



# Current Status of Pulsed UV Light Technology for Food, Water, and Food Processing Surface Decontamination

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## Abstract

As the world's population grows, it is becoming more and more challenging for people to access safe and nutritious food due to contamination issues. Decontamination of foods, water/wastewater, packaging materials, and contact surfaces are essential to eliminate the harmful microorganisms. Furthermore, conventional decontamination technologies lead to some problems in the targeted food product, such as loss of nutrients, chemical residues in the foods, chemical wastes affecting natural sources, and an increase in energy consumption. Therefore, novel decontamination technologies are needed. Especially, non-thermal, innovative, and emerging decontamination technologies are getting significant attention. Among these technologies, Pulsed UV light (PUV) is one of the non-thermal technologies used for decontamination purposes. PUV consists of a broad spectrum from ultraviolet to infrared range, and is rich in the highly germicidal UV-C light range. In the PUV system, high-intensity electromagnetic energy is stored and emitted as short-duration, high-intensity light pulses. The PUV decontamination technique is more sustainable and environmentally friendly than conventional techniques due to its fast decontamination time, no chemical residues, and lower energy requirements. Furthermore, it has less negative impact on the quality characteristics and nutritional values of the targeted product compared to traditional decontamination techniques. Therefore, this review presents recent PUV applications for the decontamination of solid and liquid foods, water/wastewater, food packaging materials and contact surfaces. In particular, the generation of PUV, the advantages and limitations of PUV applications, decontamination mechanisms throughout the target material, and the effect of PUV application on the product quality have been discussed.

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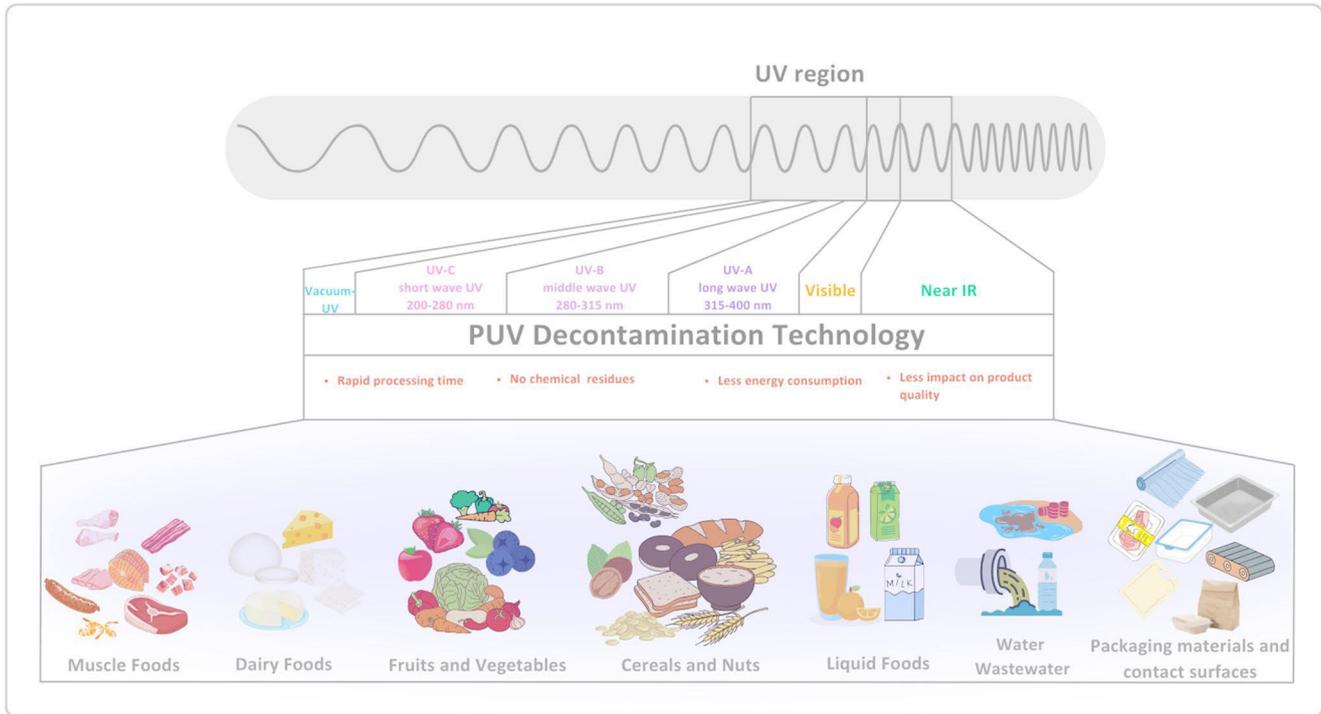
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## Graphical Abstract



**Keywords** Pulsed ultraviolet light · Non-thermal · Decontamination · Food safety · Food processing

## Introduction

In recent years, there is still a concern about access to safe, high-quality, and nutritious food by consumers [1]. Foods contaminated with pathogenic microorganisms, such as *Escherichia coli* O157:H7, *Campylobacter jejuni*, *Clostridium perfringens*, *Listeria monocytogenes*, *Staphylococcus aureus*, and *Salmonella* spp. causes serious and harmful impacts on human health all around the world and is a major public health concern nowadays [2]. Every year, throughout the world, unsafe food causes 600 million foodborne diseases and 420,000 fatalities [3]. Many traditional technologies have been using for microbial decontamination in the food industry, for example, thermal processes and preservatives or chemicals for the extent of shelf-life of desired food products [1]. Generally, most foods are treated under heat to ensure desired level of decontamination, which involves briefly heating foods at temperatures between 60 and 100 °C for 30 s to 2–5 min. Unfortunately, thermal decontamination methods cause undesirable organoleptic and nutritional changes in the product. For example, products or compounds that are temperature sensitive can degrade quickly, causing changes in nutritional value, color, texture, and generation of off-flavors and harmful

compounds. Nevertheless, the use of chemicals for microbial decontamination can increase toxicity and generate undesirable compounds or by-products in the foods [4, 5]. Due to these negative impacts, novel, sustainable, and non-thermal decontamination techniques are required in the food industry. In recent years, there has been a strong interest in novel non-thermal decontamination technologies. Pulsed UV light (PUV) is one of these non-thermal decontamination technologies. Among these non-thermal and emerging technologies, PUV and UV light-emitting diode (UV-LED) are getting significant attention for the decontamination of foods, packaging materials, and water/wastewater as well as processing equipments.

Therefore, the main purposes of this review are to discuss recent applications of the PUV decontamination technique in solid, liquid, packaging materials, water/wastewater, and food-contact surfaces and the effect of the PUV application on product quality parameters, including texture, color, bioactive compound content, protein and lipid oxidation, and post-harvest application. Also, this review paper explains the fundamentals of PUV, including the generation of PUV light, different types of PUV decontamination equipment, advantages and challenging factors in PUV decontamination applications. Additionally, this review paper provides

an in-depth explanation of the effects of PUV irradiation on the decontamination mechanism of microorganisms, which includes photochemical, photothermal, and photophysical effects.

### Fundamentals of Ultraviolet (UV), UV Light-emitting Diodes (UV-LED), and Pulsed UV Light (PUV)

The interaction between light and matter can be described by ultraviolet light (UV), UV-LED, and PUV as follows. Atoms and ions are made up of electron orbiting a protons and neutrons nucleus. Each orbital contains a distinct energy state occupied by electrons; the electrons that are nearest to the nucleus have lower energy, while those that are farther away have higher energy. A distinct amount of energy is generated as photons of light when electrons move from having a higher energy ( $E_2$ ) to having lower energy ( $E_1$ ) and which can be identified by the use of the wavelength of light (Eq. 1) [2, 6].

$$E = E_2 - E_1 = hv = \frac{hc}{\lambda} \quad (1)$$

Where, ( $E$ ) is the photon energy ( $eV$  or  $kJ/Einstein$ ),  $h$  is Planck's constant ( $6.626 \times 10^{-34}$   $J/second$ ),  $v$  is light frequency ( $s^{-1}$ ),  $c$  is the light speed in vacuum environment ( $2.998 \times 10^8$   $m/s$ ), and  $\lambda$  is the wavelength of light ( $m$ ). Also, this equation demonstrate that higher photon energy is produced when using shorter wavelengths.

UV is generated artificially by mercury lamps, which emit an electromagnetic radiation spectrum ranging from 100 to 400 nm. The UV light spectrum is divided into four regions with different characteristics: vacuum-UV (100–200 nm), UV-C (200–280 nm), UV-B (280–315 nm), and UV-A (315–400 nm) [4, 6]. Furthermore, these types of UV regions create changes during the application period on the target material: UV-A causes tanning, which makes a change in human skin; UV-B can be responsible for skin burning and result in skin cancer; UV-C is decontaminate bacteria and viruses; and all substances can be absorbed by vacuum-UV and can be transmitted only in a vacuum [6].

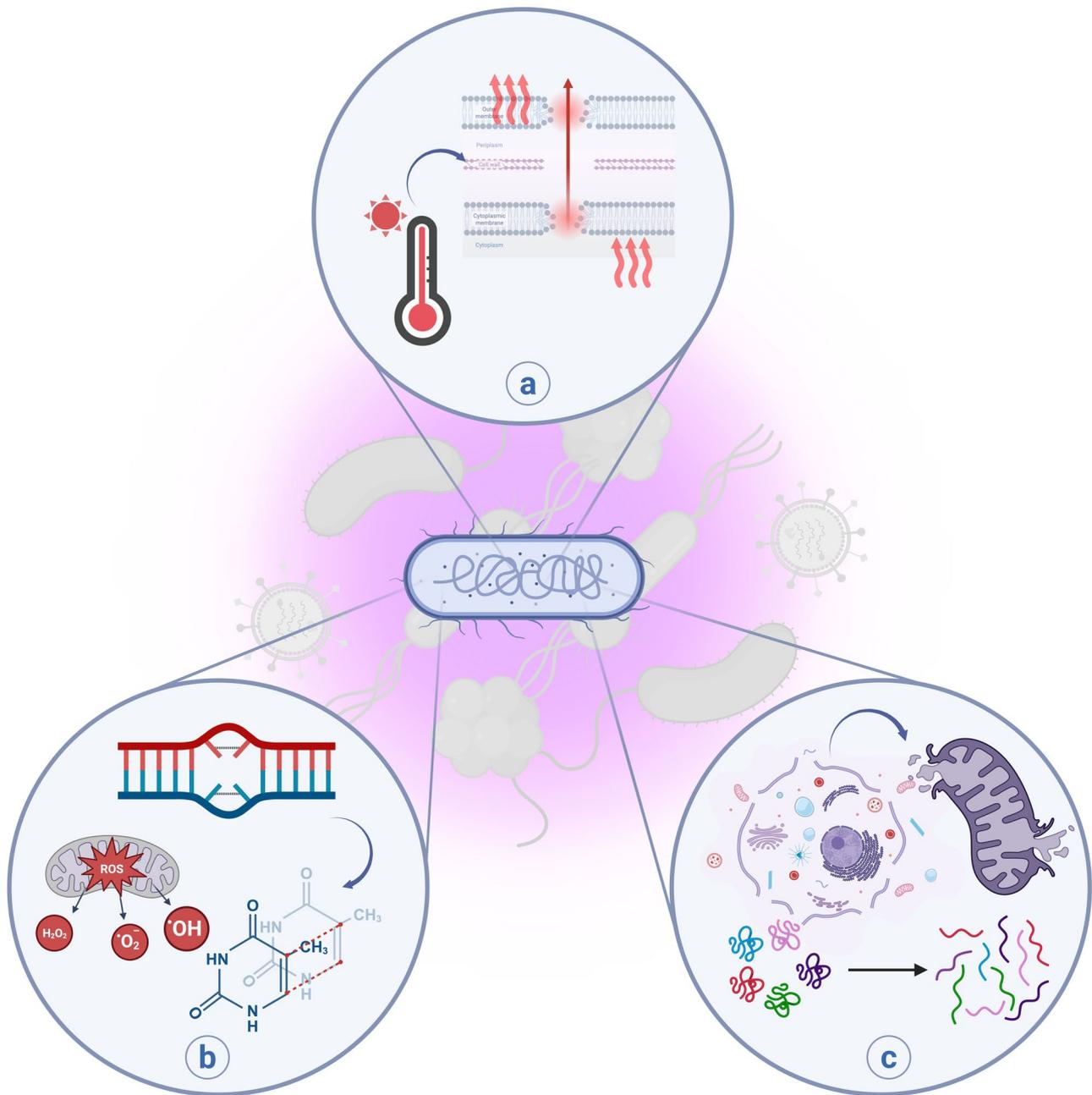
Light emitting diodes (LEDs) are one of the significant sources of ultraviolet light technology [7]. LEDs are made up negative and positive semiconductors, these are emitted light when certain voltage is imposed through the both terminals (p-n junction or hole and electron) and to generate band gaps [7, 8]. Different semiconductor materials emit light in different wavelengths, emission of wavelengths depend on a unique property of the semiconductors called the 'band gap'. Materials of semiconductors are usually present as direct band gaps, and these are very effective in the generation of light from electrical current, and this phenomenon

called as electroluminescence [7]. These semiconducting materials generate light with a narrow spectrum, which is significantly different from conventional light sources [8]. As previously emphasized, LEDs use various semiconducting materials to emit light at different wavelengths, such as, 400–450 nm with gallium nitrite (GaN) semiconducting material is responsible for blue and 620–750 nm with GaAsP is responsible for red. III-nitrite, aluminum gallium nitrite (AlGaN), GaN, and aluminum nitrite (AlN) based materials are mostly used for the generation of UV-LEDs (200–400 nm). The emitted photon's energy and the emitted light's wavelength increase with the material's band gap [7]. UV-LEDs show a germicidal effect when they emit light with wavelengths shorter than 300 nm [4].

PUV is an emerging and non-thermal food decontamination technology that uses high-intensity short-duration pulses rich in UV-C light [4, 9]. Conventional UV light systems including mercury lamps with low-, medium-, and high-pressure modes, continuously emit radiation. On the other hand, in PUV systems, over a short duration ( $10^{-2}$  s), the electromagnetic energy is stored in a capacitor and then released as short-duration ( $10^{-9}$  s) high-intensity light pulses [2, 10]. PUV is generated by stimulating inert gases (e.g., Ar, Kr, Xe) in a flash lamp and colliding inert gas molecules using an electric pulse [1]. These specific condition allows ionized gas molecules to generate a wide spectrum of light between the UV and near-infrared spectrum (200–1100 nm) [2]. PUV application enables 1–20 flashes with an energy density ranging from 0.01 to 50 J/cm. The application of PUV for the production, processing, and handling of food materials and the decontamination of food contact surfaces were approved by the U.S. Food and Drug Administration (FDA) [11]. The usage of PUV decontamination with xenon lamps with surface emission of wavelengths between 200 and 1100 nm and pulse width wavelengths between 200 and 1100 nm was commonly used. Additionally, the total treatment should not exceed 12 J/cm<sup>2</sup> and 2 ms according to the FDA's approval.

### Mode of Inactivation Mechanisms of UV-light and Pulsed-UV Light

UV-light enables the decontamination of targeted microorganisms, which is based on several complex physicochemical processes [1]. The mode of inactivation mechanism of UV-light is associated with photochemical, photothermal, and photophysical effects on the targeted microorganism (Fig. 1). Also, these photo-effects depend on the targeted microorganism, the nature of the material, and the fluence. Studies show that the UV range is the most effective range, with the UV-C region (200–280 nm) playing an important



**Fig. 1** Inactivation mechanism of the PUV; (a) photothermal effect; (b) photochemical effect; (c) photophysical effect. This figure was generated using BioRender under Biorender licence (<https://www.biorender.com/>)

key factor for the decontamination of microorganisms in the spectral range and theoretical decontamination wavelength of 253.7 nm [1]. The wavelength of 253.7 nm effects the O-H, C-C, C-H, C-N, H-N, and S-S bonds when it is absorbed [6]. This effect causes the breakdown of bonds and leads to the decontamination of microorganisms. Absorption of UV-C radiation leads to the generation of DNA photoproducts, which are cyclobutene-pyrimidine dimers (CPDs), pyrimidine 6 – 4 pyrimidone (6-4PP), and these photoproducts

prohibit transcription and replication processes [12]. However, UV-A radiation is less absorbed by DNA than UV-C and UV-B, which generates insufficient mode to damage the DNA of targeted microorganism for decontamination [13]. Decontamination of the targeted microorganism can be occurred directly or indirectly by the absorption of UV light. Direct decontamination occurs when by DNA of microbial cells absorbs the incident light, which causes disruption of the structure. In indirect decontamination, UV

light radiation interacts with cellular chromophores acting as photosensitizers, resulting in the formation of reactive oxygen species (ROS) [12]. Increasing formation of ROS leads to mutations, growth delays and destruction of cellular components, which are proteins, nucleic acids, DNA, lipids, and membranes (Fig. 2) [13, 16]. Furthermore, UV light irradiation can reduce the protective enzyme activity, such as catalase, glutathione peroxidase, and superoxide dismutase. Decreasing in protective enzyme activity can lead to the accumulation of ROS, which results in the inactivation of microorganisms [16].

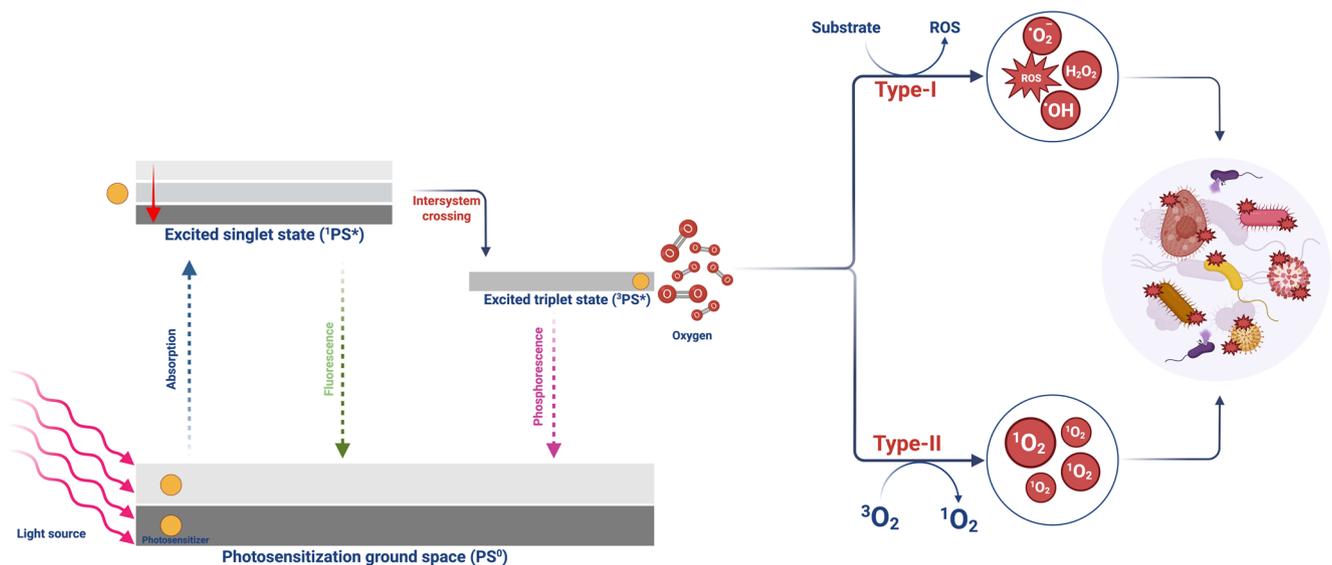
On the other hand, PUV is rich in UV light spectrum and its decontamination mechanism attributed to the UV light region. High peak power, short duration, and the capacity to adjust the pulse duration and frequency of flash lamp can affect the decontamination mechanism. Also, no killing effect has been observed when a filter applied to remove the UV region below 320 nm. In contrast, the killing effect has been observed when the visible and infrared region applied with high peak power [12, 17]. There are some mechanism to explain the decontamination behavior of PUV, including photochemical, photothermal, and photophysical. Additionally, all of these mechanism related to the UV region of the spectrum.

## Photochemical Mechanism

Researchers clearly indicated that the significant reason for PUV decontamination mechanism is a photochemical effect similar to UV-light in terms of photochemical effect [1]. The crucial step for the germicidal effect of PUV irradiation is the absorption of UV light by the DNA of microorganisms,

which generates the pyrimidine dimers (mostly thymine dimers) (Fig. 1b) [1, 9]. The formation of thymine-thymine dimer is the main photochemical effect on the decontamination of microorganisms. Also, in microorganisms, some generation or breakdown of chemical bonds can occur due to PUV irradiation [12]. Krishnamurthy et al. [18] have studied the decontamination of *Staphylococcus aureus* by PUV, and their results indicated that some *S. aureus* cells were decontaminated due to the thymine dimer formation without any structural changes.

The photochemical effect of PUV light has another effect, called photosensitization [1]. Most researchers suppose that photosensitization has high a potential for decontamination of microorganisms, including, bacteria, fungi, and viruses [19]. Photosensitization is a process that includes the aggregation of photoactive compounds in the target microorganism and then emitting with visible light. The microbial decontamination mode is generated when photosensitizers interact with light in the presence of oxygen [9]. The decontamination mechanism of photosensitization processes can lead to the breakdown of single stranded and double stranded DNA [20]. Photosensitization has two types of decontamination modes, type-I and type-II. In type-I mode, different types of ROS can be generated through Fenton reaction with the presence of oxygen, including hydrogen peroxide ( $H_2O_2$ ), hydroxyl radical ( $\cdot OH$ ), and superoxide radical anion ( $O_2^{\cdot -}$ ). These ROS components have a high oxidative effect on biomolecules and lead to biological damage. On the other hand, in the type-II mode, highly reactive singlet oxygen ( $^1O_2$ ) is generated due to the transfer of energy to molecular oxygen by an excited photosensitizer. This ROS promotes the cell membrane disruption due to



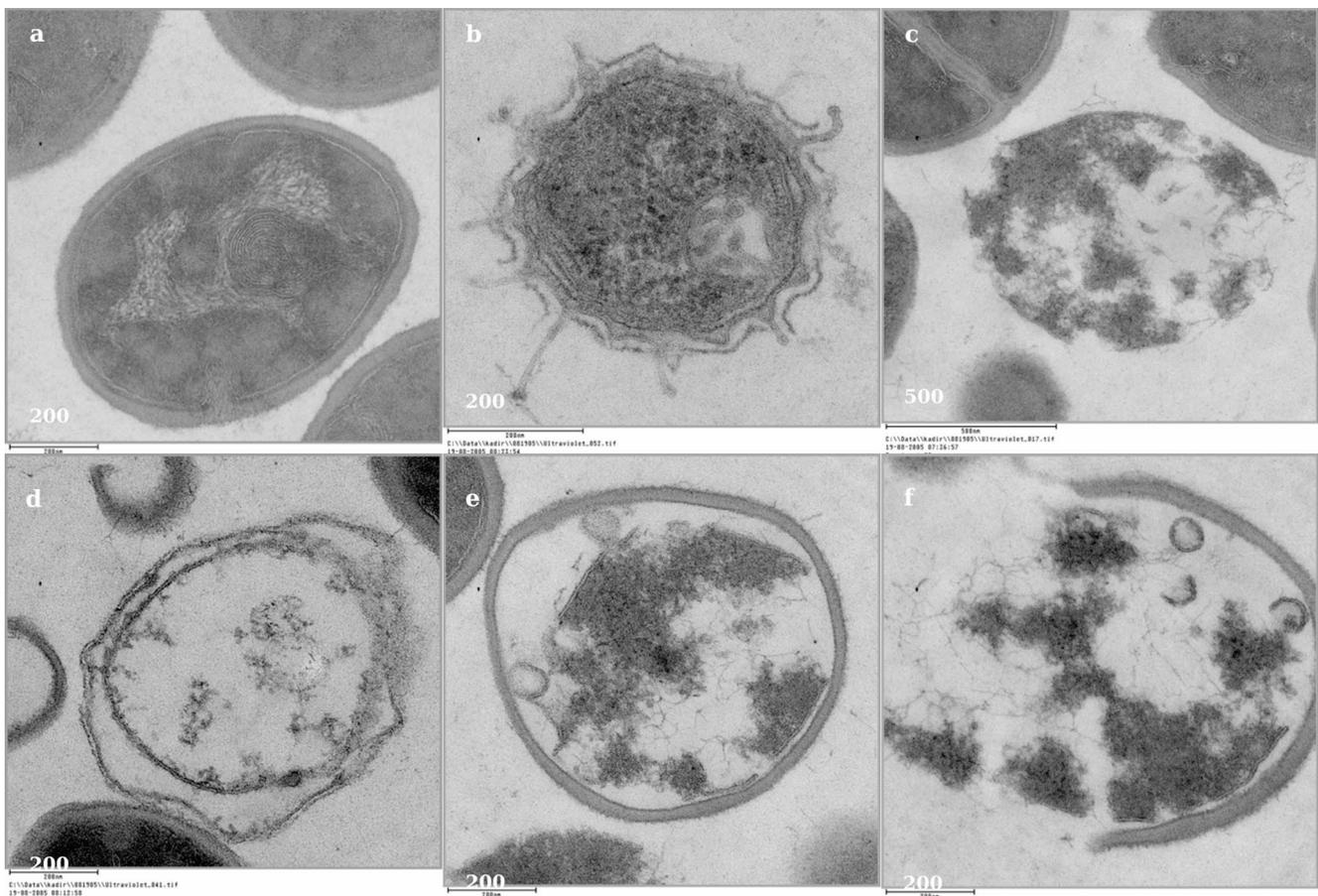
**Fig. 2** Photosensitization mechanism and effect on microorganism (adapted [14, 15]). This figure was generated using BioRender under Biorender licence (<https://www.biorender.com/>)

photo-oxidation of biomolecules (proteins and lipids, etc.) (Fig. 3) [21]. In a deeper form, Gram (+) bacteria consist of a cytoplasmic membrane which have a porous peptidoglycan layer and lipoteichoic acid, this unique structure allows the penetration of photosensitizers through inside the targeted microorganism [20]. Additionally, in the UV range of 160 to 240 nm and the presence of oxygen, ozone ( $O_3$ ), a powerful antioxidant, can be generated as a result of its reaction with various organic compounds [22]. Also, there are some parameters to identify the antibacterial efficiency, (i) the photosensitizer's physico-chemical characteristics and ability to bind the cell, (ii) bacteria's physiological condition, and (iii) the organization and structure of the cell [19]. For example, the characteristics of the microorganism and its interaction with the photosensitizer are the crucial factors to reach the highest antimicrobial efficiency. As mentioned above, in Gram (+) bacteria, there are approximately 100 peptidoglycan layers, which is closely related to lipoteichoic and negatively charged teichuronic acids. This characteristic of the wall allows a relatively high degree of permeability for many macromolecules, including glycopeptides and

polysaccharides. Therefore, the cell wall of Gram (+) bacteria does not exhibit behavior that would prevent the passage of photosensitizers. However, in Gram (-) bacteria, an additional 10–15 nm thick structural layer exists on the cell wall, which consists of lipopolysaccharide trimers, proteins with porin function, and lipoproteins. These structural elements give an external layer to the peptidoglycan network and an outer surface a quasi-continuum of densely packed negative charges. The complex structure inhibits the permeability of the cell wall [23]. Ultimately, photosensitization has a significant effect on microbial decontamination [24].

### Photothermal Mechanism

The photothermal effect of PUV light is one of the destructive responses for the decontamination of microorganisms (Fig. 1a) [12]. Decontamination can be done by disrupting microorganisms due to temporarily overheating during absorption of the entire UV light with an exceeding energy of  $0.5 \text{ J/cm}^2$  [17]. High power pulses generate a localized heating on targeting microorganisms, which results in drying of



**Fig. 3** Effect of PUV in *S. aureus* by TEM (sample treated for 5 s at 8 cm of distance between the quartz window and the sample at a total fluence of  $4.95 \text{ J/cm}^2$ ): (a) untreated sample; (b–f) treated sample, (b)

cell wall rupture; (c) lack of cell wall; (d) cytoplasm shrinkage and cell wall damage; (e) membrane damage and cytoplasm shrinkage; (f) cell wall damage and cellular content leakage [18].

the cellular wall and destruction of cellular components [4]. The application of intense doses of PUV vaporizes the water and generates a differential heating rate inside the targeted microorganism, which creates a vapor flow across the cell membrane that breaks down the cell membrane and internal organelles. These structural and physiological changes of PUV can be result in cell death and are defined as photo-stress [1, 4]. Levy et al. [25] were observed photothermal effect on *Aspergillus niger* ATCC 16,404. The photothermal effect of the PUV is depend on the thermal and optical characteristics of the targeted material and microorganism, intensity of PUV, and exposure time. The photothermal effect of PUV can be negligible when short treatment times (< 10 s), temperature increase is not significant under the < 10 s of PUV treatment. On the other hand, longer PUV treatment results in a significant temperature increase [18]. According to the study of Krishnamurthy et al. [18], they had not observed a significant temperature increase ( $\sim 2^\circ\text{C}$ ) in short PUV treatment times (5 s).

### Photophysical Mechanism

The photophysical effect is one of the decontamination effects of PUV (Fig. 1c). As mentioned in the previous section, PUV generates an evaporation of water inside the microorganism, creating an internal pressure through the cell membrane, which destroys the cell wall and organelles (cell lysis). Photophysical effect can be explained by the pulsing effect, the light energy stored in the capacitor and then released in high-energy pulses at nano- or microsecond intermittent. These continuously emitting pulses generate stress that results in structural damage to the targeted microorganism (Fig. 2) [18]. Cassar et al. [26] reported that these destructive effects can be associated with intense micro vibrations generated by short power bursts of broad-spectrum wavelengths. Cassar et al. [26] analyzed the morphology of *Escherichia coli* K12-NSR before and after PUV treatment by using transmission electron microscopy (TEM), and they reported that TEM images clearly showed the photophysical effect of PUV, such as abnormal cell shape, cell lysis, and destroyed intracellular structures.

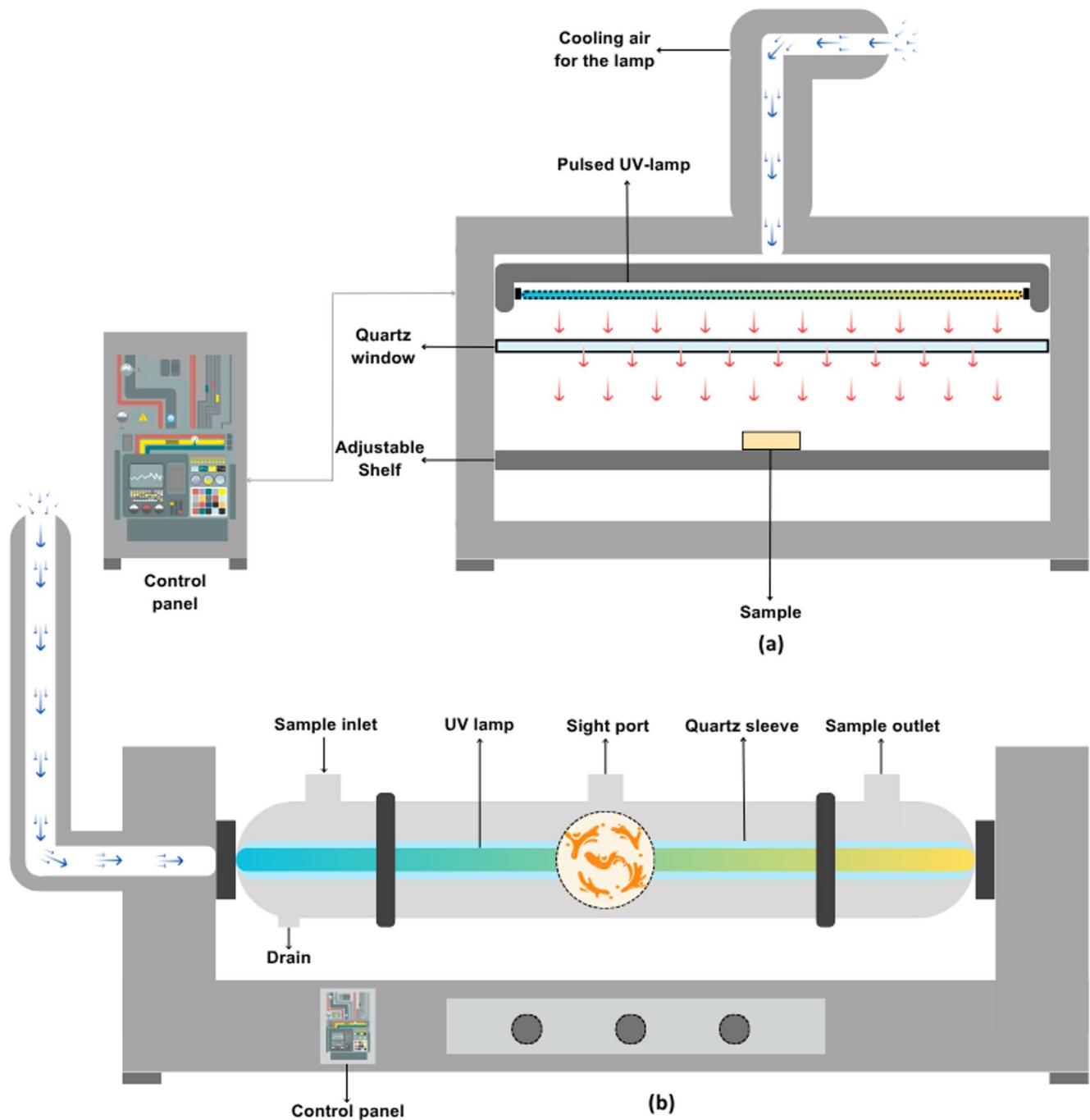
### Pulsed-UV Light Systems

One of the most emerging and innovative decontamination technique is the PUV, also referred to as high intensity pulsed light and intense pulsed light. Universities, industries, and research groups have intensely studied and developed lab-scale and pilot-scale PUV light systems for decontamination purposes [27–32] (Figs. 4 and 5). Generally, PUV light systems consist of four main parts, which

are lamp, power supply, pulse configuration unit, and chamber [33]. Figures 4 and 5 show these parts of the static and flow-through lab-scale PUV light system, respectively, as schematic diagram and actual system. The static PUV light system can be used for packaging materials and solid foods, including meat, poultry, fish, and fruit and vegetables. On the other hand, the continuous PUV system can be used for liquids such as milk, fruit juices, water, and wastewater. In both systems, the produced energy is briefly stored in a condenser, and then it is quickly flashed by a controller into a chamber with reflecting walls via a lamp (e.g., lamps of Ar, Kr, or Xe) that produce PUV. The thermocouples that are placed on the safety door or around the quartz tube for the flow-through PUV system are used to control the temperature of the chamber. The hot air that is produced due to the PUV, is exhausted by using the cooling fan. Additionally, the efficacy of the PUV system is regulated by the sample's morphology, chemical composition, and microbiological characteristics [34].

### The Benefits and Challenges of Pulsed-UV Light as a Nonthermal Decontamination Technique for Food Safety and Sustainable Food Processing

In order to ensure food safety and availability, traditional preservation technologies including canning, adding chemicals, freezing, and refrigeration have been crucial. Nevertheless, conventional technologies cause the health problems and environmental issues, such as harmful chemical residues, consumption of high energy, and the producing of greenhouse gases. Moreover, conventional decontamination techniques affect the targeted food product's quality, such as color, flavor, nutritional and bioactive components, and taste [1]. As sustainability is becoming more and more important, the food industry should integrate environmentally friendly, innovative and emerging decontamination technologies to reduce environmental impacts and safe foods to ensure the public health [36]. The food industry can reach sustainable and green technology standards by enhancing recycling of by-products and decreasing of waste generation, footprint, and energy consumption [37]. Non-thermal decontamination techniques have great potential to achieve these sustainability goals and standards. As a non-thermal decontamination technology, PUV gives a broad application area to decontamination of harmful microorganisms without or minimal changing on product quality. PUV decontamination has several advantages compared to traditional or conventional decontamination methods, such as reduced treatment time, energy consumption, and chemical usage. Additionally, PUV enables packaged and unpackaged foods



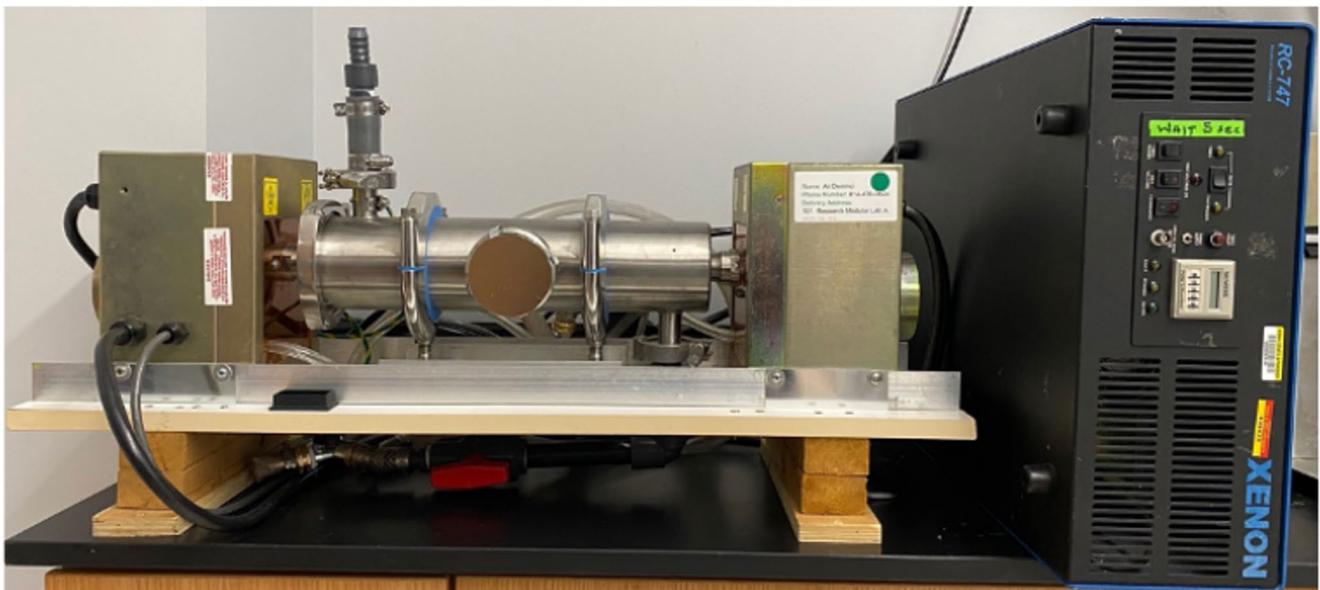
**Fig. 4** Schematic diagram of the lab-scale PUV decontamination systems (a) static system and (b) flow-through system. (Adapted from [4, 35])

and contact surfaces decontamination by using mercury-free and non-toxic xenon flash lamps without any chemical disinfectants and/or synthetic preservatives and chemical residue. Also, this non-thermal decontamination technology offers low operation cost for each treatment and good consumer's acceptance, they choose foods that are high in organoleptic quality and minimally processed, and they favor foods that are fresh and healthful [38].

Also, there are some challenging aspects of the PUV decontamination technique. One of the most challenging factors is the penetration of PUV during treatment. The most challenging factor is heating of the targeted sample in the PUV decontamination applications. Heat can be generated by the food absorbing light or by the PUV lamp heating up during treatment [9]. Temperature increase happens during longer treatment times, in the first few seconds, there



(a)



(b)

**Fig. 5** Lab-scale PUV systems (a) Static benchtop PUV system; (b) flow-through PUV system [27]

is no significant temperature increase. An efficient cooling system should be integrated into the PUV decontamination system to overcome the problem with minimum negative effect on the quality of the targeted sample for long-term treatments. Additionally, there are some strategies to minimize the temperature increasing during treatment, such as applying short-duration pulses necessary, the PUV lamps should be turned on or off right away during treatment, a cooling time should be permitted between pulses, using of

a high pulse peak power to reduce high average power, and it is necessary to provide a low infrared spectrum content [17]. PUV penetrates a very limited depth in the targeted sample, and it decontaminates only microorganisms those are exposed to the PUV. For this reason, the targeted sample should be transparent to reach the maximum decontamination rate. The decontamination rate decreases with increasing sample opacity [39]. Another important challenging factor is the shadowing effect. Microorganisms can pass

through fissures or irregular shapes that are located on the targeted sample or through the epidermis of fruits and vegetables. A treatment is required for the decontamination of the fungal population at higher energy levels, 2 to 6 times higher than those found in solid culture media, due to the shadowing effect [17]. Smoothness of the targeted sample, cracks and folds on the surface negatively affect the PUV decontamination efficiency. To achieve the highest microbial decontamination rate, avoid irregular surfaces, cracks and folds areas [39]. Also, the composition of the targeted food sample is another challenging factor for the PUV decontamination purposes [1]. For example, protein- and fat-rich foods can reduce the efficiency of the PUV decontamination by absorbing applied PUV radiation [39]. The following sections summarize the major and recent applications of PUV on foods, packaging materials, and water/wastewater.

### Application of Pulsed-UV Light for the Decontamination of Foods, Packaging Materials, and Water/Wastewater

There are many studies in the literature for the application of PUV on solid foods, liquid foods, water/wastewater, packaging materials, and food contact surfaces. These studies determine the effect of process parameters and sample characteristics, such as transparency of the targeted sample, the distance between the sample and the PUV source, the fluency and pulse width, treatment time, the nutritional composition of the food sample, and the nature of the microorganism for the decontamination efficiency of the PUV treatment. These studies are summarized as follows:

#### Solid Foods

PUV has been extensively studied for solid foods by many researchers. However, it was repeatedly shown that the light intensity depends on the depth and absorption coefficient of the solid food [1]. Three fundamental factors can affect the efficiency of the PUV decontamination technique: (i) the level of microbial contamination, (ii) the characteristics of the targeted microorganism, and (iii) the process parameters (e.g., lamp distance, treatment time, pulse width). Also, surface characteristics, opacity or transparent properties, and composition of the sample can affect the decontamination capacity of PUV treatment. The transmission coefficient, low reflection and high absorption characteristics of the sample enable the optimum decontamination efficiency. Semi-solid foods or samples can absorb and transfer a certain amount of PUV through their surfaces, which affects the PUV efficiency [40]. Bialka et al. [41] have demonstrated

the penetration of PUV in different thicknesses of solid model systems. They used two different solid model systems, including agar and whey protein isolate gels for clear and opaque solid model system, respectively, to understand the penetration behavior of PUV in solid environments. According to their findings, they observed that the transparency and thickness of the selected model were significantly affected the penetration efficiency, increasing of thickness (2–10 mm) of the solid model system resulted in energy decrease by 30 and 45% for agar and whey protein isolate gels, respectively. Also, they observed that the fraction of survivor *E. coli* K12 cells was much greater in the denaturalized whey protein isolate sample than agar sample,  $-0.91$  and  $-3.67$  log at 2 mm thickness, respectively, at a fluence of  $\sim 73$  J/cm<sup>2</sup> for 120 s. Therefore, the effectiveness of PUV depending on the target solid food. The following sections will summarize the PUV applications for specific solid food groups.

#### Muscle Foods

Muscle foods, including meat, poultry, and fish products, contain high amount of protein and vital nutrients. Nevertheless, they are extremely vulnerable to degradation and microbial spoilage because of their high nutritional level, moisture content, water activity and pH values [42, 43]. Moreover, meat has a low carbohydrate level, it also prevents the formation of lactic acid bacteria, which can be important for the inhibition of the growth of some pathogens [44]. Also, muscle foods such as meat, fish, and shellfish are one of the primary sources of foodborne illnesses, and pathogens are causing more than 200 different kinds of illnesses, most of them caused by bacteria. The most spoilage microorganisms are bacteria, which are also the cause of slime formation and off-odor, especially present in refrigerated meats stored under aerobic environments [42]. Unprocessed or raw muscle foods contain lots of pathogenic microorganisms, such as *E. coli*, *Salmonella* spp., *Listeria monocytogenes*, *Campylobacter jejuni*, *Clostridium* spp., *Vibrio* spp., and *Aeromonas* spp [42, 45, 46]. Decontamination of muscle foods are very crucial to increase the shelf life of the product and decrease foodborne illnesses for public health. Traditional decontamination methods have been used in the meat industry, which include the application of chemicals like chlorine sanitizers and heat treatment. Unfortunately, these traditional methods can be effective to decontaminate the microorganism, but they have disadvantages, including chemical treatment can cause harmful residues, heat treatment with high temperatures have an adverse effect on nutritional and sensory qualities, and high energy consumption [47]. Considering these negative impacts, PUV has a great potential for the decontamination of muscle

food as a sustainable and green method. Many studies have been conducted to evaluate the decontamination efficacy of PUV on muscle foods (Table 1). For example, Söbeli et al. [54] were applied PUV to evaluate the decontamination efficiency on beef tenderloin steak and they reported that the total aerobic mesophilic bacteria decreased by 3.49 log CFU/g with a dose of 4.2 J/cm<sup>2</sup>. Pedrós-Garrido et al. [55] evaluated the decontamination of raw salmon by using PUV and UV-C light they reported that PUV (9 s, 3.5 cm and 152.2 mJ/cm<sup>2</sup> for 1.3 log CFU/g) was more effective than UV-C (30 s, 6 cm, and 127.2 mJ/cm<sup>2</sup> for 0.9 log CFU/g) light treatment. Another research conducted by Koch et al. [56], they applied PUV at a fluences of 0.52 to 19.11 J/cm<sup>2</sup> to understand the decontamination behavior of *Salmonella* Typhimurium and *Yersinia enterocolitica* on pork skin and they observed that *S. Typhimurium* and *Y. enterocolitica* were reduced in the range of 1.73–3.16 and 1.48–4.37 log CFU/cm<sup>2</sup>, respectively. Wang et al. [53] applied PUV to the decontamination of *Aeromonas salmonicida* on chicken meat and skin. Their results showed that PUV was successfully decontaminated the *A. salmonicida* on chicken meat and skin with 7 V at 5 s.

### Dairy Foods

Dairy foods are a rich source of macro- and micro-nutrients, including proteins (casein), carbohydrates (lactose), lipids, enzymes, essential amino acids, minerals (Ca), and vitamins (vit-D, -B<sub>12</sub>). These high nutritional characteristics of dairy foods lead to the growth of pathogenic microorganisms, such as *Staphylococcus aureus*, *Listeria monocytogenes*, *E. coli*, *Salmonella*, and *Campylobacter* [82, 83]. For example, *Pseudomonas fluorescens* led to the recall of contaminated mozzarella cheese (approx. 70,000 balls) and Latin-style fresh cheese (queso fresco) that was responsible for blue discoloration in Italy and the United States, respectively [84]. Furthermore, these pathogenic microorganisms pose a threat to human health, for example, *L. monocytogenes* causes meningitis, abortion, and meningoencephalitis in humans [85]. Due to these life-critical effects, the dairy products need to be free of pathogenic microorganisms to decrease foodborne outbreaks and ensure public health. Unfortunately, thermal processing can cause some undesirable changes in the nutritional and sensory characteristics of dairy products, such as degradation of bioactive compounds and vitamins, lipid oxidation, enzyme inactivation, denaturation of proteins, and change in texture, flavor, and color [82]. Note that, the essential step to preventing microbial contamination of dairy products after the pasteurization process is to follow good manufacturing practices and appropriate sanitation requirements. An additional decontamination process can be very effective to prevent the recontamination

after processing, handling, and packaging steps. Application of PUV can be successful for eliminate this problem [84]. In the literature, most studies have shown that PUV treatment is powerful to the decontamination of dairy products from pathogenic microorganisms (Table 1). Chen et al. [57] studied the decontamination of non-fat dry milk from *Cronobacter sakazakii* by using PUV treatment, and they stated that *C. sakazakii*, inactivated by 3.18 log CFU/g at 29.36 J/cm<sup>2</sup>. Moraes et al. [58] observed the synergistic effect of PUV and antimicrobial starch film (ASF and containing citric acid) on decontamination of Cheddar cheese, and reported that *L. innocua* was successfully inactivated on the Cheddar cheese surface with a reduction of 4.5 log CFU at 9.22 J/cm<sup>2</sup>. after 3 days of storage at 4 °C. Ricciardi et al. [59] analyzed the effect of PUV on fresh ricotta cheese at an intensity range of 1.3–15.0 J/cm<sup>2</sup>, and they reported that the PUV treatment significantly reduced microbial growth (*Pseudomonas* spp., *Enterobacteriaceae*, and yeast) compared to the untreated sample after storage at 4 °C.

### Fruits and Vegetables

Fruit and vegetables are a good source of vital nutrients, including vitamins, bioactive compounds, minerals, dietary fibers, antioxidants, and phytochemicals [34]. In the fresh-cut industry, there are serious post-harvest losses of products due to the highly perishable (i.e., high moisture content and a<sub>w</sub>) characteristics of the products and the microbiological, biochemical, and enzymatic degradations that take place from farm to fork, reduce the shelf-life of these products [86]. Also, these degradation processes can increase formation of the toxic by-products and foodborne outbreaks. In industry, traditionally, chlorinated water is used in the decontamination process. However, studies release that the combination of chlorine and organic matters can lead to the formation of toxic compounds (Gomez-Lopez et al., 2005). Due to these harmful effects, the fruit and vegetable industry needs to adopt innovative and emerging decontamination technologies with sustainable approaches. PUV technology has been evaluated by many researchers for the decontamination of microorganisms in the fruit and vegetable industry as an environmentally safe technique (Table 1). Mukhopadhyay et al. [87] demonstrated the effect of PUV on decontamination of Romaine lettuce, reported that the *E. coli* O157:H7 was reduced by 2.7 log CFU/g. Additionally, they studied the effect of the combination of PUV and cold plasma technology (CP) on decontamination efficiency and their results showed a synergistic effect on decontamination efficiency with a >5-log reduction. The decontamination characteristics of PUV on dried minced onion were studied by Gomathi Padma Priya et al. [66]. Their results indicated that the 2.98, 2.96, 5.00 and 3.14-log reductions

**Table 1** The effect of PUV decontamination technique on solid foods

Product Type	Name of the specific product	Targeted microorganism	Treatment conditions	Outcomes	Reference
Muscle foods	Yellow croaker ( <i>Pseudosciaena crocea</i> )	Total viable count	100–500 J/pulse for 30 pulse, 5 cm of distance between PUV lamp and sample	Initial sterilization efficiency was reached 86.27% at a fluence of 300 J/pulse.	[48]
	Sliced mortadella	<i>Listeria monocytogenes</i>	2.64–6.57 J/cm <sup>2</sup>	Reduced up to 1.44 log CFU/cm <sup>2</sup>	[49]
	Cured smoked meat sausage	<i>Listeria monocytogenes</i>	1.74–16.11 J/cm <sup>2</sup> of fluence, 3 and 9 of number of pulses, and 2.6–5.4 cm distance between sample and PUV light	The maximum log reduction was 1.58 log CFU/g sample at a fluence of 5.31 J/cm <sup>2</sup> .	[50]
	Pastirma (Turkish jerky meat)	<i>Staphylococcus aureus</i>	0.83–1.61 J/cm <sup>2</sup> s for irradiance 5–45 s for treatment time 5–13 cm for distance between sample and quartz window	Reduced from 0.47 to 2.99 log CFU/cm <sup>2</sup>	[51]
	Chicken meat	<i>Campylobacter</i>	2.82–9.67 J/cm <sup>2</sup> 2.6–5.4 cm distance between sample and PUV lamp	4.5 log CFU/g reduced at a highest fluence.	[52]
	Chicken meat and skin	<i>Aeromonas salmonicida</i>	3.5–7.5 V and 1–10 s of treatment time	<i>A. salmonicida</i> reduction ranged from 0.37 to 0.75 log CFU/cm <sup>2</sup> at 7 V for 5 s, with the skin group samples showing highest reduction while the meat group samples showed less reduction (0.37 log CFU/cm <sup>2</sup> ).	[53]
	Tenderloin steak	Aerobic mesophilic bacteria	0.525–4.2 J/cm <sup>2</sup> of fluences, 7.5–60 s of treatment time,	The highest reduction was observed at 4.2 J/cm <sup>2</sup> , 3.49 log CFU/g. The microbial reduction was significantly affected by the treatment conditions of 2.1 and 4.2 J/cm <sup>2</sup> .	[54]
	Raw salmon	<i>Listeria</i> spp., lactic acid bacteria, <i>Brochothrix thermosphacta</i> , <i>Photobacterium phosphoreum</i> , psychrophilic, <i>Pseudomonas</i> spp. and mesophilic viable count	40.1–508.5.1.5 mJ/cm <sup>2</sup> of treatment dose, 1–30 s of treatment time, 3.5–11 cm of distance between sample and PUV.	The decontamination level of PUV treatment was significantly higher than the UV-C light treatment.	[55]
	Pork skin	<i>Salmonella</i> Thphimurium and <i>Yersinia enterocolitica</i>	0.52–19.11 J/cm <sup>2</sup> of treatment dose, 1–30 s of treatment time, and 8.3–13.4 cm of distance between sample and PUV.	The log reduction ranged between <i>Salmonella</i> and <i>Yersinia</i> as 1.73–3.16 and 1.48–4.37, respectively.	[56]
	Raw salmon fillets	<i>E. coli</i> O157:H7 and <i>Listeria monocytogenes</i>	5.6 J/cm <sup>2</sup> /pulse, 3 pulses/s, 15–60 s of treatment time, 3–8 cm of distance between sample and UV strobe.	For <i>E. coli</i> O157:H7 and <i>L. monocytogenes</i> , the maximum log reduction was observed as 1.09 and 0.74 log CFU/g, respectively.	[11]
Dairy foods	Non-fat dry milk	<i>Cronobacter sakazakii</i>	1.27 J/cm <sup>2</sup> , 8 cm of distance from quartz window, 18, 25, and 28 s for treatment time, and 2 mm sample thickness.	Maximum inactivation of 3.18 log CFU/g.	[57]
	Cheddar cheese	<i>Listeria innocua</i>	1.02–12.29 J/cm <sup>2</sup> , distance between sample and PUV is 5.8 cm.	Average reduction of 4.5 log CFU/cheese slices.	[58]
	Fresh ricotta cheese	<i>Pseudomonas</i> spp., <i>Enterobacteriaceae</i> , yeast	1.3–15.0 J/cm <sup>2</sup> and distance between sample and PUV is 2 cm.	Fluences of 1.3 and 3.1 J/cm <sup>2</sup> were allowed to sufficient decontamination of the sample.	[59]
	Table eggs	<i>E. coli</i> K12-NSR and <i>Enterococcus faecium</i>	1.0–4.9 J/cm <sup>2</sup> , 3 pulses/s (360 µs/pulse), 4.8 cm/s of flow rate of conveyor, 26.7 s/pass	For <i>E. coli</i> , the log reduction ranged between 3.43–4.54 log CFU/cm <sup>2</sup> . For <i>E. faecium</i> , the log reduction ranged between 2.03–3.52 log CFU/cm <sup>2</sup> .	[60]

**Table 1** (continued)

Product Type	Name of the specific product	Targeted microorganism	Treatment conditions	Outcomes	Reference
	Fresh kashar cheese	<i>E. coli</i> O157:H7 NCTC 12,900 and <i>Staphylococcus aureus</i> ATCC 25,923	7.61–123.25 J/cm <sup>2</sup> , 5–60 s treatment time, 5, 8, and 13 cm distance between quartz window and PUV.	1.62 and 3.02 log CFU/cm <sup>2</sup> reduction was observed at 45 s–13 cm for <i>S. aureus</i> and <i>E. coli</i> O157: H7, respectively.	[61]
	Gouda and Manchego	<i>Listeria</i> spp.	0.9–8.4 J/cm <sup>2</sup> , distance between sample and PUV is 10 cm, and 1.5–2 mm sample thickness.	For Gouda cheese, 3 log CFU/cm <sup>2</sup> reduction was observed at a lowest fluence. For Manchego cheese, less than 1 log CFU/cm <sup>2</sup> reduction was observed.	[62]
Fruits and vegetables	Fresh-cut watermelon	<i>E. coli</i> , <i>S. aureus</i> , <i>L. monocytogenes</i> , and <i>Salmonella</i>	4–12 J/cm <sup>2</sup> of total fluences, 10–30 number of pulses, and pulsed cycles were settled as 1 Hz and 520 μs.	At the highest fluence, <i>E. coli</i> , <i>S. aureus</i> , <i>L. monocytogenes</i> , and <i>Salmonella</i> were reduced as 4.19, 4.63, 4.37, and 3.95 log CFU/g, respectively.	[63]
	Whole white button mushroom ( <i>Agaricus bisporus</i> )	<i>Aspergillus niger</i> , <i>E. coli</i> , and <i>L. monocytogenes</i>	5.27–10.35 W/cm <sup>2</sup> of fluence rate, 60–180 s of treatment time, 60–180 number of pulses, pulsed cycles were settled as 1 Hz and 400 μs, and 6 cm of distance between sample and PUV.	<i>A. niger</i> , <i>E. coli</i> , and <i>L. monocytogenes</i> were reduced by 0.91, 0.87, and 0.91 log CFU/g.	[64]
	Romania lettuce	<i>E. coli</i> O157: H7	1.05–63 J/cm <sup>2</sup> , sample dimensions of 2.5 × 2.5 cm, distance between sample and PUV is 14 cm, and 1–60 s of treatment time	2.3 log CFU/g reduction was observed at an optimum condition.	[65]
	Dried minced onion	<i>E. coli</i> ATCC 43,888, <i>Bacillus cereus</i> 10,876, TPC, and YMC	2.09–8.52 J/cm <sup>2</sup> /pulse and 5–150 s of treatment time.c	2.98, 2.96, 5, and 3.14 log CFU/g reduction were observed for <i>E. coli</i> , <i>B. cereus</i> , TPC, and YMC, respectively.	[66]
	Cherry tomato	<i>Salmonella enterica</i> ( <i>S. Stanley</i> H0558, <i>S. Montevideo</i> G4639, and <i>S. Newport</i> H1275), aerobic mesophilic bacteria, and mold and yeast	1.05–63 J/cm <sup>2</sup> , 1–60 s treatment time, and 14 cm distance between sample and PUV.	Reduced up to 2.7 log CFU/g.	[67]
	Red chilies ( <i>Capsicum annuum</i> var. <i>longum</i> )	<i>Aspergillus flavus</i> , <i>Salmonella</i> Typhimurium, and <i>Bacillus cereus</i>	0.53–2.59 J/cm <sup>2</sup> , treatment time 120–360 s, and 3.4 cm distance between sample and PUV	8 log CFU/g reduction was observed at highest fluence.	[68]
	Green chilies ( <i>Capsicum annuum</i> var. <i>longum</i> )	<i>Aspergillus flavus</i> MTCC 578, <i>Bacillus cereus</i> ATCC 7644, and <i>Salmonella</i> Typhimurium ATCC 14,028,	0.53–2.59 J/cm <sup>2</sup> , treatment time 120–360 s.	>5 log CFU/g reduction was observed for <i>A. flavus</i> at 1.77, 2.02, and 2.21 J/cm <sup>2</sup> . The complete decontamination of <i>B. cereus</i> and <i>S. Typhimurium</i> were observed at 2.02 J/cm <sup>2</sup>	[69]
	Green onion	<i>E. coli</i> O157:H7	5–56.1 J/cm <sup>2</sup> , 5–60 s of treatment time,	4.1–5.2 log CFU/g reduction was observed.	[70]
	Raspberries	<i>Salmonella</i> and <i>E. coli</i> O157:H7	5.0–28.2 J/cm <sup>2</sup> , 5–30 s of treatment time, 5.8 cm of distance between quartz window and sample	After highest fluence of treatment, <i>Salmonella</i> and <i>E. coli</i> were reduced as 4.5 and 3.9 log CFU/g, respectively.	[71]
Other solid-based foods	Sunflower and quinoa seeds	<i>Salmonella</i> Typhimurium	4.05–20.25 J/cm <sup>2</sup> , 9–45 pulses, and 3–15 s of treatment time	<i>Salmonella</i> Typhimurium was reduced 2 and 3 log CFU/g seed at intensity of 12.15 and 16.20 J/cm <sup>2</sup> , respectively.	[72]
	Wheat flour	TPC and YMC	100–500 J, 10–50 c of pulsed frequency, and 9–21 cm of treatment distance.	TPC and YMC were reduced significantly by using PUV treatment.	[73]
	Black peppercorns	<i>Salmonella</i> spp.	0.28 J/cm <sup>2</sup> /pulse, 520 μs of time for each pulse and 10–80 pulses, and 12 cm of distance between sample and PUV	At highest fluence, 1.9 and 1.5 log CFU/g reduction was observed on wave-shaped and flat surface, respectively.	[74]
	Wetting raw almonds	<i>Salmonella</i> spp.	0.39–0.96 W/cm <sup>2</sup> , 0–21 min of treatment time, and 16–27 cm of distance between sample and PUV	To achieve a >5 log reduction, PUV treatment should be 7 min for 16 cm of distance.	[75]

**Table 1** (continued)

Product Type	Name of the specific product	Targeted microorganism	Treatment conditions	Outcomes	Reference
Shelled walnut		<i>Salmonella</i> Enteritidis PT8NSR	5.6 J/cm <sup>2</sup> /pulse, 3 pulse/s, 1–45 s of treatment time, and 5–13 cm of distance between sample and quartz window.	The maximum log reduction of <i>S. Enteritidis</i> was observed as 3.18 CFU/g.	[76]
Barley		Deoxynivalenol produced by <i>Fusarium</i> fungi	1.27 J/cm <sup>2</sup> with a pulsed rate of 3 Hz. and width of 360 μs, 0–360 pulses, 5–8 cm of distance between sample and quartz window	Deoxynivalenol value was decreased by 35.5% after 180 pulses and 60 s PUV treatment.	[77]
Egg white powder		<i>Cronobacter sakazakii</i> ATCC 29,544 and <i>Enterococcus faecium</i> NRRL B-2354	1.27 J/cm <sup>2</sup> with a pulsed rate of 3 Hz. and width of 360 μs, 0–360 pulses. Samples were passed 10 1–4 times (each pass is 28 s) of PUV.	After 3–4 passes, <i>C. sakazakii</i> and <i>E. faecium</i> were reduced by 5.3 and 2.74 log CFU/g, respectively.	[78]
Rough rice and rice bran		aflatoxin-B <sub>1</sub> and -B <sub>2</sub>	1.27 J/cm <sup>2</sup> /pulse, 3 pulses/s, 20–80 s of treatment time, 9 cm of distance between sample and quartz window.	Aflatoxin-B <sub>1</sub> and -B <sub>2</sub> in rough rice and rice bran were reduced by 75.0, 39.2, 90.3, and 86.7%, respectively.	[79]
Wheat grain		Molds	0.4 J/cm <sup>2</sup> /pulse, 5–40 number of pulses, 8.5 cm of distance between sample and PUV.	Naturally occurring molds decontamination resulted in 3–4 log cycles.	[80]
Corn meal		<i>Aspergillus niger</i> spores	2000–3800 V, 20–100 s of treatment time, and 3–13 cm of distance between sample and PUV.	At the optimum conditions, 4.93 log reduction was observed.	[81]

AMC: aerobic mesophilic count; YMC: yeast and mold count; TPC: total plate count; PUV: pulsed ultraviolet light; CFU: colony forming unit

were observed at 0.444 J/cm<sup>2</sup> for *E. coli*, *Bacillus cereus*, total plate count, and yeast and mold count. Jaiswal and Srivastava [63] have studied the decontamination behavior of fresh-cut watermelon by using of various PUV treatment conditions, 10–30 pulses and 4–12 J/cm<sup>2</sup>. They reported that the food-borne pathogenic microorganisms of *E. coli*, *S. aureus*, *L. monocytogenes*, and *Salmonella* were reduced by 2.31, 1.87, 2.13, and 2.55 log CFU/g, respectively, at 12 J/cm<sup>2</sup>. Recently, Kim et al. [88] studied the decontamination of murine norovirus-1 (MNV-1) and hepatitis A (HAV) on frozen blueberry (F1), blackberry (F2), strawberry (F3), raspberry (F4), cranberry (F5), cherry (F6), mango (F7), and pineapple (F8) by using PUV treatment. According to their findings, MNV-1 was decontaminated by 2.13, 2.59, 2.19, 1.82, 5.42, 2.02, 1.98, and 0.86-log reduction and HAV was decontaminated by 2.32, 1.34, 1.1, 1.74, 5.98, 1.74, 2.2, and 1.33-log reduction for F1, F2, F3, F4, F5, F6, F7, and F8, respectively at 16 pulses (11.52 J/cm<sup>2</sup>) of PUV treatment.

### Other Solid Foods

In literature, there are several PUV technology applications to decontaminate other solid-based foods, such as walnut, almond, wheat grain, rice and rice bran, corn, and flour. Also, characteristics of the targeted product can affect the decontamination efficacy of the PUV system (Table 1). Aron Maftai et al. [80] studied the decontamination characteristics of naturally occurring molds on wheat grain (Romanian and Spanish wheat) by using PUV technology.

They indicated that the decontamination resulted in 3–4 log cycles by using PUV, and the germination percentage changed minimally. Another study conducted by Wang et al. [79], they evaluated the effect of PUV on degradation and detoxification of aflatoxin-B<sub>1</sub> and -B<sub>2</sub> in rough rice and rice bran at 0.52 J/cm<sup>2</sup>/pulse intensity for a treatment interval of 20–80 s (3 pulse/s). Their result indicated that PUV treatment reduced the aflatoxin-B<sub>1</sub> and -B<sub>2</sub> in rough rice and rice bran by 75.0, 39.2, 90.3, and 86.7%, respectively. Izmirlioglu et al. [76] have studied the inactivation of *Salmonella* Enteritidis on shelled walnut by using of PUV, they reached maximum log reduction of 3.18 CFU/g shelled walnut with a fluence of 5.18 J/cm<sup>2</sup> at 45 s. Liu et al. [75] demonstrated the role of PUV on decontamination of wet raw almonds and they reported that the *Salmonella* reduced maximum 5-log reduction for 18 min with minimum effect on quality characteristics. Recently, Reyes-Jurado et al. [72] have screened the effect of the PUV and lemongrass essential oil combination on the decontamination of *Salmonella* Typhimurium on sunflower and quinoa seeds. According to their results, for both seeds, *Salmonella* Typhimurium decreased by 2 and 3 log CFU/g seed at fluence of 12.15 and 16.20 J/cm<sup>2</sup>, respectively.

### Liquid Foods

PUV decontamination of liquid samples is more complex than solid samples, microorganisms are dispersed throughout liquid volume. Therefore, PUV decontamination

efficiency of liquid samples depends on some internal and external parameters, including exposure time, distance between the sample and the lamp, depth of the sample, turbidity, and physicochemical and optical characteristics of the selected sample. For instance, microbial inactivation is higher with longer exposures times and decontamination efficiency increases with decreasing the distance between the sample and the PUV lamp. Also, there is a negative correlation between optical characteristics (e.g., turbidity and transparency) of the sample and PUV decontamination efficiency; and increase in turbidity leads to a decrease in efficiency due to the light scattering [1]. Krishnamurthy et al. [89] were studied the decontamination of *S. aureus* to indicate the effect of sample depth on PUV decontamination efficiency in a liquid system. They prepared *S. aureus* cell suspensions of 12, 24, and 48 mL with an initial viable cell population of 7–8 log CFU/mL and transferred to a sterile aluminum cup (dia 70 mm). They applied PUV treatment at a power of 16.8, 33.6, 84, and 504 J/cm<sup>2</sup>/s for treatment times of 1, 2, 5, and 30 s, respectively. Their findings indicated that the complete decontamination of *S. aureus* for 12 and 24 mL was achieved at 1 and 2 s, respectively. On the other hand, they observed that the log reduction of 48 mL was expanded exponentially during the 5 s treatment. These findings revealed that the interaction of treatment time and sample depth was found to be significant on the decontamination efficiency of PUV. Recently, Hwang et al. [90] have investigated the effects of specific wavelengths and intensity of PUV on microbial decontamination in a model liquid system. They used nine different filters to determine the effect of the total ratio of UV, visible light, and infrared ranges on the decontamination of Gram (+) bacteria, Gram (-) bacteria, and yeast. According to their findings, Gram (+) bacteria showed a significant 6 log reduction when treated under a total UV light source of 85.29% at the fluence of 2.16 J/cm<sup>2</sup>. Moreover, they observed the same log reduction when treated under a total UV light source of 11.66% at the fluence of 3.94 J/cm<sup>2</sup>. Their study confirmed that the PUV treatment has shown significant damage and a high decontamination rate even in low UV proportion in radiation.

Thermal processes (sterilization, pasteurization, evaporation, and spray drying) and the use of chemical additives or sugar are applied to ensure sufficient decontamination and increase shelf-life in liquid foods, including milk and fruit juices. Nonetheless, nutritional and sensory characteristics of the sample affected these thermal processes [91]. Nowadays, consumers want to consumption of safely milk and fruit juice without any chemical or toxic material residue and any change in nutritional content. The milk and fruit juice industry needs non-thermal and emerging decontamination technologies. Therefore, PUV technology can be highly effective in decontaminating pathogenic

microorganisms in liquid foods (Table 2). Krishnamurthy et al. [105] were screened the effect of flow-through PUV treatment on decontamination of *S. aureus* in cow milk. Their results suggested that the *S. aureus* was reduced from an initial content of 8–9 log CFU/mL to 0.55 to 7.26 log CFU/mL. Bhagat and Chakraborty [101] were studied the effect of PUV on the decontamination of pomegranate juice, and they indicated that a 5-log reduction was observed in *E. coli*, aerobic mesophiles (AM), and yeast and molds count (YM). Sahoo and Chakraborty [107] were studied the inactivation of aerobic mesophile count and yeast and mold count in sweet orange juice by using of PUV. Their result suggested that AM and YC were reduced by 5-log. Jayachandran et al. [94] have shown the role of PUV treatment on microbial load of sugarcane juice. They reported the initial populations of AM, YM, and total coliform (TC) as follows: 6.8, 5.5, and 5.1 log CFU/mL, respectively. After the PUV treatment, AM, YM, and TC values were decreased to < 1 log CFU/mL at 2.7 kV. Li et al. [99] indicated the degradation of patulin in apple juice by using PUV treatment, and their result showed that the patulin degradation was reached 96.27% at a fluence of 40.50 J/cm<sup>2</sup> for 6.5 min. Ding et al. (2024) were studied the PUV inactivation mechanism of *Alicyclobacillus acidoterrestris* in apple juice. They found that the spores and vegetative cells of *A. acidoterrestris* were decreased by 3.5 and 2.1 log CFU/mL, respectively, and transmission electron microscopy images clearly showed that the spores and vegetative cells of *A. acidoterrestris* were highly damaged after PUV treatment. Kasahara et al. [91] have demonstrated the PUV decontamination of *E. coli* in goat milk, and they reported that a 6-log reduction was observed at a 10 J/cm<sup>2</sup>.

## Packaging Materials

One of the important steps for microbiologically safe food and increasing the shelf life of the targeted product is the decontamination of food packaging material's, also it is critical in aseptic packaging operations [108]. Packaging materials can be contaminated with pathogenic microorganism, s especially molds from the air or contaminated other materials, if not stored in the suggested storage conditions. These contaminated packaging materials contaminate foods and cause spoilage, and economic and environmental issues. Moreover, they can also affect public health when mycotoxins are produced [109]. Traditional thermal decontamination techniques can applied to pathogenic microorganisms that are present on the surface. However, these thermal techniques can be unsuitable for heat-sensitive packaging materials [110]. PUV is one of the innovative and emerging non-thermal technology for decontamination of pathogenic microorganisms on heat-sensitive packaging materials

**Table 2** The effect of PUV decontamination technique on liquid foods

Name of the specific product	Targeted microorganism	Treatment conditions	Outcomes	Reference
Skim milk	<i>Clostridium sporogenes</i> , <i>E. coli</i> , and <i>L. innocua</i>	17.05–22.47 J/cm <sup>2</sup> ,	The maximum log <sub>10</sub> reduction of <i>C. sporogenes</i> , <i>E. coli</i> , and <i>L. innocua</i> were determined as 0.81, 4.09, and 3.6, respectively.	[92]
Human milk	TPC and LAB	2.0–2.9.0.9 kV and 10–30 s of treatment time	1.25 and 1.44 log CFU/mL reduction was observed for TPC and LAB, respectively.	[93]
Sugarcane juice	AMC, YMC, and TC	21.7–490 J/cm <sup>2</sup> of total fluence, 100–200 s of treatment time, 100–200 number of pulses, and 4 cm of distance between sample and PUV.	AM, YM, and TC were reduced to less than 1 log CFU/mL from the initial microbial load of 6.8, 5.5, and 6.1 log CFU/mL, respectively.	[94]
Watermelon juice	<i>Clostridium sporogenes</i> ATCC 7955, <i>E. coli</i> ATCC 29,055, and <i>L. innocua</i> ATCC 33,090	Anular tube, 0.15–3.51 J/cm <sup>2</sup> , 14.3–74.9 L/h of flow rate, 3.12–16.35 s of treatment time.	After 3.52 J/cm <sup>2</sup> fluence treatment, <i>C. sporogenes</i> , <i>E. coli</i> and <i>L. innocua</i> were reduced by 4.93, 5.67, and 5.37 log CFU/mL, respectively.	[95]
Red grape juice	<i>Clostridium sporogenes</i> ATCC 7955, <i>E. coli</i> ATCC 29,055, and <i>L. innocua</i> ATCC 33,090	Anular tube, 0.15–3.51 J/cm <sup>2</sup> , 14.3–74.9 L/h of flow rate, 3.12–16.35 s of treatment time.	After 3.52 J/cm <sup>2</sup> fluence treatment, <i>C. sporogenes</i> , <i>E. coli</i> and <i>L. innocua</i> were reduced by 4.91, 5.08, and 5.40 log CFU/mL, respectively.	[95]
Apple juice (concentrated)	<i>Alicyclobacillus acidoterrestris</i>	6.75–54.00 J/cm <sup>2</sup> , 1.83–8.66 min of treatment time, 8.7 cm of distance between sample and PUV.	<i>A. acidoterrestris</i> cells were completely decontaminated within a fluence rate of 20.25–47.25 J/cm <sup>2</sup> .	[96]
Apple juice	<i>Alicyclobacillus acidoterrestris</i> vegetative cells and spores	12 J/cm <sup>2</sup> /pulse, 3 pulses, 12–70 °Brix, 10–70 mL of juice volume, 0.15–1.1 cm of liquid layer depth,	<i>A. acidoterrestris</i> vegetative cells and spores were decreased by 3.5 and 2.1 log CFU/mL, respectively.	[97]
Goat milk	<i>E. coli</i> DH5α	1.3–10 J/cm <sup>2</sup> , 3 pulses, 1–8 s of treatment time for lower and higher doses, respectively.	6 log reduction was observed at a fluence of 10 J/cm <sup>2</sup> .	[91]
Mulberry juice (lactic-acid-fermented)	<i>Lactobacillus</i> (L.) <i>plantarum</i> ATCC SD5209	3.36–14.52 J/cm <sup>2</sup> , 2–12 s of treatment time, 1–2 mm of sample thickness, 2–10 cm of distance between sample and PUV.	The microbial reduction range was observed as 1.17–1.58 log CFU/mL.	[98]
Apple juice	Patulin	40.5 J/cm <sup>2</sup> , 12 °Brix, 6.5 min of treatment time, 3.5 cm of distance between sample and quartz glass.	The degradation of patulin was observed as 96.27%.	[99]
Dragon fruit juice	<i>E. coli</i> ATCC 43,888, AMC, and YMC	8–20 W/cm <sup>2</sup> /pulse of average fluence, 30–180 s of treatment time, 30–180 number of pulses, and 2.9 cm of distance between sample and lamp holder.	PUV treatment for 30–80 s resulted in a 2–6-log reduction of <i>E. coli</i> and AMC and YMC were detected below the limit.	[100]
Pomegranate juice	<i>E. coli</i> ATCC 43,888, Aerobic mesophiles, yeast and mold counts	7.15–9.96 W/cm <sup>2</sup> , 90–300 s of treatment time, 3.8 cm of distance between quartz glass and PUV.	<i>E. coli</i> reduced by 3–5 log CFU/mL at a fluence of 8.46 W/cm <sup>2</sup> for 60–90 s. The complete decontamination of <i>E. coli</i> was observed at 2.7 kV for 90 s. and the AMC and YMC were detected less than 10 CFU/mL.	[101]
Pineapple ( <i>Ananas comosus</i> [L.] Merr.) juice	AMC and YMC	3.4–7.9 J/cm <sup>2</sup> of a fluence, 47–187 of number of pulses, 30–120 s of treatment time, 50 mL of sample vol., and 50 mm of sample thickness.	For AMC and YMC, a 5-log reduction was observed at a fluence of 7.9–8.0 J/cm <sup>2</sup> and number of pulses of 94 or 187.	[102]
Coconut water	<i>E. coli</i> MTCC 433	0.18–5.6 W/cm <sup>2</sup> of fluence, 3 pulses/s, and 0–15 s of treatment time.	The highest decontamination of <i>E. coli</i> was observed as 5.33 log CFU/mL at a fluence of 5.6 W/cm <sup>2</sup> .	[103]
Orange juice			The maximum decontamination of <i>E. coli</i> was observed as 4.0 log CFU/mL at a fluence of 5.6 W/cm <sup>2</sup> .	

**Table 2** (continued)

Name of the specific product	Targeted microorganism	Treatment conditions	Outcomes	Reference
Pineapple juice			The maximum decontamination of <i>E. coli</i> was observed as 4.5 log CFU/mL at a fluence of 5.6 W/cm <sup>2</sup> .	
Liquid egg white	<i>E. coli</i> K12NSR and <i>Salmonella</i> Enteritidis PT8NSR	2.68–6.85 J/pulse of fluence, 20–40 s of treatment time, 5–9 mL of sample volume, and 5, 9, and 13 cm of distance between sample and quartz window.	Maximum decontamination of <i>E. coli</i> and <i>S. Enteritidis</i> was observed to be 1.28 and 1.98 log CFU/mL at a fluence of 45.6 J/cm <sup>2</sup> , a treatment time of 40 s, a distance of 5 cm, and a sample volume of 5 mL, respectively.	[104]
Cow milk	<i>Staphylococcus aureus</i>	1.27 J/cm <sup>2</sup> /pulse, 3 pulses/s, 20–40 mL/min of flow rate, 5–11 cm of distance from quartz window, and 1–3 number of passes.	0.55–7.26 log CFU/mL reduction range was observed for <i>S. aureus</i> .	[105]
Clover honey	<i>Clostridium sporogenes</i>	5.6 J/cm <sup>2</sup> /pulse of a fluence, 15–540 of number of pulses, 5–180 s of treatment time, 8–20 cm of shelf height, and 2 and 8 mm of depth of sample.	<i>C. sporogenes</i> spores were decontaminated up to 90%.	[106]

AMC: aerobic mesophilic count; LAB: lactic acid bacteria; YMC: yeast and mold count; TC: total coliforms; TPC: total plate count; PUV: pulsed ultraviolet light; CFU: colony forming unit

[109]. In general, PUV treatment is used to eliminate post-processing contamination in prepackaged foods (Table 3) (Marangoni Junior et al., 2020). Nowadays, researchers have studied the effect of PUV treatment on the decontamination of packaging materials. Ringus and Moraru [108] have studied the decontamination of *Listeria innocua* on different food packaging materials (high density polyethylene (HDPE), low density polyethylene (LDPE), polyethylene coated paperboard (PP), polyethylene coated aluminum foil paperboard laminate (PAP), and polyethylene laminated ultra-metalized polyethylene terephthalate (MET)) by using of PUV technology. Their results indicated that *L. innocua* on HDPE, LDPE, PP, PAP, and MET packaging materials were reduced from the initial value of 8 log<sub>10</sub> CFU/coupon to 7.1, 7.2, 4.5, 3.5, and 4.4 log CFU/coupon, respectively. Also, they stated another important decontamination characteristic of PUV that highly reflective and rough surfaces of PE-based packaging materials can result in less decontamination efficiency than less reflective and smoother surfaces. Haughton et al. [113] studied the decontamination of *Escherichia coli* on polyolefin (PO), polyethylene terephthalate/polypropylene (PET/PP), and polyvinyl chloride (PVC) packaging materials. They reported that pulsed UV-light treatment reduced *E. coli* by 4.0, 3.5, and 4.2 log CFU/cm<sup>2</sup> at an intensity of 6.0 J/cm<sup>2</sup>, respectively. Liu et al. [121] were demonstrated the effect of PUV treatment on polyamide/polyethylene-based packaging film. They applied PUV treatment before and after chicken packaging, and their results showed that the shelf-life of chicken increased by 2–3 days in both treatments. Recently, Jin et al. [111] studied the PUV treatment to activate the TiO<sub>2</sub>-polylactic acid film (TiO<sub>2</sub>-PLA) and evaluate the decontamination potential for 5 s treatment time (0.35 J/cm<sup>2</sup>/pulse and 3 pulses/s).

According to their findings, after 5 s PUV treatment, *E. coli* was reduced from 6.2 to 1.1 log CFU/cm<sup>2</sup> on the TiO<sub>2</sub>-PLA film surface.

## Water/Wastewater

Water safety is one of the most challenging issues all around the world, especially in developing countries and rural areas. The main sources of pollution, for example, biological pollutants can easily contaminate clean water and include several types of pathogenic microorganisms that lead to the spread and outbreak of water-borne diseases [12]. Also, organic micropollutants impact the water quality that contaminated water bodies, including industrial additives, hormones, personal care products, pharmaceuticals, etc [116]. The currently available water decontamination techniques showed important issues due to their low efficiency in decontamination of recurrent pathogenic microorganisms, including some microbial species and parasite organisms [122]. The conventional wastewater decontamination is based on the use of chemicals, including chlorine and chlorine derived chemicals. However, conventional water/wastewater decontamination techniques can impact human health and the environment due to their by-products, such as chlorinated organic by-products, which have the potential to cause irreversible genetic damage that can lead to the generation of cancerous tissues [117, 122]. Due to these negative impacts, innovative and emerging water/wastewater treatment technologies have been proposed, such as PUV decontamination technology. In the literature, several researchers have studied the decontamination efficiency of PUV for water/wastewater treatments (Table 3). Demirci and Krishnamurthy [123]. have studied the evaluation of a

**Table 3** The effect of PUV decontamination technique on packaging materials, water/wastewater, and food contact surfaces

Product Type	Name of the specific product	Targeted microorganism	Treatment conditions	Outcomes	Reference
Packaging materials	TiO <sub>2</sub> -polylactic acid film	<i>E. coli</i>	0.35 J/cm <sup>2</sup> /pulse of a fluence (3 pulses/s) and 5 s of treatment time	<i>E. coli</i> was reduced from 6.2 to 1.1 log CFU/cm <sup>2</sup>	[111]
	Polystyrene	<i>A. brasiliensis</i> DSM1988, <i>A. carbonarius</i> DSM872, and <i>Penicillium rubens</i> DSM848 conidia	0.23–4.0 J/cm <sup>2</sup> and 1–4 s of treatment time.	At 0.75 J/cm <sup>2</sup> fluence of PUV treatment, more than 5-log reduction was observed for the three strains.	[112]
	LDPE	<i>Listeria innocua</i>	0.67 J/cm <sup>2</sup> of a fluence, 3 pulse/s, 1–12 pulse of treatment.	7.2-log reduction was observed.	[108]
	HDPE			7.1-log reduction was observed.	
	TR			4.5-log reduction was observed.	
	MET			4.4-log reduction was observed.	
	EP			3.5-log reduction was observed.	
	PO	<i>Campylobacter jejuni</i> , <i>E. coli</i> , and <i>Salmonella</i> Enteritidis	0.9–6.0 J/cm <sup>2</sup> of a fluence, 1–5 s of treatment time, and 11.5 and 14 cm of distance between sample and quartz window	<i>C. jejuni</i> , <i>E. coli</i> , and <i>Salmonella</i> Enteritidis were significantly ( $p < 0.05$ ) reduced by all PUV treatments.	[113]
	Polyethylene-polypropylene (PET-PP)				
	Polyvinyl chloride				
Water/wastewater	Aluminium chloride tray (Al)				
	Water/wastewater	<i>E. coli</i> , <i>S. aureus</i> , and <i>L. innocua</i>	112–269 mJ/cm <sup>2</sup> of aver UV dosage, 0.38–0.60 L/min of flow rate, and 75–120 s of treatment time	Maximum reductions of 5.3-, 5.2-, and 4.3-log were observed for <i>E. coli</i> , <i>S. aureus</i> , and <i>L. innocua</i> , respectively.	[114]
	Artificial contaminated seawater	<i>E. coli</i> , <i>S. aureus</i> , <i>Salmonella typhimurium</i> , <i>Bacillus cereus</i> and <i>Candida albicans</i>	0.03–12.9 J/cm <sup>2</sup> of UV output, 60 and 600 s of treatment time, and 10 mL/s of flow rate	At the optimum conditions, 4.55-, 5.63-, 5-, 4.59-, and 5.15-log reductions were observed for <i>E. coli</i> , <i>S. aureus</i> , <i>Salmonella typhimurium</i> , <i>Bacillus cereus</i> and <i>Candida albicans</i> , respectively.	[115]
	Aqueous solution	<i>E. coli</i> K-12 MG1655	190 and 240 nm lamps were used, 0–190 J/cm <sup>2</sup> of fluences, and 3 mL of sample volume.	11 and 6 log CFU/mL reductions were observed for 76 and 95 J/cm <sup>2</sup> of fluence, respectively.	[22]
	Aqueous solution	Organic pollutants (PHAs)	190 and 240 nm lamps were used, 0–190 J/cm <sup>2</sup> of fluences, and 30 ml of sample volume.	After 57 J/cm <sup>2</sup> treatment, no PAHs were detected in the sample.	[22]
	Water	Organic micro-pollutants	2–10 J/cm <sup>2</sup> of fluences, 1–20 times of pulses, 2.5 cm of distance between sample and PUV.	After 20 ms (10 J/cm <sup>2</sup> ) of PUV treatment, 8 out of 11 organic micro-pollutants were degraded by >90%.	[116]
	SMW	<i>E. coli</i> and <i>Bacillus subtilis</i> spores	3800 V of input voltage, 3 pulses/s (360 μs), 2–20 L/min of flow rate, and 8–88 s of treatment time.	The complete decontamination of <i>E. coli</i> and <i>B. subtilis</i> spores were observed in a one pass at a flow rate of 10 and 6 L/min, respectively.	[35]
	RMW	<i>E. coli</i> and <i>Bacillus subtilis</i> spores	3800 V of input voltage, 3 pulses/s (360 μs), 2–20 L/min of flow rate, and 8–88 s of treatment time.	The complete decontamination of <i>E. coli</i> and <i>B. subtilis</i> spores were observed in a one pass and at a flow rate of 10 and 6 L/min, respectively.	

**Table 3** (continued)

Product Type	Name of the specific product	Targeted microorganism	Treatment conditions	Outcomes	Reference
	SMW	<i>E. coli</i> and <i>Bacillus subtilis</i>	2.25–18.23 J/cm <sup>2</sup> of fluence, 5–25 s of treatment time, 15–45 mL of sample volume, 8–13 cm of distance between sample and PUV.	For <i>E. coli</i> and <i>B. subtilis</i> , the log reductions were observed as 3.34–8.53 CFU/mL and 1.21–7.27 CFU/mL, respectively.	[117]
	RMW			The log reductions of microorganisms ranged between 1.72–4.88 CFU/mL for 3 and 10 s of treatment time, respectively.	
Food-contact surfaces	Polystyrene	<i>B. subtilis</i> spores and <i>A. niger</i> spores	0.17–5.28 J/cm <sup>2</sup> of fluence, 250 μs of pulse duration,	For <i>B. subtilis</i> and <i>A. niger</i> , a 5-log reduction was observed at a fluence of 1.25 J/cm <sup>2</sup> .	[25]
	Glass			For <i>B. subtilis</i> , a 5-log reduction was observed at a fluence of 1.25 J/cm <sup>2</sup> . For <i>A. niger</i> , a 4-log reduction was observed at 1.25 J/cm <sup>2</sup>	
	Aluminum			For <i>B. subtilis</i> , a 5-log reduction was observed at a fluence of 1.25 J/cm <sup>2</sup> .	
	Polyethylene cutting board	<i>P. fluorescens</i>	14–201 mJ/cm <sup>2</sup> , 3 pulses/s, and pulse width of 360 μs	Lower doses (>17 mJ/cm <sup>2</sup> ) were necessary to achieve the detection limit of 0.25 log CFU/cm <sup>2</sup> .	[55]
	Stainless-steel			higher doses (>80 mJ/cm <sup>2</sup> ) were necessary to achieve the detection limit of 0.25 log CFU/cm <sup>2</sup> .	
	Stainless-steel chain belt	<i>E. coli</i> K12-NSR	0.33, 0.66, and 3.31 J/cm <sup>2</sup> of fluence, 3.05, 15.24, and 30.48 cm/s of conveyor speed, 3 pulses/s, and pulse width of 360 μs	3.91 log CFU/cm <sup>2</sup> reduction was observed at a fluence of 3.31 J/cm <sup>2</sup> .	[118]
	Solid pliable polymer belt			4.90 log CFU/cm <sup>2</sup> reduction was observed at a fluence of 3.31 J/cm <sup>2</sup> .	
	Rigid linked polymer belt			3.34 log CFU/cm <sup>2</sup> reduction was observed at a fluence of 3.31 J/cm <sup>2</sup> .	
	PTFE-coated fabric belt			5.04 log CFU/cm <sup>2</sup> reduction was observed at a fluence of 3.31 J/cm <sup>2</sup> .	
	Stainless-steel	<i>L. monocytogenes</i>	0.8–1277 mJ/cm <sup>2</sup> of a fluence, 0.08–10 min of treatment time, 1–25 Hz of frequency	A 5.59-log reduction was observed for 0.5 min of treatment time at 25 Hz and a fluence of 151.2 mJ/cm <sup>2</sup> .	[119]
Stainless-steel	Six <i>Salmonella</i> spp. ( <i>S. Agona</i> , <i>S. Derby</i> , <i>S. Infantis</i> , <i>S. Indiana</i> , <i>S. Typhimurium</i> , and <i>S. Enteritidis</i> )	3.5–7.5 V of vantage, 1–10 s of treatment time, 30–90 m of flash distance, 0.125–1 Hz of pulse frequency	The highest reduction of 1.4 log CFU/cm <sup>2</sup> was observed at a voltage of 7.5 V with 9 pulses treatment.	[120]	

PUV: pulsed ultraviolet light; CFU: colony forming unit; TR: LDPE-paperboard-LDPE; MET: PET-LDPE-ultra metalized PET-LDPE-LLDPE metallocene bags; EP: PE-paperboard-PE-Al foil-T8IE-PE; SMW: synthetic wastewater; RMW: real municipal wastewater

flow-through PUV system for the decontamination of water from *Bacillus subtilis* at different flow rates (2–14 L/min) and treatment times (13–88 s), at an intensity of 1.27 J/cm<sup>2</sup>/pulse (3 pulse/s). According to their findings, *B. subtilis* was completely decontaminated at all flow rates reaching a ≥ 5.5 log reduction. Also, they observed that the turbidity of the water was decreased after PUV treatment, which indicated that PUV has a potential for disintegration of the organic materials due to the product of photochemical reactions (generation of oxidative compounds). Bohrerova et al.

[124] compared the decontamination efficiency of PUV and continuous-wave UV treatments for water decontamination. Their findings indicated that the *E. coli* and pathogen surrogates T4 and T7 were reduced by 4.26, 4.29, and 2.72 log/mL, respectively at an average UV fluence of 3 mJ/cm<sup>2</sup> and decontamination of pathogenic microorganisms by PUV was faster and more effective than continuous-wave UV treatment. Garvey et al. [125] have demonstrated the impact of PUV treatment on biofilms of *Pseudomonas aeruginosa* and *Staphylococcus aureus* for water treatment. Their outcomes

suggested that the PUV technology has highly potential for the decontamination of plankton and biofilm cells. *P. aeruginosa* and *S. aureus* were reduced by 7.2 and 5.9 log/mL, respectively up to a UV dose of 21.6  $\mu\text{J}/\text{cm}^2$ . Uslu et al. [117] have optimized the PUV treatment for inactivation of *E. coli* and *Bacillus subtilis* in municipal wastewater. They reported that *E. coli* and *B. subtilis* were reduced by 8.53 and 7.57 log CFU/mL, respectively at a fluence of 10.9 J/cm<sup>2</sup>. Also, they studied the reduction of suspended solid content in wastewater. Their results clearly showed that the suspended solid content was further reduced by an additional 26.5 and 21.4% during the optimized conditions for *E. coli* and *B. subtilis*, respectively.

### Food-contact Surfaces

Food contact surfaces have a great potential to contaminate foods during processing operations due to the cross-contamination issues. According to the FDA, the current Good Manufacturing Practices report explains the food-contact surfaces as the direct contact with human foods and the surfaces that drain directly onto the food or food contact surfaces during the processing operations [118]. Generally, stainless steel or plastic materials are used for food contact surfaces. On the other hand, rubber, wood, ceramic, and glass materials can be used for these contact surfaces. Microorganisms have a tendency to attach to surfaces due to their natural characteristics. They can be detached by mild cleaning when they are attached to the surfaces. However, they cannot be detached or cleaned when a favorable environment is created to grow them and form layers of bacteria (biofilms) and extracellular products that can irreversibly absorb by the surfaces [126]. In the industry, there are many decontamination methods have been applied to reduce the microbial population and cross-contamination on the food contact surfaces. The mixing of chemicals and/or organic acids in aqueous solutions is one of the most applied decontamination methods in the processing lines [118]. Some chemical agents are commonly used for decontamination purposes of food contact surfaces, including iodine, chlorine, carboxylic acid, acid-anionic sanitizers, and quaternary ammonium compounds (QAC) [126]. Nevertheless, these chemical-based decontamination methods are insufficient to prevent outbreaks with sub-lethal processing that leaves spores or toxins of pathogens behind after decontamination treatment. Moreover, these chemical-based methods can generate free radicals, which can cause textural changes on the contacted foods [127]. Additionally, these chemical-based decontamination methods can be harmful to human health, and the lifetime of processing material due to the chemical residues. Therefore, the food industry needs a novel and efficient decontamination method. PUV

is one of the effective and greener alternatives for the decontamination of food-contact surfaces (Table 3). In the literature, the application of the PUV for food-contact surface decontamination has not been intensely studied. Woodling and Moraru [128] have studied the decontamination of *L. innocua* on two types of stainless-steel (mill and aluminum oxide treated finishes) surfaces by using PUV. According to their findings, 4.08 and 4.98-log reductions were observed on mill finish and aluminum oxide finish coupons, respectively at a fluence of 6.4 J/cm<sup>2</sup>. Cassar et al. [118] demonstrated the decontamination of *E. coli* K12-NSR by using PUV on different types of meat conveyor material surfaces, including stainless-steel chain belt, solid pliable polymer belt, rigid linked polymer belt, and PTFE-coated fabric belt. They reported that *E. coli* K12-NSR was decontaminated by 3.91, 4.90, 3.34, and 5.04 log CFU/cm<sup>2</sup> on surfaces of stainless-steel chain belt, solid pliable polymer belt, rigid linked polymer belt, and PTFE-coated fabric belt, respectively at a fluence of 3.31 J/cm<sup>2</sup>. Recently, Gao et al. [120] have screened the effect of PUV treatment on the decontamination of a cocktail of six *Salmonella* spp. biofilms formed on the stainless-steel surfaces. Their findings showed that the biofilm reduction ranged between 0.7 and 1.1 log CFU/cm<sup>2</sup> at different flash distances (3–9 cm) and pulse frequencies (0.5–0.125 Hz).

### The Effect of Pulsed-UV Light Application on the Quality Characteristics of Foods and Its Post-harvest Applications

The effect of PUV decontamination on quality characteristics (e.g., texture, flavor, color, nutritional and bioactive compounds content) of foods has also been extensively studied in the literature. Valdivia-Nájjar et al. [129] studied the effect of PUV treatment on the texture characteristics of fresh-cut tomatoes. They applied PUV to treat the tomatoes at fluences of 4, 6, and 8 J/cm<sup>2</sup> and stored 20 days at 4 °C. They observed that the firmness of the fresh cut tomatoes was significantly decreased during the storage time and reported that increased fluence of PUV accelerated the firmness reduction. They explained this reduction by triggered physicochemical changes, PUV treatment can lead to increasing of respiration rate and stress, and lignification-like processes. These physicochemical processes cause the structural changes in the sample, including dehydration, water-soaked areas, and cellular degradation. Also, similar findings were observed by Aguiló-Aguayo et al. [130]. On the other hand, Gyawali et al. [131] have studied the effect of PUV treatment on quality characteristics of pecan halves. They observed that there was no significant change between control and PUV treated sample in terms

of texture, color, moisture content, water activity, and peroxide value.

Ouyang et al. [104] studied the effect of flow-through PUV treatment on liquid egg white. According to their findings, there was a significant change on pH and turbidity of liquid egg white between the control and PUV treated sample. The pH and turbidity values of liquid egg white were increased after PUV treatment. They stated that the reason for the increase in turbidity after PUV treatment can be explained by protein denaturation or aggregation at higher intensities of PUV treatment. Higher PUV treatments cause an increase in temperature, and the structure of egg white protein can be affected by the rising temperature. On the other hand, Ding et al. [97] treated apple juice by using PUV and conventional (heat application) technique and studied on quality characteristics. They reported that PUV and conventional treatment did not significantly affect the pH, soluble solids, and turbidity. Pratap-Singh and Mandal [95] were studied the effect of thin profile continuous-flow PUV on red grape and watermelon juices. They reported that the pH values of red grape and watermelon juices were not significantly affected after PUV treatment. They stated that the applied intensities of UV radiation were not enough to change the ionic equilibrium in juices. Therefore, the pH values of the samples were not significantly affected. However, they observed significant TPC change in red grape and watermelon juices after PUV treatment due to the photodegradation of phenolic compounds.

Denoya et al. [132] indicated the effect of postharvest PUV treatment on quality characteristic changes of persimmons (*Diospyros virginiana*) during storage. They applied the PUV at a fluence of 20 and 60 mJ/cm<sup>2</sup> and stored for 6 days. They controlled the TPC and the antioxidant capacity (AC) of PUV treated unripe and ripe persimmons every 3 days. According to their findings, TCC and AC of 20 mJ/cm<sup>2</sup>-unripe-PUV treated persimmon were higher than control-unripe and 60 mJ/cm<sup>2</sup>-unripe-PUV treated persimmon. They stated that the increase in TPC and AC can be explained by the photo-protective antioxidative defense response to oxidative stress in the sample after PUV treatment. Other research conducted by Xu and Wu [71], observed a similar trend in PUV treated fresh raspberries. In their study, fresh raspberries were treated by PUV at a fluence of 1.27 J/cm<sup>2</sup> for 5, 15, and 30 s and stored for 10 days. They reported that the TPC and total anthocyanin content of the raspberries increased after 15 and 30 s of PUV treatment. The increase in TCC after a certain fluence can be explained by the generation of an oxidative defense response to oxidative stress. Specifically, PUV treatment causes the abiotic stress, which affects the phenylpropanoid metabolism and leads to the synthesis of secondary metabolites such as phenolic compounds [133]. Kalaras et al. [133]

have studied the postharvest influence of PUV application on vitamin-D<sub>2</sub> (Vit-D<sub>2</sub>) and quality characteristics of white button mushrooms (*Agaricus bisporus*). They indicated that the Vit-D<sub>2</sub> content of mushroom samples were increased by over 100% after 3 pulses, and the Vit-D<sub>2</sub> content reached its maximum value (27 µg/g dw) after treatment of 12 pulses. They also reported that there was no significant difference in the quality characteristics of PUV treated mushroom samples compared to untreated samples. Another research of Kalaras et al. [134] reported the formation of bioactive ergosterol-derived compounds in white button mushrooms after PUV treatment. They treated the mushroom samples for a range of 3–60 pulses (0.791 J/cm<sup>2</sup>/pulse) and observed that the bioactive ergosterol-derived photoproducts (vitamin D<sub>2</sub>, previtamin D<sub>2</sub>, lumisterol<sub>2</sub>, and tachysterol<sub>2</sub>) were significantly increased after PUV treatment.

Color is one of the main quality parameters of foods and is of critical importance for consumers. The impact of PUV on the color of foods should be evaluated and reported as well. Borges et al. [50] have evaluated the effect of PUV treatment on the color values of ready-to-eat traditional cured smoked meat sausage. They observed that the a\* value (redness) was significantly reduced and b\* value (yellowness) was changed due to the independent energy dose, and they did not observe any change for L\* value (lightness) between the control and PUV treated sample. Also, they stated that the b\* value was increased with increasing applied fluence. Additionally, they reported that the color change of meat is attributed to the local heating effect, PUV treatment or lipid oxidation effect on the sensory characteristics of meat products. Another study conducted by Keklik et al. [135] indicated the effect of PUV treatment on the color characteristics of unpackaged and packaged boneless chicken breast meat. They applied PUV for unpackaged and packaged samples as follows: 13 cm-5 s, 8 cm-30 s, and 5 cm-60 s. They reported that, for unpackaged and packaged samples, there was a significant difference between the treated and untreated samples for 60 s treatment at a distance of 5 cm between the sample and the lamp. Also, they stated that the intensive PUV treatment resulted in decrease in L\*, a\*, and b\* values, while mild and moderate PUV treatments had no significant effect on color values.

Protein oxidation is one of the main important quality parameters for foods. The effects of protein oxidation on food quality may not be sensed immediately by humans, due to this situation protein oxidation has received less remarked over the years [136]. ROS or secondary by-products of oxidative stress can cause the covalent alteration of proteins, which is known as protein oxidation [137]. According to the diet related pathological studies, the consumption of oxidized protein in food products and oxidized meat can have serious effects on human health, such as cancer and several

neurological disorders [138, 139]. Elmnasser et al. [140] evaluated the influence of PUV application on milk proteins  $\beta$ -Lactoglobulin (BLG),  $\alpha$ -lactalbumin (ALA), and sodium caseinate. They reported that there was no significant conformational change effect of PUV treatment on milk proteins of BLG, ALA, and sodium caseinate and no oxidation products were observed. Fernández et al. [141] have also studied the effect of PUV treatment on protein oxidation in vacuum packaged of processed cheese slices. They used the fluences of 0.7, 2.1, 4.2, 8.4, and 11.9 J/cm<sup>2</sup> and stored for 30 days at 4 °C and compared with bovine serum albumin (BSA) protein model to assess the PUV effect. Their results showed that the carbonyl content was significantly increased after a fluence of 8.4 J/cm<sup>2</sup> in BSA. In cheese, the carbonyl content was only significantly increased at the highest fluence. Also, the significant difference of protein oxidation in BSA at a fluence of 8.4 J/cm<sup>2</sup> can be explained by the absorption of PUV. As we stated previous section, BSA is more transparent than the cheese sample, increasing in transparency can be result in higher protein oxidation. Additionally, they stated that protein oxidation can occur through a direct mechanism via the absorption of UV light by amino acids or through an indirect mechanism involving photosensitizers. The oxidation that occurred in BSA can be explained by direct mechanism. BSA shows maximum absorbance at 280 nm, which is the wavelength absorbed by aromatic amino acids (phenylalanine, tyrosine, and tryptophan), cysteine, and histidine. The oxidation that occurred in cheese can be explained by indirect mechanism. In more deeply, cheese contains riboflavin (vitamin B<sub>2</sub>), which is a good photosensitizer. Riboflavin produces reactive oxygen species (singlet oxygen or reactive hydroxyl radical) when irradiated under PUV due to its conjugated double system and in the presence of oxygen. Lastly, they stated that vacuum-packaging and the low penetration of light into the samples helped light-induced oxidation and overcome this problem. Another research of the effect of PUV treatment on protein oxidation in Spanish dry-cured ham slices was conducted by Fernández et al. [142]. They applied the fluences of 2.1, 4.2, and 8.4 J/cm<sup>2</sup> for two types of Serrano and Iberian types of ham slices, respectively and stored for 30 days at 4 and 20 °C. According to their volatile profile analysis results, they detected the sulphur volatile compounds after a fluence of 8.4 J/cm<sup>2</sup> in Serrano and Iberian ham slices. Consequently, the sulphur volatile compounds can be synthesized as a result of protein oxidation, increasing in fluence of PUV treatment led to protein oxidation.

Lipid oxidation is also a vital parameter to determine the quality of foods, and causes significant effects on texture, flavor, appearance, nutritional contents of food products, reducing the shelf-life of food, and leading to huge economic losses [143]. Keklik et al. [61] evaluated the effect

of PUV on lipid oxidation in fresh kashar cheese. They reported that the increasing of the fluence led to increasing of the lipid oxidation values, but PUV treatments did not significantly affect the lipid oxidation in fresh kashar cheese. Zhang et al. [48] have demonstrated the influence of PUV treatment on lipid oxidation compounds in large yellow croaker fish (*Pseudosciaena crocea*) and to understand the lipid oxidation behaviour of treated fish samples, they were stored at 4 °C for 10 days and compared with an untreated sample. According to their results, the initial degree of lipid oxidation of the PUV treated samples was higher than the untreated sample after the PUV treatment. However, they showed that the degree of lipid oxidation of the untreated sample was higher than that of the PUV treated samples at the end of storage. Fracari et al. [49] were studied the influence of the PUV treatment on the oxidation stability of traditional Italian sausage (mortadella). They applied the four PUV treatment, including pulse width of 1260  $\mu$ s for 2 pulses (2P<sub>1260</sub>), 1260  $\mu$ s for 3 pulses (3P<sub>1260</sub>), 2520  $\mu$ s for one pulse (1P<sub>2520</sub>), and 2520  $\mu$ s for 2 pulses (2P<sub>2520</sub>), at a voltage of 3000 V. After the PUV treatment, they vacuum-packed the samples and stored at 4 °C for 30 days. They reported that the highest lipid oxidation was observed at the highest fluences of 2P<sub>2520</sub> (5.28 J/cm<sup>2</sup>) and 3P<sub>1260</sub> (6.57 J/cm<sup>2</sup>) and explained possible reasons for high lipid oxidation values, a higher fluences can lead to oxidation reactions in the desired product due to the formation of ROS. Nevertheless, for the 2P<sub>1260</sub> treated sample at a fluence of 4.36 J/cm<sup>2</sup>, they observed similar oxidative stability behaviour to the control sample at the end of 30 days of storage. They also stated that the undesirable compounds formation of PUV can be mitigated by lower fluence and higher irradiance.

Effective post-harvest management is crucial for the freshness, safety, and shelf life of foods, which also reduces food waste and ensures food security. Conventional post-harvest techniques for preservation of foods, such as refrigeration and chemical applications, have drawbacks, including environmental impact and insufficient shelf-life extension [144]. Nowadays, PUV decontamination technique gaining importance due to its ability to improve target product quality and shelf life in post-harvest applications. Tang et al. [145] have studied the decontamination of *Botrytis cinerea* on cherry tomatoes using PUV. They applied 60 (PUV-60) and 150 (PUV-150) pulses after inoculation and determined the effect of the PUV treatment on *Botrytis cinerea* growing on cherry tomatoes after 4 days of storage at 25 °C. According to their findings, the control and PUV-60 samples began to spoil on the first day of storage; however, the PUV-150 samples did not show infected tomatoes for 4 days. Cui et al. [146] have demonstrated the decontamination of *Penicillium ochrochloron* spores on strawberries using PUV decontamination technique. They treated the samples under

fluences of 1.24 (PUV-1), 3.31 (PUV-2), and 6.19 (PUV-3) J/cm<sup>2</sup> and stored each treated group at 4, 14, and 25 °C for 14, 8, and 6 days, respectively, to examine the decay rate. Their results showed that, when compared to the control group, the lowest decay rate observed at PUV-3 groups for each parameter.

## Conclusions and Future Trends

Foodborne illnesses have a serious impact on public health and food safety, lead to life-critical illnesses and costly recalls all around the world. Therefore, the decontamination of foods and the sustainability of decontamination are important to prevent these issues. This review paper aimed to demonstrate the recent PUV decontamination applications for different kinds of foods, packaging materials, water/wastewater treatments, and food-contact surfaces as well as to understand its effect on quality characteristics. PUV has a great potential to decontaminate food products, packaging materials, and water/wastewater treatments, and it is used as a non-thermal, innovative, and sustainable decontamination technique. In recent years, PUV has gained importance due to its short treatment time, no toxic material formation, and less energy usage compared to conventional decontamination techniques. Unfortunately, more research is needed to understand and effect of the PUV application on different microorganisms and compounds and also pilot-scale studies should be done for various applications to encourage the food industry to consider this emerging technology.

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**Data Availability** No datasets were generated or analysed during the current study.

## Declarations

**Competing interests** The authors declare no competing interests.

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## References

- Mandal R, Mohammadi X, Wiktor A, Singh A, Pratap Singh A (2020) Applications of pulsed light decontamination technology in food processing: an overview. *Appl Sci* 10(10):3606. <https://doi.org/10.3390/app10103606>
- Demirci A, Krishnamurthy K (2010) Pulsed Ultraviolet Light. In: Zhang HQ, Barbosa-Cánovas GV, Balasubramaniam VM, Dunne P, Farkas D, Yuan J (eds) *Nonthermal Processing Technologies for Food*. Blackwell Publishing, Ames, IA, pp 249–261
- Estimating the burden of foodborne diseases. In: World Health Organization. <https://www.who.int/activities/estimating-the-burden-of-foodborne-diseases#:~:text=Each%20year%20worldwide%2C%20unsafe%20food,number%20is%20likely%20an%20underestimation>. Accessed on 10 Oct 2024
- Cassar JR, Ouyang B, Krishnamurthy K, Demirci A (2020) Microbial decontamination of food by light-Based technologies: ultraviolet (UV) light, pulsed UV light (PUV), and UV light-Emitting diodes (UV-LED). In: Feng H, Krishnamurthy K (eds) *Food safety Engineering*. Demirci Ali, 1st edn. Springer Cham., pp 493–521
- Waghmare R, Kumar M, Zhang B, Yadav R, Dukare A, Chandran D, Nayi P, Hasan M, Dhuma S, Dharmarao T, Malik T, Sarma R, Biswas S, Lorenzo JM (2024) Pulsed light: innovative non-thermal technology for preservation of fruits and vegetables. *Food Phys* 1:100022. <https://doi.org/10.1016/j.foodp.2024.100022>
- Koutchma T (2019) *Ultraviolet light in food technology*, 2nd edn. CRC, Boca Raton
- Hinds LM, O'Donnell CP, Akhter M, Tiwari BK (2019) Principles and mechanisms of ultraviolet light emitting diode technology for food industry applications. *Innov Food Sci Emerg Technol* 56:102153. <https://doi.org/10.1016/j.ifset.2019.04.006>
- Nicolau T, Gomes Filho N, Padrão J, Zille A (2022) A comprehensive analysis of the UVC leds' applications and decontamination capability. *Materials* 15:2854. <https://doi.org/10.3390/ma15082854>
- Gómez-López VM, Ragaert P, Debevere J, Devlieghere F (2007) Pulsed light for food decontamination: a review. *Trends Food Sci Technol* 18(9):464–473. <https://doi.org/10.1016/j.tifs.2007.03.010>
- Oms-Oliu G, Martín-Belloso O, Soliva-Fortuny R (2010) Pulsed light treatments for food preservation. A review. *Food Bioprocess Technol* 3:13–23. <https://doi.org/10.1007/s11947-008-0147-x>
- Ozer NP, Demirci A (2006) Inactivation of *Escherichia coli* O157:H7 and *Listeria monocytogenes* inoculated on raw salmon fillets by pulsed UV-light treatment. *Int J Food Sci Technol* 41(4):354–360. <https://doi.org/10.1111/j.1365-2621.2005.01071.x>
- Uslu-Senel G, Demirci A (2024) Pulsed ultraviolet light for microbial inactivation and its applications for food decontamination. In: Jaiswal AK, Shankar S (eds) *Food packaging and preservation*. Academic, Cambridge, pp 275–298
- Song K, Mohseni M, Taghipour F (2019) Mechanisms investigation on bacterial inactivation through combinations of UV wavelengths. *Water Res* 163:114875. <https://doi.org/10.1016/j.watres.2019.114875>
- Mesquita Q, Dias C MJ, Neves PMS, Almeida MG, Faustino AF MA (2018) Revisiting current photoactive materials for

- antimicrobial photodynamic therapy. *Molecules* 23:2424. <https://doi.org/10.3390/molecules23102424>
15. Luksiene Z, Brovko L (2013) Antibacterial photosensitization-based treatment for food safety. *Food Eng Rev* 5:185–199. <https://doi.org/10.1007/s12393-013-9070-7>
  16. Farrell H, Hayes J, Laffey J, Rowan N (2011) Studies on the relationship between pulsed UV light irradiation and the simultaneous occurrence of molecular and cellular damage in clinically-relevant *Candida albicans*. *J Microbiol Methods* 84(2):317–326. <https://doi.org/10.1016/j.mimet.2010.12.021>
  17. Elmnasser N, Guillou S, Leroi F, Orange N, Bakhrouf A, Federighi M (2007) Pulsed-light system as a novel food decontamination technology: a review. *Can J Microbiol* 53(7):813–821. <https://doi.org/10.1139/W07-042>
  18. Krishnamurthy K, Tewari JC, Irudayaraj J, Demirci A (2010) Microscopic and spectroscopic evaluation of inactivation of *Staphylococcus aureus* by pulsed UV light and infrared heating. *Food Bioprocess Technol* 3:93–104. <https://doi.org/10.1007/s11947-008-0084-8>
  19. Buchovec I, Paskeviciute E, Luksiene Z (2010) Photosensitization-based inactivation of food pathogen *Listeria monocytogenes* in vitro and on the surface of packaging material. *J Photochem Photobiol B* 99(1):9–14. <https://doi.org/10.1016/j.jphotobiol.2010.01.007>
  20. Lukšienė Ž (2005) New approach to inactivation of harmful and pathogenic microorganisms by photosensitization. *Food Technol Biotechnol* 43(4):411–418
  21. Tim M (2015) Strategies to optimize photosensitizers for photodynamic inactivation of bacteria. *J Photochem Photobiol B Biol* 150:2–10. <https://doi.org/10.1016/j.jphotobiol.2015.05.010>
  22. Faghhihadeh F, Anaya NM, Hadjeres H, Boving TB, Oyanedel-Craver V (2019) Pulse UV light effect on microbial biomolecules and organic pollutants degradation in aqueous solutions. *Chemosphere* 216:677–683. <https://doi.org/10.1016/j.chemosphere.2018.10.176>
  23. Jori G, Fabris C, Soncin M, Ferro M, Coppellotti O, Dei D, Fantetti L, Chiti G, Roncucci G (2006) Photodynamic therapy in the treatment of microbial infections: basic principles and perspective applications. *Lasers Surg Med* 38:468–481. <https://doi.org/10.1002/lsm.20361>
  24. Kaavya R, Rajasekaran B, Shah K, Nickhil C, Palanisamy S, Palamae S, Khanashyam AC, Pandiselvam R, Benjakul S, Thorakattu P, Ramesh B, Aurum FS, Babu KS, Rustagi S, Ramniwas S (2025) Radical species generating technologies for decontamination of *Listeria* species in food: a recent review report. *Crit Rev Food Sci Nutr* 65:1974–1998. <https://doi.org/10.1080/10408398.2024.2316295>
  25. Levy C, Aubert X, Lacour B, Carlin F (2012) Relevant factors affecting microbial surface decontamination by pulsed light. *Int J Food Microbiol* 152(3):168–174. <https://doi.org/10.1016/j.ijfoodmicro.2011.08.022>
  26. Cassar JR, Mills EW, Demirci A (2022) Characterization of pulsed light for microbial inactivation. *J Food Eng* 334:111152. <https://doi.org/10.1016/j.jfoodeng.2022.111152>
  27. Xenon Corp (2025) <https://xenoncorp.com/products/>
  28. Amglo (2025) Accessed on August 14. <https://amglo.com/applications/disinfection/>
  29. Claranor (2025) <https://www.claranor.com/en/>
  30. Phoxene (2025) <https://www.phoxene.com/category/applications/pulsed-light-sterilization/>
  31. Food Process Engineering Laboratory at The University of British Columbia (2025) <https://fpel.landfood.ubc.ca>
  32. Moraru Lab at Cornell University (2025) <https://blogs.cornell.edu/morarulab/papers/>
  33. Franco-Vega A, Reyes-Jurado F, González-Albarrán D, Ramírez-Corona N, Palou E, López-Malo A (2021) Developments and advances of high intensity pulsed light and its combination with other treatments for microbial inactivation in food products. *Food Eng Rev* 13:741–768. <https://doi.org/10.1007/s12393-021-09280-1>
  34. Salazar-Zúñiga MN, Lugo-Cervantes E, Rodríguez-Campos J, Sanchez-Vega R, Rodríguez-Roque MJ, Valdivia-Nájar CG (2023) Pulsed light processing in the preservation of juices and fresh-cut fruits: a review. *Food Bioprocess Technol* 16(3):510–525. <https://doi.org/10.1007/s11947-022-02891-4>
  35. Uslu G, Demirci A, Regan JM (2016) Disinfection of synthetic and real municipal wastewater effluent by flow-through pulsed UV-light treatment system. *J Water Process Eng* 10:89–97. <https://doi.org/10.1016/j.jwpe.2016.02.004>
  36. Lisboa HM, Pasquali MB, dos Anjos AI, Sarinho AM, de Melo ED, Andrade R, Batista L, Lima J, Diniz Y, Barros A (2024) Innovative and sustainable food preservation techniques: enhancing food Quality, Safety, and environmental sustainability. *Sustain* 16(4):8223. <https://doi.org/10.3390/su16188223>
  37. Chakka AK, Sriraksha MS, Ravishankar CN (2021) Sustainability of emerging green non-thermal technologies in the food industry with food safety perspective: a review. *LWT* 151:112140. <https://doi.org/10.1016/j.lwt.2021.112140>
  38. Mahendran R, Ramanan KR, Barba FJ, Lorenzo JM, Lopez-Fernandez O, Munekata PES, Sant’Ana, Tiwari B (2019) Recent advances in the application of pulsed light processing for improving food safety and increasing shelf life. *Trends Food Sci Technol* 88:67–79. <https://doi.org/10.1016/j.tifs.2019.03.010>
  39. Jaiswal M, Nungleppam M, Kumar M, Srivastava B (2024) Pulsed light technology for fresh-cut produce: a review on mechanism and inactivation kinetics of microbes and enzymes. *J Food Process Eng* 47(9):e14738. <https://doi.org/10.1111/jfpe.14738>
  40. Heinrich V, Zunabovic M, Bergmair J, Kneifel W, Jaeger H (2015) Post-packaging application of pulsed light for microbial decontamination of solid foods: A review. *Innov Food Sci Emerg Technol* 30:145–156. <https://doi.org/10.1016/j.ifset.2015.06.005>
  41. Bialka KL, Demirci A, Walker PN, Puri VM (2008) Pulsed UV-Light penetration of characterization and the inactivation of *Escherichia coli* K12 in solid model systems. *Trans ASABE* 51:195–204. <https://doi.org/10.13031/2013.24204>
  42. Rathod NB, Smaoui S, Agrawal R, Bhagwat P, Amobonye A, Pillai S, Yilmaz N, Ozogul F (2024) Sustainable processing technologies (pulsed light, electrolysed water and ozonation) for microbial decontamination of muscle foods. *Innov Food Sci Emerg Technol* 96:103778. <https://doi.org/10.1016/j.ifset.2024.103778>
  43. Lee Y, Yoon Y (2024) Principles and applications of non-thermal technologies for meat decontamination. *Food Sci Anim Resour* 44(1):19–38. <https://doi.org/10.5851/kosfa.2023.e72>
  44. Satin M (2002) Use of irradiation for microbial decontamination of meat: situation and perspectives. *Meat Sci* 62(3):277–283. [https://doi.org/10.1016/S0309-1740\(02\)00129-8](https://doi.org/10.1016/S0309-1740(02)00129-8)
  45. Wang J, Chen J, Sun Y, He J, Zhou C, Xia Q, Dang Y, Pan D, Du L (2023) Ultraviolet-radiation technology for preservation of meat and meat products: recent advances and future trends. *Food Control* 148:109684. <https://doi.org/10.1016/j.foodcont.2023.109684>
  46. Speranza B, Racioppo A, Bevilacqua A, Buzzo V, Marigliano P, Mocerino E, Scognamiglio R, Corbo MR, Scognamiglio G, Sinigaglia M (2021) Innovative preservation methods improving the quality and safety of fish products: beneficial effects and limits. *Foods* 10(11):2854. <https://doi.org/10.3390/foods10112854>
  47. Chen B-R, Roobab U, Madni GM, Abdi G, Zeng XA, Aadil RM (2024) A review of emerging applications of ultrasonication in comparison with non-ionizing technologies for meat decontamination. *Ultrason Sonochem* 108:106962. <https://doi.org/10.1016/j.ultsonch.2024.106962>

48. Zhang J, Zhou G, Ji S, Zou L, Liang J, Walayat N, Chen J, Lyu F, Ding Y (2022) Effect of pulse light on the quality of refrigerated (4°C) large yellow croaker (*Pseudosciaena crocea*). LWT 167:113855. <https://doi.org/10.1016/j.lwt.2022.113855>
49. Fracari PR, Massia AG, Laroque DA, Santos BAD, Cichoski AJ, Carciofi BAM, Campagnol PCB (2024) Pulsed light treatment effect on color, oxidative stability, and *Listeria monocytogenes* population of sliced Mortadella. Foods 13:2976. <https://doi.org/10.3390/foods13182976>
50. Borges A, Baptista E, Aymerich T, Alves SP, Gama LT, Fraqueza MJ (2023) Inactivation of *Listeria monocytogenes* by pulsed light in packaged and sliced salpicão, a ready-to-eat traditional cured smoked meat sausage. LWT 179:114641. <https://doi.org/10.1016/j.lwt.2023.114641>
51. Keklik NM (2020) Treatment of Pastirma with pulsed UV light: modeling of *Staphylococcus aureus* inactivation and assessment of quality changes. Food Sci Technol Int 26:185–198. <https://doi.org/10.1177/1082013219889231>
52. Baptista E, Borges A, Aymerich T, Alves SP, Gama LTd, Fernandes H, Fernandes MJ, Fraqueza MJ (2022) Pulsed light application for *Campylobacter* control on poultry meat and its effect on colour and volatile profile. Foods 11(18):2848. <https://doi.org/10.3390/foods11182848>
53. Wang J, Ning Z, Chen Y, Xu X, Wang H (2024) Model prediction of inactivation of *Aeromonas salmonicida* grown on poultry *in situ* by intense pulsed light. Food Sci Hum Wellness 13(2):1011–1017. <https://doi.org/10.26599/FSHW.2022.9250087>
54. Söbeli C, Uyarcan M, Kayaardı S (2021) Pulsed UV-C radiation of beef loin steaks: effects on microbial inactivation, quality attributes and volatile compounds. Innov Food Sci Emerg Technol 67:102558. <https://doi.org/10.1016/j.ifset.2020.102558>
55. Pedrós-Garrido S, Condón-Abanto S, Clemente I, Beltrán JA, Lyng JG, Bolton D, Brunton N, Whyte P (2018) Efficacy of ultraviolet light (UV-C) and pulsed light (PL) for the Microbiological decontamination of Raw salmon (*Salmo salar*) and food contact surface materials. Innov Food Sci Emerg Technol 50:124–131. <https://doi.org/10.1016/j.ifset.2018.10.001>
56. Koch F, Wiacek C, Braun PG (2019) Pulsed light treatment for the reduction of *Salmonella typhimurium* and *yersinia Enterocolitica* on pork skin and pork loin. Int J Food Microbiol 292:64–71. <https://doi.org/10.1016/j.ijfoodmicro.2018.11.014>
57. Chen D, Wiertzema J, Peng P, Cheng Y, Liu J, Mao Q, Ma Y, Anderson E, Chen P, Baumler DJ, Chen C, Vickers Z, Feirtag J, Lee L, Ruan R (2018) Effects of intense pulsed light on *Cronobacter sakazakii* inoculated in non-fat dry milk. J Food Eng 238:178–187. <https://doi.org/10.1016/j.jfoodeng.2018.06.022>
58. de Moraes JO, Hilton ST, Moraru CI (2020) The effect of pulsed light and starch films with antimicrobials on *Listeria innocua* and the quality of sliced cheddar cheese during refrigerated storage. Food Control 112:107134. <https://doi.org/10.1016/j.foodcont.2020.107134>
59. Ricciardi FE, Plazzotta S, Conte A, Manzocco L (2021) Effect of pulsed light on microbial inactivation, sensory properties and protein structure of fresh Ricotta cheese. LWT 139:110556. <https://doi.org/10.1016/j.lwt.2020.110556>
60. Cassar JR, Bright LM, Patterson PH, Mills EW, Demirci A (2021) The efficacy of pulsed ultraviolet light processing for table and hatching eggs. Poult Sci 100(3):100923. <https://doi.org/10.1016/j.psj.2020.12.021>
61. Keklik NM, Elik A, Salgin U, Demirci A, Koçer G (2019) Inactivation of *Staphylococcus aureus* and *Escherichia coli* O157:H7 on fresh Kasha cheese with pulsed ultraviolet light. Food Sci Technol Int 25(8):680–691. <https://doi.org/10.1177/1082013219860925>
62. Fernández M, Hospital XF, Arias K, Hierro E (2016) Application of pulsed light to sliced cheese: effect on *Listeria* inactivation, sensory quality and volatile profile. Food Bioprocess Technol 9:1335–1344. <https://doi.org/10.1007/s11947-016-1721-2>
63. Jaiswal M, Srivastava B (2024) Evaluating the impact of pulsed light treatment on microbial and enzyme inactivation and quality attributes in fresh-cut watermelon. J Food Process Eng 47(5):e14626. <https://doi.org/10.1111/jfpe.14626>
64. Dhawan A, Chakraborty S (2024) Pulsed light treatment of whole white button mushroom (*Agaricus bisporus*): kinetics and mechanism of microbial inactivation and storage study. J Food Sci 89(9):5319–5334. <https://doi.org/10.1111/1750-3841.17255>
65. Mukhopadhyay S, Ukuku DO, Olanya OM, Niemira BA, Jin ZT, Fan X (2024) Combined treatment of pulsed light and nisin-organic acid based antimicrobial wash for inactivation of *Escherichia coli* O157:H7 in Romaine lettuce, reduction of microbial loads, and retention of quality. Food Microbiol 118:104402. <https://doi.org/10.1016/j.fm.2023.104402>
66. Gomathi Padma Priya P, Savitha S, Chakraborty S, Thorat BN (2024) Effect of dehydration and pulsed light treatment on decontamination of minced onions: microbial safety and physicochemical properties. J Food Sci 89:2025–2039. <https://doi.org/10.1111/1750-3841.16990>
67. Mukhopadhyay S, Ukuku DO, Jin T, Olanya OM, Fan X (2023) Evaluation of pulsed light treatment for inactivation of *Salmonella* in packaged Cherry tomato and impact on background microbiota and quality. J Food Saf 43(3):e13035. <https://doi.org/10.1111/jfs.13035>
68. Pravallika K, Chakraborty S (2024) Pulsed light decontamination of red chilies (*Capsicum annum* var. *longum*). J Food Saf 44(5):e13168. <https://doi.org/10.1111/jfs.13168>
69. Pravallika K, Chakraborty S (2024) Effect of pulsed light technology on microbial quality, enzyme activity and physicochemical attributes of green chilies (*Capsicum annum* var. *longum*) at different levels of water activity. J Food Meas Charact 18:5982–5999. <https://doi.org/10.1007/s11694-024-02623-6>
70. 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. Int J Food Microbiol 166(1):102–108. <https://doi.org/10.1016/j.ijfoodmicro.2013.06.027>
71. Xu W, Wu C (2016) The impact of pulsed light on decontamination, quality, and bacterial attachment of fresh raspberries. Food Microbiol 57:135–143. <https://doi.org/10.1016/j.fm.2016.02.009>
72. Reyes-Jurado F, Sucar-Escamilla DP, Etchegaray-Bello M, Ávila-Sosa R, López-Malo A, Mani-López E, Palou E (2025) Intense light pulses in combination with Lemongrass essential oil in vapor phase to inactivate *Salmonella typhimurium* on sunflower and Quinoa seeds. Food Control 169:111004. <https://doi.org/10.1016/j.foodcont.2024.111004>
73. Li X, Zhang J, Liu X et al (2022) Effect of pulsed light treatment on the physicochemical properties of wheat flour and quality of fresh wet noodles. Cereal Chem 99(4):920–930. <https://doi.org/10.1002/cche.10551>
74. Xie J, Hung Y (2020) Efficacy of pulsed-ultraviolet light for inactivation of *Salmonella* spp. on black peppercorns. J Food Sci 85(3):755–761. <https://doi.org/10.1111/1750-3841.15059>
75. Liu X, Fan X, Wang W, Yao S, Chen H (2021) Wetting raw almonds to enhance pulse light inactivation of *Salmonella* and preserve quality. Food Control 125:107946. <https://doi.org/10.1016/j.foodcont.2021.107946>
76. Izmirlioglu G, Ouyang B, Demirci A (2020) Utilization of pulsed UV light for inactivation of *Salmonella enteritidis* on shelled walnuts. LWT 134:110023. <https://doi.org/10.1016/j.lwt.2020.110023>
77. Chen D, Chen P, Cheng Y et al (2019) Deoxyrnivalenol decontamination in Raw and G-germinating barley treated by plasma-Activated water and intense pulsed light. Food Bioprocess Technol 12:246–254. <https://doi.org/10.1007/s11947-018-2206-2>

78. Chen D, Cheng Y, Peng P et al (2019) Effects of intense pulsed light on *Cronobacter sakazakii* and *Salmonella* surrogate *Enterococcus faecium* inoculated in different powdered foods. *Food Chem* 296:23–28. <https://doi.org/10.1016/j.foodchem.2019.05.180>
79. Wang B, Mahoney NE, Pan Z, Khir R, Wu B, Ma H, Zhao L (2016) Effectiveness of pulsed light treatment for degradation and detoxification of aflatoxin B1 and B2 in rough rice and rice bran. *Food Control* 59:461–467. <https://doi.org/10.1016/j.foodcont.2015.06.030>
80. Aron Maftei N, Ramos-Villarreal AY, Nicolau AI, Martín-Belloso O, Soliva-Fortuny R (2014) Pulsed light inactivation of naturally occurring moulds on wheat grain. *J Sci Food Agric* 94(4):721–726. <https://doi.org/10.1002/jsfa.6324>
81. Jun S, Irudayaraj J, Demirci A, Geiser D (2003) Pulsed UV-light treatment of corn meal for inactivation of *Aspergillus niger* spores. *Int J Food Sci Technol* 38(8):883–888. <https://doi.org/10.1046/j.0950-5423.2003.00752.x>
82. Delorme MM, Guimarães JT, Coutinho NM, Balthazar CF, Rocha RS, Silva R, Margalho LP, Pimentel TC, Silva MC, Freitas MQ, Granato D, Sant'Ana A, Duarte MCKH, Cruz AG (2020) Ultraviolet radiation: an interesting technology to preserve quality and safety of milk and dairy foods. *Trends Food Sci Technol* 102:146–154. <https://doi.org/10.1016/j.tifs.2020.06.001>
83. Verraes C, Vlaemynck G, Van Weyenberg S, De Zutter L, Daube G, Sindic M, Uyttendaele M, Herman L (2015) A review of the microbiological hazards of dairy products made from raw milk. *Int Dairy J* 50:32–44. <https://doi.org/10.1016/j.idairyj.2015.05.011>
84. Proulx J, Hsu LC, Miller BM, Sullivan G, Paradis K, Moraru CI (2015) Pulsed-light inactivation of pathogenic and spoilage bacteria on cheese surface. *J Dairy Sci* 98(9):5890–5898. <https://doi.org/10.3168/jds.2015.9410>
85. Dalzini E, Bernini V, Bertasi B, Daminelli P, Losio MN, Varisco G (2016) Survey of prevalence and seasonal variability of *Listeria monocytogenes* in raw cow milk from Northern Italy. *Food Control* 60:466–470. <https://doi.org/10.1016/j.foodcont.2015.08.019>
86. Vargas-Ramella M, Pateiro M, Gavahian M, Franco D, Zhang W, Khaneghah AM, Guerrero-Sánchez Y, Lorenzo JM (2021) Impact of pulsed light processing technology on phenolic compounds of fruits and vegetables. *Trends Food Sci Technol* 115:1–11. <https://doi.org/10.1016/j.tifs.2021.06.037>
87. Mukhopadhyay S, Niemira BA, Ukuku DO, Olanya OM, Boyd G, Jin ZT, Fan X (2024) Cold plasma and pulsed light inactivates *Escherichia coli* O157: H7 in Romaine lettuce and preserves produce quality. *J Food Saf* 44(6):e70000. <https://doi.org/10.1111/jfs.70000>
88. Kim H-J, Jubinville E, Goulet-Beaulieu V, Jean J (2024) Inactivation of murine norovirus and hepatitis A virus on various frozen fruits using pulsed light. *Int J Food Microbiol* 424:110851. <https://doi.org/10.1016/j.ijfoodmicro.2024.110851>
89. Krishnamurthy K, Demirci A, Irudayaraj J (2004) Inactivation of *Staphylococcus aureus* by pulsed UV-light sterilization. *J Food Prot* 67(5):1027–1030. <https://doi.org/10.4315/0362-028X-67.5.1027>
90. Hwang HJ, Kim JW, Choi JB, Chung MS (2025) Effects of the specific wavelength and intensity of intense pulsed light (IPL) on microbial inactivation. *Food Bioprocess Technol* 18:1719–1729. <https://doi.org/10.1007/s11947-024-03560-4>
91. Kasahara I, Carrasco V, Aguilar L (2015) Inactivation of *Escherichia coli* in goat milk using pulsed ultraviolet light. *J Food Eng* 152:43–49. <https://doi.org/10.1016/j.jfoodeng.2014.11.012>
92. Mandal R, Pratap-Singh A (2025) Computational F fluid dynamics analysis and biodosimetry-based microbial validation for continuous-flow pulsed UV light reactors for processing of model liquid foods. *Food Bioprocess Technol* 18:1656–1677. <https://doi.org/10.1007/s11947-024-03540-8>
93. Kumari-Maurya S, Annapure US (2024) Comparative assessment of pulse light treatment and holder pasteurization on nutritional, physicochemical, antioxidant, and microbiological profile of human milk. *J Hum Lact* 40(1):179–179. <https://doi.org/10.1177/08903344231212468>
94. Jayachandran LE, Puliserry OJS SK (2024) Pulsed light processing of sugarcane juice: quality evaluation and microbial load assessment. *J Sci Food Agric* 104:9076–9083. <https://doi.org/10.1002/jsfa.13699>
95. Pratap-Singh A, Mandal R (2024) Non-thermal processing of watermelon and red grape juices in thin-profile continuous-flow pulsed UV light reactors: effect on microbiological safety and nutritional value. *LWT* 191:115516. <https://doi.org/10.1016/j.lwt.2023.115516>
96. Cai R, Ma Y, Wang Z, Yuan Y, Guo H, Sheng Q, Yue T (2024) Inactivation activity and mechanism of pulsed light against *Alicyclobacillus acidoterrestris* vegetative cells and spores in concentrated Apple juice. *Int J Food Microbiol* 413:110576. <https://doi.org/10.1016/j.ijfoodmicro.2024.110576>
97. Ding H, Wang Z, Yuan Y, Yue T (2024) Inactivation of *Alicyclobacillus acidoterrestris* in Apple juice using pulsed light. *Food Control* 163:110439. <https://doi.org/10.1016/j.foodcont.2024.110439>
98. Kwaw E, Osaer R, Apaliya MT, Alolga RN, Sackey AS, Yongkun M, Tchabo W, Obikyembi V (2024) Effect of optimized pulsed light treatment conditions on microbiological safety, phytochemical and sensory properties of lactic-acid-fermented mulberry juice. *J Food Measur Charact* 18(3):1878–1888. <https://doi.org/10.1007/s11694-023-02306-8>
99. Li Y, Cai R, Fu C et al (2023) Degradation of patulin in apple juice by pulsed light and its effect on the quality. *Food Bioprocess Technol* 16:870–880. <https://doi.org/10.1007/s11947-022-02978-y>
100. Kamble SV, Lele SS, Chakraborty S, Annapure US (2024) Impact of pulsed light treatment on achieving microbial safety, enzymatic stability, and shelf life extension of Dragon fruit juice. *Food Saf Health* 2(4):509–523. <https://doi.org/10.1002/fsh3.12068>
101. Bhagat B, Chakraborty S (2022) Potential of pulsed light treatment to pasteurize pomegranate juice: microbial safety, enzyme inactivation, and phytochemical retention. *LWT* 159:113215. <https://doi.org/10.1016/j.lwt.2022.113215>
102. Vollmer K, Chakraborty S, Bhalerao PP, Carle R, Frank J, Steingass (2020) Effect of pulsed light treatment on natural Microbiota, enzyme Activity, and phytochemical composition of pineapple (*Ananas comosus* [L.] Merr.) juice. *Food Bioprocess Technol* 13:1095–1109. <https://doi.org/10.1007/s11947-020-02460-7>
103. Preetha P, Pandiselvam R, Varadharaju N, Kennedy ZJ, Balakrishnan M, Kothakota A (2021) Effect of pulsed light treatment on inactivation kinetics of *Escherichia coli* (MTCC 433) in fruit juices. *Food Control* 121:107547. <https://doi.org/10.1016/j.foodcont.2020.107547>
104. Ouyang B, Demirci A, Patterson PH (2020) Inactivation of *Escherichia coli* and *Salmonella* in liquid egg white by pulsed UV light and its effects on quality. *J Food Process Eng* 43(5):e13243. <https://doi.org/10.1111/jfpe.13243>
105. Krishnamurthy K, Demirci A, Irudayaraj JM (2007) Inactivation of *Staphylococcus aureus* in milk using flow-through pulsed UV-light treatment system. *J Food Sci* 72(7):233–239. <https://doi.org/10.1111/j.1750-3841.2007.00438.x>
106. Hillegas SL, Demirci A (2003) Inactivation of Clostridium sporogenes in clover honey by pulsed UV-light treatment. *Agricultural Engineering International: the CIGR J Sci Res Dev* Vol 7 pp. Manuscript FP: 03–009

107. Sahoo P, Chakraborty S (2023) Influence of pulsed light, ultrasound, and series treatments on quality attributes, pectin methyl esterase, and native flora inactivation in sweet orange juice (*Citrus sinensis* L. Osbeck). *Food Bioprocess Technol* 16:2095–2112. <https://doi.org/10.1007/s11947-023-03042-z>
108. Ringus DL, Moraru CI (2013) Pulsed light inactivation of *Listeria innocua* on food packaging materials of different surface roughness and reflectivity. *J Food Eng* 114(3):331–337. <https://doi.org/10.1016/j.jfoodeng.2012.08.022>
109. Turtoi M, Nicolau A (2007) Intense light pulse treatment as alternative method for mould spores destruction on paper–polyethylene packaging material. *J Food Eng* 83(1):47–53. <https://doi.org/10.1016/j.jfoodeng.2006.11.017>
110. Luksiene Z, Paskeviciute E (2011) Novel approach to decontaminate food-packaging from pathogens in non-thermal and not chemical way: Chlorophyllin-based photosensitization. *J Food Eng* 106(2):152–158. <https://doi.org/10.1016/j.jfoodeng.2011.04.024>
111. Jin TZ, Fan X, Mukhopadhyay S (2024) Antimicrobial effects of pulsed light activated TiO<sub>2</sub>-Polylactic acid film. *Heliyon* 10:e38891. <https://doi.org/10.1016/j.heliyon.2024.e38891>
112. Dorbani I, Berberian A, Riedel C, Dupont C, Carlin F (2024) Comparing resistance of bacterial spores and fungal conidia to pulsed light and UVC radiation at a wavelength of 254 Nm. *Food Microbiol* 121:104518. <https://doi.org/10.1016/j.fm.2024.104518>
113. Haughton PN, Lyng JG, Cronin DA, Morgan DJ, Fanning S, Whyte P (2011) Efficacy of UV light treatment for the microbiological decontamination of chicken, associated packaging, and contact surfaces. *J Food Prot* 74(4):565–572. <https://doi.org/10.4315/0362-028X.JFP-10-356>
114. Fitzhenry K, Clifford E, Rowan N, del Val A (2021) Bacterial inactivation, photoreactivation and dark repair post flow-through pulsed UV disinfection. *J Water Process Eng* 41:102070. <https://doi.org/10.1016/j.jwpe.2021.102070>
115. Fehrenbach GW, Murphy E, Pogue R, Carter F, Clifford E, Major I, Rowan N (2023) Pulsed ultraviolet (PUV) disinfection of artificially contaminated seawater seeded with high levels of pathogen disease indicators as an alternative for the shellfish industry depuration systems. *Environ Sci Pollut Res* 30(27):70771–70782. <https://doi.org/10.1007/s11356-023-27286-6>
116. Fortunato L, Yarali E, Sanchez-Huerta C, Anthopoulos TD (2021) Rapid photodegradation of organic micro-pollutants in water using high-intensity pulsed light. *J Water Process Eng* 44:102414. <https://doi.org/10.1016/j.jwpe.2021.102414>
117. Uslu G, Demirci A, Regan JM (2015) Efficacy of pulsed UV-light treatment on wastewater effluent disinfection and suspended solid reduction. *J Environ Eng* 141(6):04014090. [https://doi.org/10.1061/\(ASCE\)EE.1943-7870.0000912](https://doi.org/10.1061/(ASCE)EE.1943-7870.0000912)
118. Cassar JR, Mills EW, Demirci A (2022) Pulsed ultraviolet light decontamination of meat conveyor surfaces. *Food Sci Technol Int* 28(8):663–671. <https://doi.org/10.1177/10820132211049610>
119. Yasoubi N, Anderson WA, Ward VCA (2023) Evaluation of pulsed Xenon UV irradiation on inactivation of *Listeria monocytogenes* on stainless-steel surfaces. *LWT* 184:115068. <https://doi.org/10.1016/j.lwt.2023.115068>
120. Gao F, Lyu C, Ning Z, Zhao S, Shao L, Xu X, Wang H (2023) Inactivation of *Salmonella* biofilms formed on stainless steel surfaces by pulsed light. *Food Control* 153:109955. <https://doi.org/10.1016/j.foodcont.2023.109955>
121. Liu S, Chen S, Shao L, Ding Z, Xu X, Wang H (2024) Spoilage bacteria growth reduction and microbial community variation of chilled chicken packaged in PA/PE treated with pulsed light. *Food Control* 157:110196. <https://doi.org/10.1016/j.foodcont.2023.110196>
122. Garvey M, Thokala N, Rowan N (2014) A comparative study on the pulsed UV and the low-pressure UV inactivation of a range of microbial species in water. *Water Environ Res* 86(12):2317–2324. <https://doi.org/10.2175/106143014X14062131178718>
123. Demirci A, Krishnamurthy K (2007) Disinfection of water by flow-through a pulsed UV light sterilization system. *Ultrapure Water J* 24(1):35–40
124. Bohrerova Z, Shemer H, Lantis R, Impellitteri CA, Linden KG (2008) Comparative disinfection efficiency of pulsed and continuous-wave UV irradiation technologies. *Water Res* 42(12):2975–2982. <https://doi.org/10.1016/j.watres.2008.04.001>
125. Garvey M, Rabbitt D, Stocca A, Rowan N (2015) Pulsed ultraviolet light inactivation of *Pseudomonas aeruginosa* and *Staphylococcus aureus* biofilms. *Water Environ J* 29(1):36–42. <https://doi.org/10.1111/wej.12088>
126. Skåra T, Rosnes JT (2016) Emerging methods and principles in food contact surface Decontamination/Prevention. In: Leadley CE (ed) *Innovation and future trends in food manufacturing and supply chain technologies*. Woodhead Publishing, Cambridge, pp 151–172
127. Garvey M, Rowan N (2019) Pulsed UV as a potential surface sanitizer in food production processes to ensure consumer safety. *Curr Opin Food Sci* 26:65–70. <https://doi.org/10.1016/j.cofs.2019.03.003>
128. Woodling SE, Moraru CI (2007) Effect of spectral range in surface inactivation of *Listeria innocua* using broad-spectrum pulsed light. *J Food Prot* 70:909–916. <https://doi.org/10.4315/0362-028X-70-4.909>
129. Valdivia-Nájar CG, Martín-Belloso O, Soliva-Fortuny R (2018) Impact of pulsed light treatments and storage time on the texture quality of fresh-cut tomatoes. *Innov Food Sci Emerg Technol* 45:29–35. <https://doi.org/10.1016/j.ifset.2017.08.007>
130. Aguiló-Aguayo I, Charles F, Renard CMGC, Page D, Carlin F (2013) Pulsed light effects on surface decontamination, physical qualities and nutritional composition of tomato fruit. *Postharvest Biol Technol* 86:29–36. <https://doi.org/10.1016/j.postharvbio.2013.06.011>
131. Gyawali R, Degala HL, Biswal AK, Bardsley CA, Mahapatra AK (2024) Effects of intense pulsed light on inactivation of *Salmonella typhimurium* and quality characteristics of Pecan halves. *LWT* 203:116344. <https://doi.org/10.1016/j.lwt.2024.116344>
132. Denoya GI, Pataro G, Ferrari G (2020) Effects of postharvest pulsed light treatments on the quality and antioxidant properties of persimmons during storage. *Postharvest Biol Technol* 160:111055. <https://doi.org/10.1016/j.postharvbio.2019.111055>
133. Kalaras MD, Beelman RB, Elias RJ (2012) Effects of postharvest pulsed UV light treatment of white button mushrooms (*Agaricus bisporus*) on vitamin D<sub>2</sub> content and quality attributes. *J Agric Food Chem* 60(1):220–225. <https://doi.org/10.1021/jf203825e>
134. Kalaras MD, Beelman RB, Holick MF, Elias RJ (2012) Generation of potentially bioactive ergosterol-derived products following pulsed ultraviolet light exposure of mushrooms (*Agaricus bisporus*). *Food Chem* 135(2):396–401. <https://doi.org/10.1016/j.foodchem.2012.04.132>
135. Keklik NM, Demirci A, Puri VM (2010) Decontamination of unpackaged and vacuum-packaged boneless chicken breast with pulsed ultraviolet light. *Poult Sci* 89(3):570–581. <https://doi.org/10.3382/ps.2008-00476>
136. Lund MN, Baron CP (2010) Protein oxidation in foods and food quality. In: Skibsted LH, Risbo J, Andersen ML (eds) *Chemical deterioration and physical instability of food and beverages*. Woodhead Publishing, Cambridge, pp 33–69
137. Zhang W, Xiao S, Ahn DU (2013) Protein oxidation: basic principles and implications for meat quality. *Crit Rev Food Sci Nutr* 53(11):1191–1201. <https://doi.org/10.1080/10408398.2011.577540>
138. Xiong YL, Guo A (2020) Animal and plant protein oxidation: chemical and functional property significance. *Foods* 10(1):40. <https://doi.org/10.3390/foods10010040>

139. Hellwig M (2020) Analysis of protein oxidation in food and feed products. *J Agric Food Chem* 68(46):12870–12885. <https://doi.org/10.1021/acs.jafc.0c00711>
140. Elmnasser N, Dalgalarrodo M, Orange N et al (2008) Effect of pulsed light treatment on milk proteins and lipids. *J Agric Food Chem* 56(6):1984–1991. <https://doi.org/10.1021/jf0729964>
141. Fernández M, Ganan M, Guerra C, Hierro E (2014) Protein oxidation in processed cheese slices treated with pulsed light technology. *Food Chem* 159:388–390. <https://doi.org/10.1016/j.foodchem.2014.02.165>
142. Fernández M, Hospital XF, Cabellos C, Hierro E (2020) Effect of pulsed light treatment on *Listeria* inactivation, sensory quality and oxidation in two varieties of Spanish dry-cured Ham. *Food Chem* 316:126294. <https://doi.org/10.1016/j.foodchem.2020.126294>
143. Wang D, Xiao H, Lyu X, Chen H, Wei F (2023) Lipid oxidation in food science and nutritional health: a comprehensive review. *Oil Crop Sci* 8(1):35–44. <https://doi.org/10.1016/j.ocsci.2023.02.002>
144. Ashraf MA, Khan AS, Azam M, Ayyup S, Kaleem MM, Nawaz S, Abubakar M, Khalid B, Riaz T, Asim M, Ahmed MM, Ateeq M (2025) Innovative technologies in postharvest management of fruits and vegetables: a review. *Eur Food Res Technol* 1–19. <https://doi.org/10.1007/s00217-025-04861-4>
145. Tang P, Cao C, Cai Y, Zhang Z, Liu Z, Pan F, Wang FF, Zhu R (2025) Inactivation of *Botrytis cinerea* by pulsed light and its corresponding mechanism. *Postharvest Biol Technol* 227:113607. <https://doi.org/10.1016/j.postharvbio.2025.113607>
146. Cui X, Bassey AP, Wang F, Xie Shudong, Li Dongnan, Fan L, Zhu Y, Bin L, Liu X (2026) Inactivation of *penicilliumochrochloron* spores by pulsed light: mechanism and preservation efficacy in strawberries. *Food Control* 179:111569. <https://doi.org/10.1016/j.foodcont.2025.111569>

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