, F., Filgueiras, H., & Sallanon, H. (2013). Pulsed light treatment as new method to maintain physical and nutritional quality of fresh-cut mangoes. *Innovative Food Science & Emerging Technologies, 18,* 190-195.

Cheigh, C., Hwang, H., & Chung, M. (2013). Intense pulsed light (IPL) and UV-C treatments for inactivating *Listeria monocytogenes* on solid medium and seafoods. *Food Research International, 54,* 745-752.

Chen, P.K., Adzahan M.N., Abedin N.H.Z., Karim, R., & Rosli, S.Z. (2017). Application of edible coatings and repetitive pulsed light for shelf life extension of fresh-cut cantaloupe (*Cucumis melo* L. reticulatus cv. Glamour). *Postharvest Biology and Technology, 129,* 64-78.

Claranor. Pulsed Light Sterilization. Claranor Products. (2018a). http://www.claranor.com/products. Accessed 28 February 2019.

Claranor. Advantages and Restrictions of pulsed light. (2018b). http://www.claranor.com/products. Accessed 28 February 2019.

Donsi, F., Marchese, E., Maresca, P., Pataro, G., Vu, K.D., Salmieri, S., Lacroix, M., & Ferrari, G. (2015). Green beans preservation by combination of a modified chitosan based-coating

containing nano-emulsion of mandarin essential oil with high pressure or pulsed light processing. *Postharvest Biology and Technology, 106,* 21-32.

Dunn, J.E., Clark, R.W., Asmus, J.F., Pearlman, J.S., Boyer, K., Painchaud, F., Hofmann, G.A. (1989). *Methods for presevation of foodstuffs*. Patent: US Patent 5034235A.

Elmnasser, N., Guillou, S., Leroi, F., Orange, N., Bakhrouf, A., & Federighi, M. (2007). Pulsed light system as a novel food decontamination technology. A review. *Canadian Journal of Microbiology, 53,* 813 - 821.

Ferrario, M., & Guerrero, S. (2016). Effect of a continuous flow-through pulsed light system combined with ultrasound on microbial survivability, color and sensory shelf life of apple juice. *Innovative Food Science and Emerging Technologies, 34,* 214–224.

Ferrario, M., & Guerrero, S. (2017) Impact of a combined processing technology involving ultrasound and pulsed light on structural and physiological changes of Saccharomyces cerevisiae KE 162 in apple juice. *Food Microbiology, 65,* 83-94

Ferrario, M., & Guerrero, S. (2018). Inactivation of Alicyclobacillus acidoterrestris ATCC 49025 spores in apple juice by pulsed light. Influence of initial contamination and required reduction levels. *Revista Argentina de Microbiología, 50*(1), 3-11

Ferrario, M., Alzamora, S.M., & Guerrero, S. (2015a). Study of the inactivation of spoilage microorganisms in apple juice by pulsed light and ultrasound. *Food Microbiology, 46,* 635-642.

Ferrario, M., Alzamora, S.T., & Guerrero, S. (2013). Inactivation kinetics of some microorganisms in apple, melon, orange and strawberry juices by high intensity light pulses. *Journal of Food Engineering,118,* 302-311

Ferrario, M., Alzamora, S.T., & Guerrero, S. (2015b). Study of pulsed light inactivation and growth dynamics during storage of Escherichia coli ATCC 35218, Listeria innocua ATCC 33090, Salmonella Enteritidis MA44 and Saccharomyces cerevisiae KE162 and native flora in apple, orange and strawberry juices. *International Journal of Food Science and Technology, 50,* 2498–2507

Fine, F., & Gervais, P. (2004). Efficiency of pulsed UV light for microbial decontamination of food powders. *Journal of Food Protection, 67*(4), 787-792.

Ganan, M., Hierro, E., Hospital, X.F., Barroso, E., & Fernández, M. (2013) Use of pulsed light to increase the safety of ready-to-eat cured meat products. *Food Control, 32,* 12-517

Heinrich V., Zunabovic M., Varzakas T., Bergmair J. & Kneifel W. (2016). Pulsed Light Treatment of Different Food Types with a Special Focus on Meat. *Critical Review Critical Reviews in Food Science and Nutrition, 56,* 591–613.

Hierro, E., Ganan, M., Barroso, E., & Fernández, M. (2012). Pulsed light treatment for the inactivation of selected pathogens and the shelf-life extension of beef and the tuna carpaccio. *International Journal of Food Microbiology, 158,* 42-48.

Hiramoto, T. (1984). *Method of Sterilization*. Patent: US Patent 4464336.

Huang Y., & Chen, H. (2014). A novel water-assisted light processing for decontamination of blueberries. *Food Microbiology, 40,* 1-8.

Huang Y., Sido R., Huang R, & Chen H (2015). Application of water-assisted pulsed light treatment to decontaminate raspberries and blueberries from Salmonella. International *Journal of Food Microbiology, 208,* 43–50.

Huang, R., & Chen, H. (2018). Evaluation of inactivating Salmonella on iceberg lettuce shreds with washing process in combination with pulsed light, ultrasound and chlorine. *International Journal of Food Microbiology, 285,* 144-151.

Huang, Y., & Chen, H. (2015). Inactivation of *Escherichia coli* 0157:H7, Salmonella and human norovirus surrogate on artificially contaminated strawberries and raspberries by water-assisted pulsed light treatment. *Food Research International, 72,* 1-7.

Huang, Y., Ye, M., Cao, X., & Chen, H (2017). Pulsed light inactivation of murine norovirus, Tulane virus, Escherichia coli O157:H7 and Salmonella in suspension and on berry surfaces. *Food Microbiology, 61,* 1-4

Hwang, H.J., Cheigh, C.I., & Chung, M.S. (2015) Relationship between optical properties of beverages and microbial inactivation by intense pulsed light. *Innovative Food Science and Emerging Technologies, 31,* 91–96.

Hwang, H.J., Cheigh, C.I., & Chung, M.S. (2017). Construction of a pilot-scale continuous-flow intense pulsed light system and its efficacy in sterilizing sesame seeds. *Innovative Food Science & Emerging Technologies, 39,* 1-6.

Ignat, A., Manzocco, L., Maifreni, M., Bartolomeoli, I., & Nicoli, M.C. (2014). Surface decontamination of fresh-cut apple by pulsed light: Effects on structure, colour and sensory properties. *Postharvest Biology and Technology, 91,* 122-127.

John, D., & Ramaswamy, H. S. (2018). Pulsed light technology to enhance food safety and quality: a mini-review. *Current Opinion in Food Science, 23,* 70 -79

Jun, S., Irudayaraj, J., Demirci, A., & Geiser, D. (2003). Pulsed UV□light treatment of corn meal for inactivation of *Aspergillus niger* spores. *International Journal of Food Science & Technology*, *38*(8), 883-888.

Karaoglan, H.A., Keklik, N. M., & Isikli, N.D. (2017) Modeling inactivation of candida inconspicua isolated from turnip juice using pulsed UV light. *Journal of Food Process Engineering, 40,* e12418.

Kasahara, I., Carrasco, V., & Aguilar, L. (2015) Inactivation of Escherichia coli in goat milk using pulsed ultraviolet light. *Journal of Food Engineering, 152,* 43–49.

Koch, F., Wiacek, C., & Braun, P.G. (2019). Pulsed light treatment for the reduction of Salmonella Typhimurium and Yersinia enterocolitica on pork skin and pork loin. *International Journal of Food Microbiology, 292,* 64-71.

Koh, P.C., Noranizan, M.A., Karim, R. & Hanani, Z.A.N. (2016a) Microbiological stability and quality of pulsed light treated cantaloupe (Cucumis melo L. reticulatus cv. Glamour) based on cut type and light fluence. *Journal of Food Science and Technology, 53,* 1798–1810.

Koh, P.C., Noranizan, M.A., Karim, R., & Hanani, Z.A.N. (2016b) Repetitive pulsed light treatment at certain interval on fresh-cut cantaloupe (Cucumis melo L. reticulatus cv. Glamour). *Innovative Food Science and Emerging Technologies, 36,* 92–103.

Kramer, B., & Muranyi, P. (2014). Effect of pulsed light on structural and physiological properties of *Listeria innocua* and *Escherichia coli*. *Journal of Applied Microbiology, 116,* 596-611.

Kramer, B., & Muranyi, P. (2017). Pulsed light decontamination of endive salad and mung bean sprouts in water. *Food Control, 73,* 367-371.

Kramer, B., Wunderlich, J., & Muranyi, P. (2015) Pulsed light decontamination of endive salad and mung bean sprouts and impact on color and respiration activity. *Journal of Food Protection, 78,* 340–348.

Krishnamurthy, K., Demirci, A., & Irudayaraj, J. M. (2007). Inactivation of Staphylococcus aureus in milk using flow□through pulsed UV□light treatment system. *Journal of Food Science*, *72*(7), M233-M239.

Lasagabaster, A., & de Marañón, I.M. (2017) Comparative Study on the Inactivation and Photoreactivation Response of Listeria monocytogenes Seafood Isolates and a Listeria innocua Surrogate after Pulsed Light Treatment. *Food and Bioprocess Technology, 10,* 1931–1935.

Levy C., Aubert X., Lacour B., & Carlin, F. (2012) Relevant factors affecting microbial surface decontamination by pulsed light. *International Journal of Food Microbiology, 152*, 168–174.

Lopes, M.M.A., Silva, E.O., Laurent, S., Charles, F., Urban, L., & de Miranda, M.R.A. (2017). The influence of pulsed light exposure mode on quality and bioactive compounds of fresh-cut mangoes. *Journal of Food Science and Technology*, *54*(8), 2332-2340.

MacGregor, S.J., Rowan, N.J., McIlvaney, L., Anderson, J.G., Fouracre, R.A., & Farish, O. (1998). Light inactivation of food□related pathogenic bacteria using a pulsed power source. *Letters in Applied Microbiology*, *27*(2), 67-70.

Maftei, N.A., Ramos-villarroel, A.Y., Nicolau, A.I., Martin - Belloso, O., Soliva - Fortuny, R. (2014). Influence of processing parameters on the pulsed - light inactivation of *Penicillium expansum* in apple juice. *Food Control, 41*, 27-31.

Manzocco, L., Ignat, A., Bartolomeoli, I., Maifreni, M., & Nicoli, M.C. (2015). Water saving in fresh cut salad washing by pulsed light. *Innovative Food Science and Emerging Technologies, 28*, 47-51.

McDonald, K. F., Curry, R. D., Clevenger, T. E., Unkelsbay, K., Eisentrack, A., Golden, J., & Morgan, R. D. (2002). A comparison of pulsed and continuous ultraviolet light sources for the decontamination of surfaces. IEEE Trans. *Plasma Science, 28*(5), 1581–1587.

Muñoz, A., Palgan, I., Morgan, D.J., Cronin, D.A., Whyte, P., & Lyng, J.G. (2011). Combinations of high intensity pulses and thermo-sonication for the inactivation of *Escherichia coli* in orange juice. *Food Microbiology, 28,* 1200-1204.

Muñoz, M, Caminiti I. M., Palgan I., Pataro G., Noci, F., Morgan, D, J., Cronin D. A., Whyte, P, Ferrari, G., & Lyng J. G. (2012) Effects on Escherichia coli inactivation and quality attributes in apple juice treated by combinations of pulsed light and thermosonication. *Food Research International, 45,* 299–305.

Nicorescu, I., Nguyen, B., Chevalier, S., & Orange, N. (2014) Effects of pulsed light on the organoleptic properties and shelf-life extension of pork and salmon. *Food Control, 44,* 138–145.

Oms-Oliu, G., Martin - Belloso, O., & Soliva-Fortuny, R. (2010). Pulsed light treatments for food preservation. A review. *Food and Bioprocess Technology, 3,* 13-23.

Ortega-Rivas, E., Ed. (2012). Pulsed light technology. In: Non-Thermal Food Engineering Operations, pp. 263–273, Food Engineering Series, New York:Springer ScienceCBusiness Media.

Palgan, I., Caminiti, I. M., Muñoz, A., Noci, F., Whyte, P., Mogan, D.J., Cronin, D.A., & Lyng, J.G. (2011a). Effectiveness of high intensity light pulse (HILP) treatments for the control of *Escherichia coli* and *Listeria innocua* in apple juice, orange juice and milk. *Food Microbiology, 28,* 14-20.

Palgan, I., Caminiti, I. M., Muñoz, A., Noci, F., Whyte, P., Mogan, D.J., Cronin, D.A., & Lyng, J.G. (2011b). Combined effect of selected non-thermal technologies on *Escherichia coli* and *Pichia fermentans* inactivation in an apple and cranberry juice blend and on product shelf life. *International Journal of Food Microbiology, 151,* 1–6.

753 Palmieri, L., & Cacace, D. (2005). High intensity pulsed light technology. In: Emerging
754 Technologies for Food Processing, pp. 279–306. Sun, D.-W., Ed., Elsevier Academic Press,
755 London.
756 Paskeviciute, E. Buchovec, I., & Luksiene, Z. (2011). High-power pulsed light for
757 decontamination of chicken from food pathogens: a study on antimicrobial efficiency and
758 organoleptic properties. *Journal of Food Safety, 31,* 61–68.
759 Pataro, G., Muñoz, A., Palgan, I., Noci, F., Ferrai, G., & Lyang, J.G. (2011). Bacterial
760 inactivation in fruit juices using a continuous flow pulsed light (PL) system. *Food Research*
761 *International*, *44*, 1642-1648.
762 Pollock, A.M., Pratap A.S., Hosahalli S.R., & Michael O.N. (2017). Pulsed light destruction
763 kinetics of *L. monocytogenes*. *Food Science and Technology*, *84*, 114-121.
764 Proulx, J., Hsu, L.C., Miller, B.M., Sullivan, G., Paradis, K., & Moraru, C.I. (2015). Pulsed-light
765 inactivation of pathogenic and spoilage bacteria on cheese surface. *Journal of Dairy Science*,
766 *98*(9), 5890-5898.
767 Rajkovic, A., Tomasevic, I., De Meulenaer, B., & Devlieghere F. (2017). The effect of pulsed
768 UV light on *Escherichia coli* O157:H7, *Listeria monocytogenes*, *Salmonella Typhimurium*,
769 *Staphylococcus aureus* and staphylococcal enterotoxin A on sliced fermented salami and its
770 chemical quality. *Food Control, 73,* 829-837.
771 Rajkovic, A., Tomasevic, I., Smigic, N., Uyttendaele, M., Radovanovic, R., & Devileghere, F.
772 (2010). Pulsed UV light as an intervention strategy against *Listeria monoytogens* and
773 *Escheria coli* 0157:H7 on the surface of a meat slicing knife. *Journal of Food Engineering,*
774 *100,* 446-451.
775 Rowan, N. J., MacGregor, S. J., Anderson, J. G., Fouracre, R. A., McIllvaney, L., & Farish, O.
776 (1999). Pulsed-light inactivation of food-related microorganisms. *Applied and Environmental*
777 *Microbiology*, *65*(3), 1312–1315.
778 Salinas-Roca, B., Soliva-Fortuny, R., Welti-Chanes, J., & Martín-Belloso, O. (2016). Combined
779 effect of pulsed light, edible coating and malic acid dipping to improve fresh-cut mango
780 safety and quality. *Food Control*, *66*, 190-197.
781 Smith, W.L., Lagunas-Solar, M.C., & Cullor, J.S. (2002). Use of pulsed ultraviolet laser light for
782 the cold pasteurization of bovine milk. *Journal of Food Protection*, *65*(9), 1480-1482.
783 Stoica, M., Mihalcea, L., Borda, D., & Alexe, P. (2013). Non-thermal novel food processing
784 technologies. An overview. *Journal of Agroalimentary Processes and Technologies*, *19*(2),
785 212-217.
786 Sun, D.W. (2005). Emerging Technologies for Food Processing. Food Science and Technology,
787 International Series. p. 278 - 280.
788 Valdivia-Nájar, C.G., Martín-Belloso, O., & Soliva-Fortuny, R. (2018). Impact of pulsed light
789 treatments and storage time on the texture quality of fresh-cut tomatoes. *Innovative Food*
790 *Science & Emerging Technologies*, *45*, 29-35.
791 Valdivia-Nájar, C. G., Martín-Belloso, O., Giner-Seguí, J., & Soliva-Fortuny, R. (2017).
792 Modeling the inactivation of Listeria innocua and Escherichia coli in fresh-cut tomato treated
793 with pulsed light. *Food and Bioprocess Technology*, *10*(2), 266-274.
794 Xenon. Sterilization Systems for High-Speed Surface Microbial Decontamination. (2016).
795 http://www.xenoncorp.com/news/xenons-steripulse-technology-3-6-log-bio-reduction/.
796 Accessed 28 February 2019.
797 Xu, W., & Wu, C. (2016). The impact of pulsed light on decontamination, quality, and bacterial
798 attachment of fresh raspberries. *Food Microbiology*, *57,* 135-143.

Xu, W., Chen, H., & Wu, C. (2016). Salmonella and Escherichia coli O157: H7 Inactivation, Color, and Bioactive Compounds Enhancement on Raspberries during Frozen Storage after Decontamination Using New Formula Sanitizer Washing or Pulsed Light. *Journal of Food Protection*, *79*(7), 1107-1114.

Xu, W., Chen, H., Huang, Y., & Wu, C. (2013). Decontamination of Escherichia coli O157: H7 on green onions using pulsed light (PL) and PL–surfactant–sanitizer combinations. *International Journal of Food Microbiology, 166*(1), 102-108.

Yi, J.Y., Lee, N.H. and Chung, M.S. (2016) Inactivation of bacteria and murine norovirus in untreated groundwater using a pilot-scale continuous-flow intense pulsed light (IPL) system. *LWT-Food Science and Technology, 66,* 108–113.

Zenklusen, M.H., Coronel, M.B., Castro, M.Á., Alzamora, S.M., & González, H.H.L (2018). Inactivation of Aspergillus carbonarius and Aspergillus flavus in malting barley by pulsed light and impact on germination capacity and microstructure. *Innovative Food Science and Emerging Technologies, 45,* 161-168.

814 **Figure captions:**

815 **Fig. 1.** Schematic diagram of a pulsed light chamber

816 **Fig. 2.** Schematic diagram of a continuous flow pulsed light system

817

818

Table 1: PL and other decontamination strategies in food

Food product	Decontamination method	Microorganism treated	Reduction (log_{10} CFU/mL)	Reference
Lettuce shreds	Wet PL	*Salmonella enterica*	1.5-2.8	Huang and Chen (2018)
	Chlorine		0.63-1.62	
Mango slices	PL	*Listeria innocua*	2.5	Salinas-Roca et al. (2016)
	Malic acid (2%)		2.9	
	Malic acid (2%) + PL		4.5	
Green onion leaves (L) and stem (S)	PL (30 and 60 s)	*Escherichia coli*	1.2 (L) and 0.9 (S)	Xu et al. (2013)
	Chlorine (10 and 100 ppm)		0.9-1.2 (L and S)	
	H_2O_2 (300 ppm)		0.4 (L) and 0.6 (S)	
	Thymol (0.2 mg/mL)		<0.5 (L and S)	
	Citric acid (1 mg/mL)		<0.5 (L and S)	

Table 2. Microbial reduction levels for liquid foods after innovative non-thermal processing

Food product	Microorganism treated	Operation conditions	Reduction (log_{10} CFU/mL)	Reference
Orange juice	*Escherichia coli*	Frequency (Hz): 3; Total fluence (J/cm^2): 5.10; Peak power (J/cm^2/pulse): 1.213; Pulse width (µs): 360; Exposure time (s): 2.81; Distance from the lamp (cm): 1.9	2.42	Muñoz *et al*. (2011)
Apple and orange juices, Milk	*Escherichia coli*	Frequency (Hz): 3; Total fluence (J/cm^2): 28; Peak power (J/cm^2/pulse): 1.17; Pulse width (µs): 360; Exposure time (s): 8; Distance from the lamp (cm): 2.5	Apple juice: 4.7 Milk: 1.06 Orange juice: 1	Palgan *et al. (*2011a)
	Listeria innocua		Apple juice: 1.93 Milk: 0.84 Orange juice: 1	
Apple and cranberry juice	*Escherichia coli* *Pichia fermentans*	Frequency (Hz): 18; Total fluence (J/cm^2): 3.3	1.8 – 6.0	Palgan *et al. (*2011b)
Apple and orange juices	*Listeria innocua*	Frequency (Hz): 3; Total fluence (J/cm^2): 4; Peak power (J/cm^2/pulse):1.21; Pulse-repetition-rate (pulses/s): 3; Discharge voltage (V): 3800; Pulse width (µs): 360; Distance from the lamp (cm):1.9	Apple juice: 2.98 Orange juice: 0.93	Pataro *et al*. (2011)
	Escherichia coli		Apple juice: 4.0 Orange juice: 2.90	
Apple juice	*Penicillium expansum*	Number of pulses: 40; Total fluence (J/cm^2): 32; Peak power (J/cm^2/pulse): 0.4; Pulse width (µs): 300; Distance from the lamp (cm): 0.60	3.76	Maftei *et al. (*2014)
Distilled water, whey, diluted whey and skimmed whey	*Listeria innocua*	Number of pulse: 10; Total fluence (J/cm^2): 11; Peak power (J/cm^2/pulse): 1.1; Discharge voltage (V): 3000; Pulse width (µs): 300	Whey and skimmed whey: <0.5 Diluted whey (3/4, 1/2, 1/4 and 1/8): 0.5, 1.4, 2.3 and 5.4 Distilled water: 5.0	Artíguez and Martínez Marañón (2015)
Apple, orange and strawberry juices	*Escherichia coli*	Frequency (Hz): 3; Total fluence (J/cm^2): 71.6; Peak power (J/cm^2/pulse): 1.213; Pulse-repetition-rate (pulses/s): 3; Pulse width (µs): 360; Exposure time (s): 60; Distance from the lamp (cm): 10	Apple juice: 2.1 Orange and strawberry juice: 0.3-0.8	Ferrario *et al. (*2015b)
	Listeria innocua		Apple juice:1.6 Orange and strawberry juice: 0.3-0.8	
	Salmonella enteritidis		Apple juice: 2.4 Orange and strawberry juice: 0.3-0.8	

	Saccharomyces cerevisiae		Apple juice: 1.0 Orange and strawberry juice: 0.3-0.8	
	Native flora		0.1-0.7	
Apple juice (commercial and natural)	*Alicyclobacillus acidoterrestris*	Frequency (Hz): 3; Total fluence (J/cm^2): 2.4-71.6; Peak power (J/cm^2/pulse): 1.27; Pulse-repetition-rate (pulses/s): 3; Discharge voltage (V): 3800; Pulse width (µs): 360; Exposure time (s): 2-60; Distance from the lamp (cm): 10	Commercial juice: 3.0 Natural juice: 1.5	Ferrario *et al.* (2015a)
	Saccharomyces cerevisiae		Commercial juice: 4.4 Natural juice: 2.0	
Mineral water, isotonic beverage, apple juice, orange juice, grape juice, carbonated beverage, plum juice, milk, coffee without milk	*Pseudomonas aeruginosa*	Total fluence (J/cm^2):0.97 for Mineral water and isotonic beverage; 12.7-24.35 for apple juice, carbonated beverage and plum juice; 29.21 for milk, coffee without milk, orange juice and grape juice.	Mineral water, isotonic beverage, apple juice, plum juice and carbonated beverage: 7.0 Orange juice, grape juice, milk, coffee without milk: 0.5-2.0	Hwang *et al.* (2015)
Goat milk	Escherichia coli	Total fluence (J/cm^2): 10; Peak power (J/cm2/pulse): 0.187; Exposure time (s): 8	6	Kasahara *et al.* (2015)
Apple juice (commercial and natural)	*Escherichia coli*	Total fluence (J/cm^2): 0.73; Peak power (J/cm^2/pulse): 0.398; Discharge voltage (V): 3800; Pulse width (µs): 360; Exposure time (s): 60; Distance from the lamp (cm): 10	3.1	Ferrario *et al. (*2016)
	Salmonella Enteritidis		4.2	
	Saccharomyces cerevisiae		1.8	
Water	*Murine norovirus*	Frequency (Hz): 5; Total fluence (J/cm^2): Distance from the lamp (cm): 9	3.35	Yi *et al.* (2016)
	Escherichia coli		4.79	
	Aerobic and facultative anaerobic		2.91	
Apple juice (commercial and natural)	*Saccharomyces cerevisiae*	Frequency (Hz): 3; Total fluence (J/cm^2): 71.6; Peak power (J/cm^2/pulse): 1.27; Discharge voltage (V): 3800 Pulse width (µs): 360; Exposure time (s): 60; Distance from the lamp (cm): 10	Commercial: 3.9 Natural: 1.0-2.0	Ferrario and Guerrero *(*2017)
Turnip juice	*Candida inconspicua*	Total fluence (J/cm^2): 19.71; Discharge voltage (V): 3800 Pulse width (µs): 360; Exposure time (s): 60; Distance from the lamp (cm): 5	2.80	Karaoglan *et al.* (2017)
Apple juice	*Alicyclobacillus acidoterrestris*	Frequency (Hz): 3; Total fluence (J/cm^2): 71.6; Peak power (J/cm^2/pulse): 1.27; Discharge voltage (V): 3800	3.0--3.5	Ferrario *et al. (*2018)

	Pulse width (µs): 360; Exposure time (s): 60; Distance from the lamp (cm): 10

Table 3: Microbial reduction levels for meat, fish, derived products and cheese after pulsed light processing

Food product	Microorganism treated	Operation conditions	Reduction (log_{10} CFU/g)	Reference
Stainless steel in contact with meat	*Listeria monocytogenes* *Escherichia coli*	Total fluence (J/cm^2): 3; Pulse width (µs): 300; Discharge voltage (V): 3000; Distance from the lamp (cm): 10	6.5	Rajkovic *et al.* (2010)
Tuna *carpaccio* Beef *carpaccio*	*Listeria monocytogenes*	Total fluence (J/cm^2): 11.9; Peak power (J/cm^2/pulse): 0.175; Pulse width (µs): 250	Beef carpaccio: 0.9 Tuna carpaccio: 0.7	Hierro *et al.* (2012)
	Escherichia coli		Beef carpaccio: 1.2	
	Salmonella Typhimurium		Beef carpaccio: 1.0	
	Vibrio parahaemolyticus		Tuna carpaccio: 1.0	
Shrimp, salmon, flatfish	*Listeria monocytogenes*	Frequency (Hz): 5; Number of pulse: 6900; Total fluence (J/cm^2): 12.1; Peak power (J/cm^2/pulse): 0.00175; Exposure time (s): 1380	Shrimp: 2.4 Salmon: 2.1 Flatfish: 1.9	Cheigh *et al.* (2013)
Dry cured meat products (salchichón and loins)	*Listeria monocytogenes*	Total fluence (J/cm^2): 11.9; Peak power (J/cm^2/pulse): 0.7; Pulse width (µs): 250	Salchichón: 1.81 Loins: 1.61	Ganan *et al.* (2013)
	Salmonella enterica serovar Typhimurium		Salchichón: 1.48 Loins: 1.73	
Raw pork roast, roast pork and raw salmon	*Aerobic flora*	Frequency (Hz): 1; Total fluence (J/cm^2): 30; Distance from the lamp (cm): 3	Raw pork roast: 0.96 Roast pork: 0.99 Raw Salmon: 0.7	Nicorescu *et al.* (2014)
	Pseudomonas fluorescens		1.0-1.5	
White cheddar cheese	*Listeria innocua*	Total fluence (J/cm^2): 3.1; Pulse width (µs): 360; Pulse-repetition-rate (pulses/s): 3;	3.0	Proulx *et al.* (2015)
	Pseudomonas fluorescens		3.0	
	Escherichia coli		5.0	
Seafood Isolates	*Listeria monocytogenes* *Listeria innocua*	Pulse energy (J/cm^2): 0.316; Peak power (J/cm^2/pulse): 0.053 Pulse width (µs): 325; Distance from the lamp (cm): 11	2.4 5.4	Lasagabaster *et al.* (2017)
Sliced fermented salami	*Listeria monocytogenes* *Escherichia coli* *Salmonella Typhimurium* *Staphylococcus aureus*	Total fluence (J/cm^2): 3; Number of pulses: 1; Pulse width (µs): 300; Discharge voltage (V): 3000; Distance from the lamp (cm): 10	2.24 2.29 2.25 2.12	Rajkovic *et al.* (2017)
Pork skin	*Salmonella typhimurium* *Yersinia enterocolitica*	Total fluence (J/cm^2): 19.11; Distance from the lamp (cm): 8.3; Pulse width (µs): 300; Treatment time: 30 s	2.97 4.2	Koch et al. (2019)
Pork loin	*Salmonella typhimurium*	Total fluence (J/cm^2): 0.52-19.11; Distance from the	0.4-1.6	

	Yersinia enterocolitica	lamp (cm): 8.3-13.4; Pulse width (µs): 300; Treatment time: 1-30 s	0.4-1.7	

Table 4: Microbial reduction levels for fruits and vegetables after pulsed light processing

Food product	Microorganism treated	Operation conditions	Reduction (log_{10} CFU/g)	Reference
Tomato fruit	Microflora in skin and peduncle	Total fluence (J/cm^2): 4 (Microflora) and 2.2 (S. cerevisiae); Discharge voltage (V): 2500; Pulse width (µs): 250	1.0	Aguiló-Aguayo *et al.* (2013)
	Saccharomyces cerevisiae		2.3	
Avocado	*Aerobic mesophilic microorganisms*	Total fluence (J/cm^2): 14; Pulse width (µs): 360; Distance from the lamp (cm): 5	1.20	Aguiló-Aguayo *et al.* (2014)
Green Onions	*Escherichia coli*	Total fluence (J/cm^2): 5; Peak power (J/cm^2/pulse): 1.27; Exposure time (s): 5	Spot inoculation: 4.8 for stems and 4.1 leaves Dip inoculation: 0.2 for stems and 0.6 leaves	Xu *et al.* (2013)
Blueberries	*Escherichia coli*	Total fluence (J/cm^2): 56.1; Peak power (J/cm^2/pulse): 1.27; Discharge voltage (V): 3800; Pulse width (µs): 360; Exposure time (s): 60; Distance from the lamp (cm): 15	4.3 calyx and >6.7 skin	Huang and Chen (2014)
	Salmonella		4.1 calyx and 5.7 skin	
Fresh-cut apples slices	*Total viable counts*	Frequency (Hz): 0.5; Pulse energy (J/cm2): 17.5 Pulse width (µs): 50; Distance from the lamp (cm): 1	1.0	Ignat *et al.* (2014)
	Lactobacillus brevis		3.0	
	Listeria monocytogenes		2.7	
Endive salad Mung bean sprouts	*Escherichia coli*	Frequency (Hz): 1; Total fluence (J/cm^2): 3; Distance from the lamp (cm): 10	Endive salad: 2.34 Mung bean sprouts: 1.91	Kramer *et al.* (2015)
	Listeria innocua		Endive salad: 2.54 Mung bean sprouts: 1.55	
Lamb's lettuce	*Native microflora*	Total fluence (J/cm^2): 11.0; Discharge voltage (V): 3000; Pulse width (µs): 50; Distance from the lamp (cm): 10	~ 4.7	Manzocco *et al.* (2015)
	Salmonella entérica		~ 5.5	
	Listeria monocytogenes		~ 6	
	Escherichia coli		5.3	
Spinach	Mesophilic aerobic bacteria	Total fluence (J/cm^2): 20 and 40; Pulse width (ms): 0.3	0.5-2.2	Agüero *et al.* 2016
	Psychrotrophic bacteria			
	Coliforms			
	Listeria spp.			
	Yeasts and molds			
Fresh-cut apples	Mesophilic and psychrophilic	Number of pulse: 40; Total fluence: (J/cm^2): 16; Peak	>1.55	Avalos *et al.* (2016)

slices	microbial	power (J/cm^2/pulse): 0.4; Pulse width (µs): 300		
	Moulds and yeast		2.3	
Cantaluope melon	Total viable count	Total fluence (J/cm^2): 15.6 followed by storage at 4 ± 1 °C for 28 days. Peak power (J/cm^2/pulse): 0.3; Distance from the lamp (cm): 10	1.39	Koh *et al.* (2016b)
	Yeast and moulds		1.45	
Cantaluope melon	Total viable count Yeast and moulds	Fluence (J/cm^2): 0.9 every 48 h up to 28 days of storage at 4 ± 1 °C; Total fluence (J/cm^2): 11.7;Peak power (J/cm^2/pulse): 0.3 Distance (cm): 10 cm	~6	Koh *et al.* (2016a)
Raspberries	*Salmonella*	Frequency (Hz): 1; Total fluence (J/cm^2): 28.2; Peak power (J/cm^2/pulse): 1.27; Discharge voltage (V): 3000; Exposure time (s): 30; Distance from the lamp (cm): 13	4.5	Xu & Wu (2016)
	Escherichia coli		3.9	
	Total viable count		1.5	
	Yeast and moulds		1.6	
	Salmonella spp.		4.5	
Raspberries	*Escherichia coli*	Fluence (J/cm^2): 14.3; Pulse-repetition-rate (pulses/s): 3; Exposure time (s): 15; Storage time (m): 3; Storage temperature (°C): -20	1-3 with SDS	Xu *et al.* (2016)
	Salmonella Newport			
Endive salad Mung bean sprouts	*Listeria innocua*	Frequency (Hz): 1; Peak power (J/cm^2/pulse): 580; Discharge voltage (V): 2000; Exposure time (s): 60; Distance from the lamp (cm): 5	Endive salad: 2.5 Mung bean sprouts: 1.6	Kramer *et al.* (2017)
	Total viable count		Endive salad: 2.0 Mung bean sprouts: 0.45	
Strawberries and blueberries	*Murine norovirus (MNV-1)*	Total fluence (J/cm^2): 22.5; Exposure time (s): 24; Distance from the lamp (cm): 16	Strawberries: 0.9 Blueberries: 3.8	Huang *et al.* (2017)
	Escherichia coli		Strawberries: 1.9 Blueberries: 5.7	
	Salmonella		Strawberries: 2.1 Blueberries: 4.2	
Blueberries	*Salmonella*	Total fluence (J/cm^2): 6; Peak power (J/cm^2/pulse): 0.066; Pulse-repetition-rate (pulses/s): 3; Pulse width (µs): 360; Exposure time (s): 30	0.9 spot inoculation and 0.6 dip inoculation	Cao *et al.* (2017)
Fresh-Cut tomatoes	*Listeria innocua*	Total fluence (J/cm^2): 8; and kept cold at 4 °C for 20 days	0.9	Valdivia-Nájar *et al.* (2017)
	Escherichia coli		1.4	
Fresh-Cut tomatoes	*Psychrophilic bacteria*	Total fluence (J/cm^2): 4, 6, and 8; and kept cold at 5 °C for 20 days	Up to 1.8	Valdivia-Nájar *et al.* (2018)
	Molds and yeasts		Up to 0.5	
Sesame seeds	*Total viable count*	Total fluence (J/cm^2): 44.46; Discharge voltage (V): 2400; Exposure time (s): 120; Pulse width (ms): 3.0	1.46	Hwang *et al.* (2017)

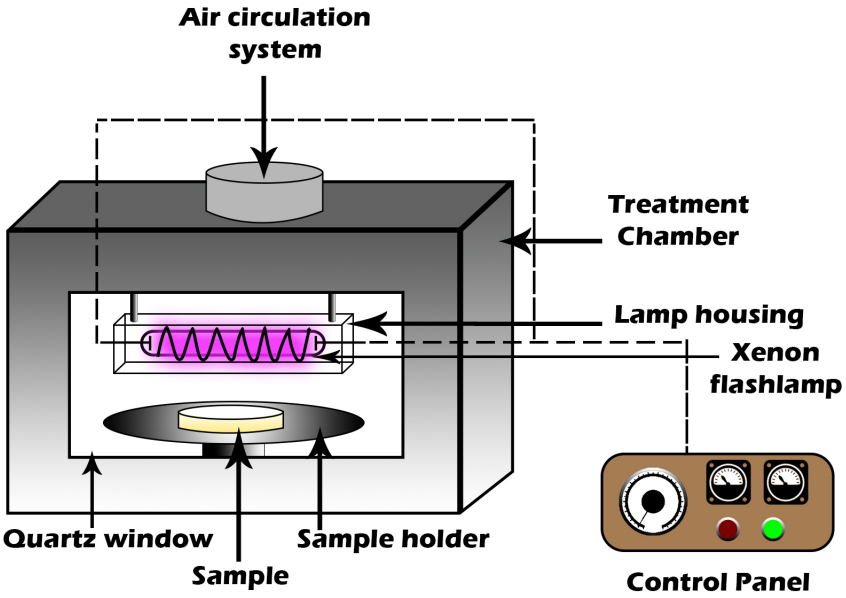
Malting barley	*Aspergillus carbonarius* *Aspergillus flavus*	Total fluence (J/cm^2): 18; Pulse width (µs): 360; Exposure time (s): 15; Distance from the lamp (cm): 10	1.2 1.7	Zenklusen *et al.* (2018)

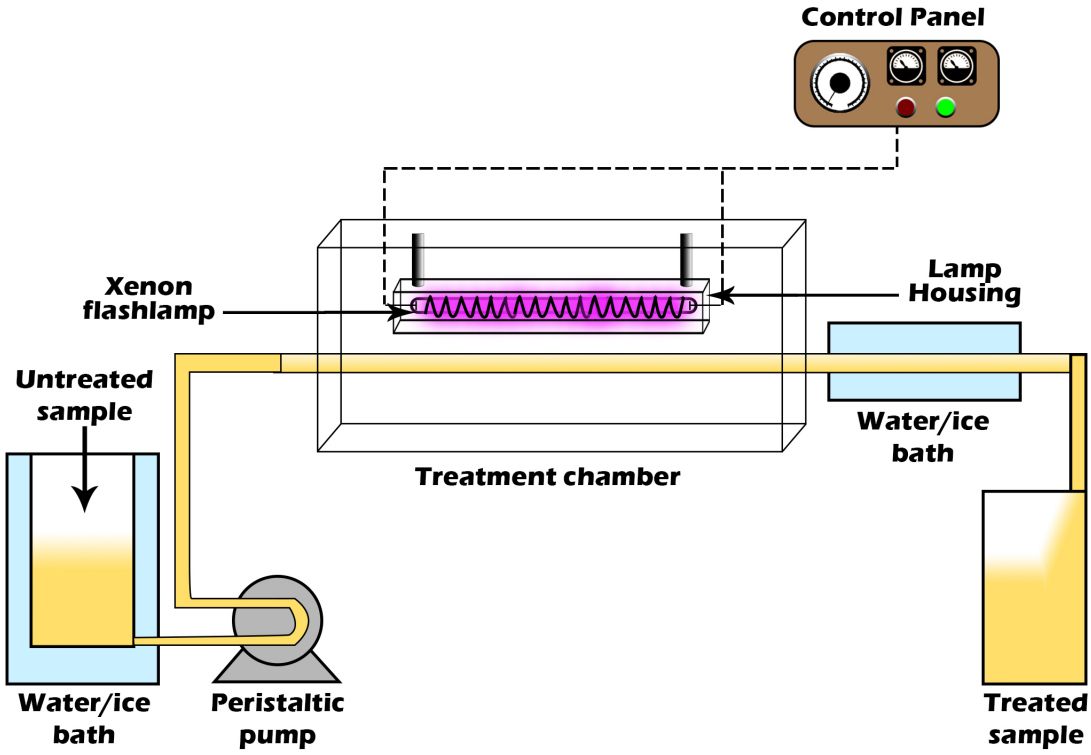
Table 5: Microbial reduction levels in foods using PL in combination with other technologies

Food product	Method of generation	Microorganism treated	Operation conditions	Reduction (log_{10} CFU/mL)	Reference
Orange juice	HILP + TS	*Escherichia coli*	Frequency: 3 Hz; Total fluence (J/cm^2): 5.10; Peak power (J/cm^2/pulse): 1.213; Pulse width (µs): 360; Exposure time (s): 2.81; Distance from the lamp (cm): 1.9	3.93	Muñoz *et al.* (2011)
Apple juice	PL + TS	*Escherichia coli*	Frequency (Hz): 3; Total fluence (J/cm^2): 5.1; Pulse width (µs): 360; Exposure time (s): 1.52 TS: (24 kHz, 100 µm) at 40 °C for 2.9 min or 50 °C for 5 min	4.9 at 40 °C 5.9 at 50 °C	Muñoz *et al.* (2012)
Green Onions (stems and leaves)	WPL	*Escherichia coli*	Total fluence (J/cm^2): 56.1; Peak power (J/cm^2/pulse): 1.27; Exposure time (s): 60	<u>Sopt inoculaion</u>: Stems: 4.1 Leaves: 4.6 <u>Dip inoculation:</u> Stems: 0.9 Leaves: 1.2	Xu *et al.* (2013)
	PL + 100 ppm chlorine			Stems: 0.9 Leaves: 2.4	
	PL + 1000 ppm SDS			Stems: 1.4 Leaves: 3.1	
Apple juice (natural and commercial)	PL + US	*Alicyclobacillus acidoterrestris*	Total fluence (J/cm^2): 71.6; Peak power (J/cm^2/pulse): 1.27; Discharge voltage (V): 3800; Pulse width (µs): 360; Exposure time (s): 60; Distance from the lamp (cm): 10 US: 30 min, 44 ºC±1	Commercial juice: 5.8 Natural juice: 2.0	Ferrario *et al.* (2015a)
		Saccharomyces cerevisiae		Commercial juice: 6.4 Natural juice: 3.0	
Blueberries	WPL	*Escherichia coli*	Peak power (J/cm^2/pulse): 1.27; Total fluence (J/cm^2): 56.1 Time (s): 60; Pulse width (µs): 360; Discharge voltage (V): 3800; Distance	Calyx: 3.0 Skin:5.8	Huang and Chen (2014)
		Salmonella		Calyx: 3.6 Skin:5.9	

			from the lamp (cm): 15		
Green Beans	HHP or PL + coating (modified chitosan containing a nanoemulsion of mandarin essential oil)	*Listeria innocua*	Discharge voltage (V): 3800; Pulse width (µs): 360; Exposure time (s): 60; Distance from the lamp (cm): 20; 400 MPa and 5 min for HHP; 1.2 x 10^5 J/m^2 per bean side for PL	HHP + coating: 4 PL + coating: 2	Donsi *et al.* (2015)
Raspberries and blueberries	WPL WPL + 1% H_2O_2	*Salmonella*	Peak power (J/cm^2/pulse): 0.298; Time (s): 60; Pulse width (µs): 360; Distance from the lamp (cm): 16	Raspberries: 3.0 for WPL and 4.0 for WPL+H_2O_2 Blueberries: 5.6 for WPL and WPL+ H_2O_2	Huang *et al.*, (2015)
Raspberries (R) and strawberries (S)	WPL WPL + 1% H_2O_2	*Escherichia coli*	Total fluence (J/cm^2): 53.9 for raspberries and 63.2 for strawberries; Pulse width (µs): 360; Exposure time (s): 60	S: 2.2 and 3.3 with H_2O_2	Huang and Chen (2015)
				R: 4.4 and 5.3 with H_2O_2	
		Salmonella		S: 2.4 and 2.8 with H_2O_2	
				R: 3.2 and 4.9 with H_2O_2	
		Murine norovirus (MNV-1)		S: 1.8 and 2.2 with H_2O_2	
				R: 3.6 and 2.5 with H_2O_2	
Apple juice (natural and commercial)	PL + US	*Escherichia coli*	Frequency (Hz): 3; Pulse energy (J/cm^2): 0.73; Peak power (J/cm^2/pulse): 0.398; Pulse-repetition-rate (pulses/s): 3; Discharge voltage (V): 3800; Pulse width (µs): 360; Exposure time (s): 60; Distance from the lamp (cm): 10; US: 30 min at room temperature	5.9	Ferrario *et al.* (2016)
		Salmonella Enteritidis		6.3	
		Saccharomyces cerevisiae		3.7	
Blueberries	WPL	*Salmonella*	Total fluence (J/cm^2): 9; Peak power (J/cm^2/pulse): 0.066; Pulse-repetition-rate (pulses/s): 3; Pulse width (µs): 360 Exposure time (s): 30	4.4 spot inoculation and 0.8 dip inoculation	Cao *et al.* (2017)
Apple juice (natural and commercial)	PL + US	*Saccharomyces cerevisiae*	Total fluence (J/cm^2): 71.6; Peak power (J/cm^2/pulse): 1.27; Discharge voltage (V): 3800; Pulse width (µs): 360; Distance from the lamp (cm): 10 US: 30 min at 20 ºC or 44 ºC	At 20 ºC: Commercial: 4.9 Natural: 3.9 At 44 ºC: Commercial: 6.4 Natural: 5.8	Ferrario *et al.* (2017)
Iceberg lettuce	PL + Chlorine washing	*Salmonella enterica*	Peak power (J/cm^2/pulse): 0.14; Pulse-repetition-rate (pulses/s): 3; Pulse width (µs): 360	1.5-2.7	Huang and Chen (2018)

PL: Pulsed Light; HILP: High Intensity Light Pulses; TS: Thermosonication; US: Ultrasonics; WPL: Water-assisted pulsed light; SDS: Dodecilsulfato sódico; H_2O_2: HHP: High hydrostatic pressure.





Highlights

► Pulsed light (PL) have emerged lately as an alternative to traditional disinfection and preservation methods

► The combination of PL with other techniques can improve the effectiveness of the decontamination process

► PL can have a negative impact on the sensory properties of food products