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An overview of pulsed light technology for food preservation

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Abstract

There has been a substantial increase in consumer awareness about high quality minimally processed food; various innovative techniques have emerged over the time to enhance the food preservation. The need for minimally processed foods from customers and increasing market competitiveness have forced processors to implement more advanced non-thermal methods that maintain the nutritional value and sensory qualities of food products. The food industry is attempting to develop non-thermal food preservation techniques. One such innovative non-thermal food processing technique that utilises white light to disinfect food products or surfaces in contact with food is pulsed light (PL). Microbial cells are destroyed by exposure to intense light pulses in the infrared, visible, and ultraviolet (UV) spectrum, making the food safe to eat at room temperature. PL technology is a non-thermal technology, where sterilization and decontamination are achieved by impinging high-intensity light pulses of short durations on surfaces of foods and high-transmission liquids. Although a few reports on the PL technology are available, in-depth studies on this are needed to adopt at a commercial level. This review paper intends to give an overview of recent pulsed light research trends, explore pulse generating principles, applications of various PL for the inactivation of microbes in vitro, in various food products, and on food contact surfaces. Apart from this, future challenges, research trends and scope of pulsed light technology are also discussed.

Keywords: pulsed light technology, microbial inactivation, quality, non-thermal process, decontamination, minimal process

Competing Interest: The authors declare that they have no known competing interest

Data Availability: All relevant data are within the paper and its supporting information files

Introduction

Pulsed light (PL) is a non-thermal innovative technique used for food preservation among other relevant non thermal technologies such as high-pressure processing, pulsed electric fields, irradiation and high electrical voltage discharges. The term pulsed light came to light in the year 1980 whereas the application of pulsed light technology in foods was approved by Food and Drug Administration in 1996 [1]. The pulsed light includes the employment of inert gas flash lamps to transform short duration as well high power electric pulses into short duration and high-power pulses of radiation having similar spectrum to that of the sun (200-1100 nm), including infrared (IR), visible light (VL) and ultraviolet (UV) [2]. The pulsed light works within a wavelength range of 180nm-1100nm including UV, visible and IR spectrum. VL has wavelength in the range of

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400-700 nm, whereas, UV light has a wavelength ranging between 100-400nm. The UV light is further sub divided into UV-A, UV-B, UV-C having wavelength in the range of 315-415nm, 280-315nm, and 180-280 nm respectively [3].

PL treatment employs 1–20 flashes/second with an energy density ranging from 0.01 to 50/ J/ cm^2 at the surface and it has potential application in food processes requiring a rapid disinfection. During the last decades, various research have confirmed the germicidal effect of PL in alfalfa seeds, blueberries, corn meal, carrot, honey, lettuce, milk, fish fillets, spinach, strawberries and food contact surfaces made of stainless steel [4, 5]. Particularly for food industrial applications, the PL technology has been successfully applied to decontaminate food packaging materials. The PL system have proportionally low operation costs and generate lower amount of solids wastes [6]. The benefits of PL technology includes lowered risk of food borne pathogens on human health, extension of shelf life of the food products and better economics during food distribution [7]. PL has observed possible applications in food processing requiring disinfection of surface microbial contamination in food products such as fresh whole fruits and vegetables, cheeses or meat slices etc. With excess demand of non-thermal treatment of food, pulse light treated can have significant potential to be implemented in the food industry for lowering the risk of microbial contamination and optimizing the quality attributes of the food products [8].

Electric current to pulsed light conversion

Low AC current with low power and low voltage, is converted into low power, high voltage and low DC current by using an electrical energy converter [9], which is further passed through pulse forming switches to obtain high power, high voltage DC, and pulsed electric field. The pulsed electric current is passed through the inert flash lamps in order to achieve the high-power pulsed light which is applied to foods for microbial decontamination as shown in flow diagram (Fig.1).

The mechanism includes conversion of electric pulses to light pulses as the pulsed electrical energy which is delivered by the switches to the flash lamp containing xenon gas converts it into light

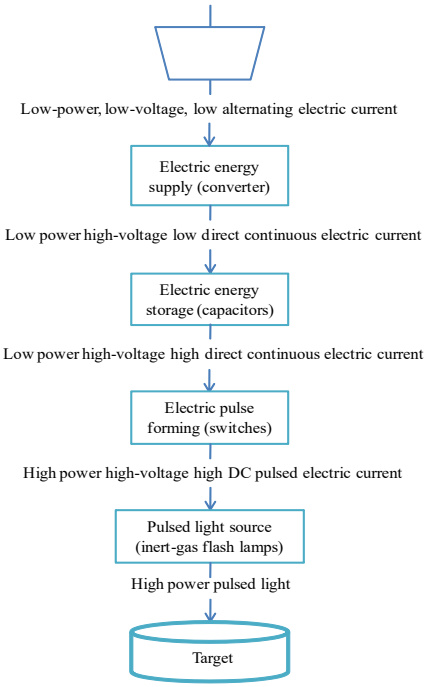

Fig. 1: Flow diagraam of conversion of electric current into pulse light [9]

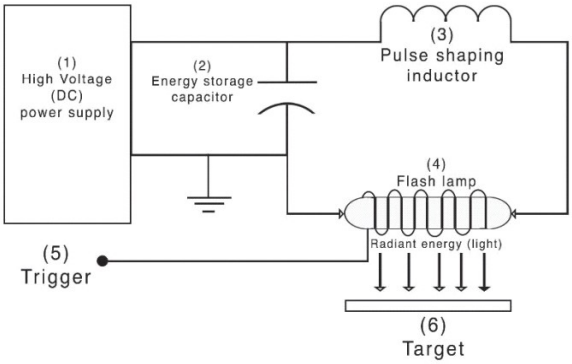

Fig. 2: Schematic diagram of a high intensity pulsed-light system [10]

pulses. The electrical current associated with the pulse electrical energy when passes through the gas, transfers its energy to the xenon atoms. As a result the xenon atoms gets excited and jumps to higher energy levels, after which the xenon atoms return back to its lower energy states thereby releasing energy in the form of light pulses (Fig. 2).

In hospitals, labs, and other facilities, light energy in continuous UV has long been utilised for

disinfection and purification. However, PL application requires a somewhat different strategy. Electrical energy is initially concentrated for a long period during PL application, dissipating it into short light pulses. Due to their higher intensity, these light flashes are more efficient in eliminating contaminants than UV light applied continuously. Although it has been debated whether pulsed light has a greater penetration depth than continuous UV, a higher adequate penetration depth can be supported by the conjecture that the penetration of light waves also depends on wavelength, i.e., the penetration depth of light in a substance increases as the wavelength of light decreases. As the PL includes wavelengths from 200 to 1100 nm, the lower bound wavelengths around 200 nm have higher penetration depth than continuous wave UV (considering 253.7 nm) [11].

There is some heating attributed to the use of PL, which is beneficial as it may add to the decontamination process. However, it has created problems for PL application on fresh produces based on the degradation of sensory qualities (Huang, 2014). Mathematically, the interaction of PL with matter can be studied by Lambert–Beer law. When light radiation of energy intensity (I_0) falls on a product superficially, it gets transmitted into its depth and then gets absorbed by the layers of the product [12], as presented in Fig 3.

The light fraction having energy I(x) is transmitted as per Lambert-Beer's law (Eqn. 1) as a function of the distance 'x' under the product surface, the wavelength of light, and the material extinction (absorption) coefficient. Most food materials show a decrease in light intensity while penetrating their bulk [13], which appears in the form of heat, leading to a temperature rise, given by Eqn. (2).

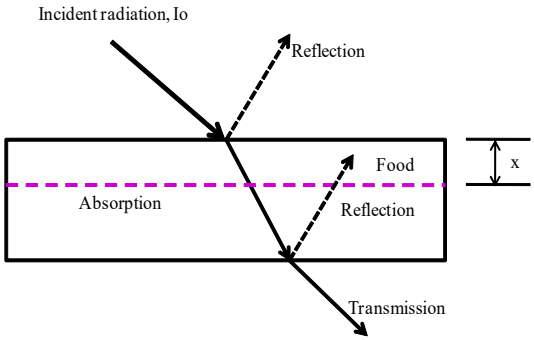

Fig 3: Interaction of light and food [13]

$$I(x) = I_0 e^{-(\alpha)^x} \quad (1)$$

$$T = \frac{I_d}{\rho C_p A} \quad (2)$$

$$I_d = I(x)\left(1 - e^{-(\alpha)^x}\right) \quad (3)$$

Overall, PL appears to be particularly efficient for treating food products and packaging material surfaces because its impact on a thin surface layer is sufficient to kill superficial vegetative cells [14]. PL processing has several advantages over conventional processing; including that most of the product is kept at or near ambient temperatures since the energy is delivered more quickly, preventing product damage to the internal components. Nevertheless, there have been cases of heated items due to extended exposure, which calls for mitigation.

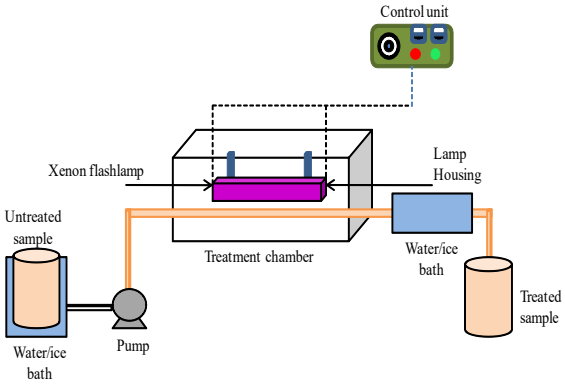

Fig. 4: Schematic diagram of the intense pulsed light (IPL) system [15]

The PL systems are helpful because, unlike continuous UV systems, their flash lamps, which produce light pulses, do not require mercury [16]. In addition, the PL systems reduce the danger of infections, enhance product quality over thermal processing, and offer better economics for processing food because of their minimal operating costs, increased flexibility, and lack of chemical or biological residues [17]. When compared to other

non-thermal technologies like HPP and PEF, PL technology also stands out favourably. Food needs to be packed before treatment in the case of HPP. Also, mild HPP treatment seems unable to inactivate spores; instead, the process promotes germination [18]. On the other hand, PL effectively inactivates spores and decontaminates food and packaging materials. Decontamination of surfaces in touch with food is also possible using PL. Although PEF processing is an excellent method for food preservation, it has several drawbacks, such as lower processing rates [19]. The use of PL processing might significantly reduce these difficulties. The schematic diagram of the intense pulsed light (IPL) system is described in Fig 4.

Pulsed light as a microbial inactivation mechanism

The high intensity light pulses are able to inactivate the microbes present in the food to different extends depending on the dosage or fluence, within a short duration of time. Several theories and mechanisms have been given to explain the reason behind microbial inactivation in foods [20]. The two effects responsible for the inactivation of microbes are; the photochemical effect and, the photo thermal effect, which is due to the energy dissipation of the light pulses when absorbed by the surface of food, material. The photochemical effect of pulsed light is caused due to the UV-light, which acts directly on the DNA of the microbial cells. The DNA absorbs the UV-light through the conjugated doubt bond present in it. The absorbed energy breaks the alignment of doubt bonds causing rearrangement in the DNA, which finally leads to the disruption of the DNA cells. It will cause activation of electronic and photochemical reactions which can lead to the formation of pyrimidine and thymine dimmers, thus, presenting the DNA reproduction [21].

The DNA molecules have an ability to modify damage due to the presence of some self- repairing but the exposure of food substances to pulsed light resulted in inactivation of such enzymes, however, UV light application showed the presence of these enzymes in foods. Thus, the inactivation effect of pulsed light is more efficient as compared with that of light application. A comparison study between pulsed light revealed that it was 7 logs inactivation of *Aspergillus niger* spores when exposed to fewer light, there was only 3-5 logs of inactivation in spite of being high energy light used for long time period [22]. There are many researchers who have used light pulses in the ultraviolet range because of its lower wavelength that is responsible for higher energy levels [20].

MacGregor *et al*. [23] used a PL generator including rectangular PVC housing, pulse generator, and a control circuit for bacterial inactivation. This bench-top experimental facility had two inoculated Petri dishes inclined at 45° received equivalent doses. Takeshita *et al.* [24] studied the damage caused by PL on *Saccharomyces cerevisiae* using the system similar to that designed by Dunn *et al.* [22] having power supply unit and a flash lamp that produce PL consisting of intense flashes of broadspectrum white light (200–1000 nm). Paskeviciute *et al.* [25] and Luksiene *et al.* [26] constructed high-power PL device in their laboratory having a chamber, a reflector with a flash lamp, and a power supply for chicken, vegetable, and fruits decontamination, respectively. Sharma and Demirci [27] and Ozer and Demirci [7] conducted the experiment to decontaminate the alfalfa seeds and fish fillets, respectively, using a PL sterilization chamber containing treatment chamber, UV strobe, tray, and a control module. Similarly, Bialka and Demirci [28] used a laboratory scale, batch PL system for decontamination of blueberries with slight modification in the set-up having a quartz window and a cooling blower. PUV treatment was carried out in the continuous flow-through system for inactivating *Staphylococcus aureus* in milk. The system included a UV chamber, UV lamp, pump with variable flow rate, and V-groove reflector [29].

Effect of pulsed light on food products

PL processing is being applied on various food products for decontaminating the foodborne pathogens that affect the human health status. Inactivation of these pathogens on food complexes are mentioned in Table 1. Pulsed light processing is influenced by various factors that dictate its efficiency on microbial inactivation, retention of quality, and other properties of the product. Important factors that determine the effectiveness of PL is the fluence level applied on the sample, the amount

Table : The effect of pulsed light treatment on microbes in various food products based on several past research

Type of food	Process parameters	Microorganism	Log reduction	Reference
Apple juice	3 pulses/s (pulse width 360 µ s) of 100–1100 nm width	*E. coliL. innocua*	4 log CFU/ml2.98 log CFU/ml	[31]
Orange juice	6 J/cm^2	*E. coliL. innocua*	2.9 log CFU/ml0.93 log CFU/ml	
Milk	200-1100 nm, 3 Hz and 360 µ s, 1.17 J/cm^2 pulse for a distance of 2.5cm, 7-28 J/cm^2	*E. coliL. innocuaS. Thyphimurium*	0.61–1.06 log CFU/ml 0.51–0.84 log CFU/ml 0.51–1.73 log CFU/cm^2	[32]
Infant food	Width 1.5 ìs; operating time 0–600 s; 2300 µ s	*L. monocytogenes*	1 log CFU/g	[33]
Dry, non-creamed cottage cheese curd	16 J/cm^2	Pseudomonas	PVR of 96.7%	[34]
Chicken wings	Broad spectrum PL	*Samonella*	2 logCFU/g	[22]
Honey	5.6[a]	Clostridium sporogenes	0.89-5.46	[35]
Corn meal	5.6[a], pulse width of 30 µ s	Aspergillus niger spores	4.93	[36]

PVR=Percentage of viability reduction

[a]Fluence: energy received from the lamp by the sample per unit area during the treatment (J/ cm^2)

of energy (dose or number of pulses) and wavelength of light/composition of the spectrum [30].

Inactivation of microbes was higher for PL treatment with higher pulse number and higher intensity [37]). Ramos-Villarroel *et al.*, [38] reported that when the spectral range of the PL treatments, particularly the UV component, was altered by using filters, the inactivation of *E. coli* and *Listeria innocua* was lower. And among the sub-divisions of UV, UV-C–containing spectrum was more effective in inactivating *B. subtilis* and *A. niger* spores [39]. Absorption of light, particularly in the UV region, and shielding of microbes by suspended matter were significant limiting factors in PL treatment of microbes in liquid substrates [40]. Nicorescu *et al.*[41] have reported that bacteria was more resistant than yeast for PL treatment, whereas viruses were more resistant to PL treatment compared to bacteria [42], *E. coli* was more sensitive to UV-C treatment than *L. monocytogenes* as the Weibull model parameters also confirms, which is a better fit compared to the linear model for evaluation the microbial inactivation [43]. *Bacillus* was more susceptible than mesophilic bacteria, and *L. innocua* was more resistant than *Pseudomonas fluorescens* to PL at low temperature andlow fluence levels [26, 44] Hilton *et al.* [44] indicated that PL treatment effectiveness was independentof temperature for *E. coli* and *P. fluorescens* in clear liquid substrates within the temperature range of 5–40°C. However, in the case of *L. innocua*, the effect of temperature and PL was observed at 50°C. Higher PL resistance shown by *Listeria* spp. compared to *Pseudomonas phosphoreum* and *Serratia liqueficans* could be related to the presence of photoreactive substances and protective compounds that contribute to the antimicrobial effectiveness of PL [45].

Combination processing with Pulsed light

The limitations of PL processing are uneven exposure, shadowing effect, browning, and sample heating. Many technologies/strategies have been developed to address and challenge the limits of processing, increase the inactivation efficacy, maintain the quality of foods, and finally obtain minimally processed foods [46]. The application of an anti-browning dipping treatment in combination with IPL would increase the shelf life of minimally processed vegetables and fruits [47]. The use of

ascorbic acid (AC) at 1% on sliced mushroom before flashing at 4.8 and 12 J/cm^2 significantly reduced browning during storage [48]. To minimize the browning on PL-irradiated apple surface, AC/ calcium chloride solution was used as an anti-browning dipping prior to PL treatment [16]. The combined application of the edible coating (gellan-gum–based (0.5% w/v) coating enriched with apple fibre) and PL (12 J/cm^2) treatment retarded the microbiological deterioration of fresh-cut apples, reduced softening and browning during 14 days of storage at 4°C [49]. The treatments combining PL (12 J/cm^2) and malic acid (MA) of 2% v/v resulted in significantly more significant inhibition of *L. innocua* and *E. coli* populations than either PL or MA alone, by achieving more than 5 log reductions for fresh products, such as fresh-cut avocado, watermelon, and mushroom throughout the storage period. Even the observations demonstrated that damage, especially to *E. coli* cells, was caused by a combination of treatments due to agglutination of cytoplasmic content and disruption of cell membrane, thus leading to microbial death [50].

Maftei *et al.* [51] stated that studies should be aimed at evaluating strategies based on the combination of PL treatments with other minimal processing technologies, e.g. addition of natural preservatives or mild heat treatment, in order to successfully tackle safety issues for clarified juices treated with PL technology. Non-thermal PL treatment inactivation tests against *L. innocua* inoculated on modified chitosan containing a nanoemulsion of mandarin essential oil-coated green beans showed that 1.2×105 J/m^2 per bean side was able to cause a reduction of about 2 log cycles. However, PL did not show any synergistic antimicrobial effect against *L. innocua* throughout the storage and colour properties had a slight detrimental impact with browning spots formation on the samples [52]. A reduction of 6 log cycle in yeast was noticed by Ferrario *et al*., [53] when PL was applied before ultrasound treatment for both industrial and naturally extracted apple juice. Caminiti *et al*. [54] reported that combining ultraviolet/high-intense pulse light (UV/HIPL) with pulsed electric field processing had no adverse effect on colour, flavour, non-enzymatic browning, total phenol content and total ascorbic acid content of apple and cranberry juice blends and received sensory scores similar to that of pasteurized sample. Thus, PL in combination with other technologies can be explored as novel technology for producing foods with minimal processing and without deteriorating the nutritional and organoleptic quality of foods.

Application of pulsed light in food industry

Pulsed light technology is treated as one of the novel non-thermal processing methods for the inactivation of microorganisms and has the potential of being an equivalent treatment for pasteurization of food products. Pasteurizing liquid goods such as milk, yoghurt, and liquid eggs has been claimed to use pulsed electric fields. Numerous studies are being conducted to commercialise the procedure in light of the efficiency of pulsed light on various food products. Besides achieving microbial safety of food products, flavour freshness, economic feasibility, extended shelf life, improvement in functional and textural attributes are some other points of interest [55] [10]. Some of the main applications for pulsed light in the food sector are discussed:

Microbial inactivation in fruit juices through pulsed light

Apple juice (pH 3.49) and orange juice (pH 3.78) were inoculated gram positive *(Listeria innocua*) and gram negative *(Escherichia coli*) bacteria. The fluence was provided between 1.8-5.5 J/cm^2 with the flashes at a constant frequency of 3 Hz and the duration of the pulse was 360 ms. It was concluded that the lethal effect of pulsed light technology depends on the type of microbes as well as the absorption parameters of the liquid food. The treatment of pulsed light on apple juice decreases the *E. coli* and *L. innocua* were reduced by 4 and 2.98 log-cycle, respectively, and in case of orange juice, a reduction of 2.90 and 0.93 log-cycles were reported for these bacteria, respectively. The change in colour of fruit juices treated with pulsed light was observed for long term storage period, i.e. 112 days at 4°C [56]. Pulsed light was also applied on combined juice obtained from apple and cranberry. The effectiveness of the combined technologies was determined by measuring sensory attributes like taste and flavour [54]. In similar study pulsed light with high intensity was used to inactivate *Escherichia*

coli in orange juice. Application of the individual technology was used as well as the combination of these two techniques was also studied and microbial reduction was found in a range of 2.5 to 3.93 log CFU/ml in case of combined process which was higher than both the techniques used individually [57].

Microbial inactivation in milk through pulsed light

Several studies have investigated the impact of a pulsed light application on dairy products such as whole milk, skim milk, and yoghurt [55]. Because milk and milk products are susceptible to developing spoilage and harmful microorganisms, thermal pasteurisation is essential. Pasteurization of milk ensures safety but also impart slight cooked flavour and nutritional losses [58]. Pulsed light was used to inactivate *Staphyloccus aureus* in milk and it was observed it to be potential in eliminating the risk of milk pathogens. The pulsed light treatment of milk was given in a continuous flow system, where the temperature of milk was raised to 38°C which dependent on the residual time and the distance of the sample from the source of light. This temperature increase caused a fouling effect as well as possible changes in milk quality with decreasing the microbial load.

Decontamination of packaging material through pulsed light

Paper-polyethylene was artificially sporulated with *Cladosporium herbarum, Aspergillus niger, Aspergillus repens, and Aspergillus cinnamomeus*, and then subjected to pulsed light with fluence varying from 0.244 to 0.977 J/cm^2. A decrease of 2.7 logs was obtained, which was the greatest degree of inactivation. The spores' ability to withstand pulsed light was influenced by colour. Different spores needed various fluences to render them inactive [59].

Decontamination of chicken from pathogens through pulsed light

Paskeviciute *et al.* [25] investigated the effect of high power pulsed light on the surface of the chicken at 1000 pulses for 200 seconds and a UV light dose of 5.4 J/cm^2. The treatment was sufficient to reduce viability of *Salmonella typhimurium* and *Listeria monocytogenes* by 2-2.4 log $_{10}$ CFU/ml. Moreover, the total aerobic mesophiles were also decreased by 2 log $_{10}$ CFU/ml. The intensity of lipid peroxidation in control and treated chicken samples differed in 0.16 milligram (mg) malondialdehyde per kilogram of chicken meat. Organoleptic properties of treated chicken did not detect any changes of raw chicken, chicken broth or cooked chicken meat when it was treated under nonthermal conditions in comparison with control.

Enhancing the shelf life of freshly cut mushroom through pulsed light

Oms-Oliu *et al*. [48] treated the freshly cut mushroom slice to pulsed light at 4.8, 12 and 28 J/cm^2. The treatment resulted in enhancement in shelf life of mushroom by 2-3 days in comparison to untreated samples. The native microflora reduction ranged from 0.6-2.2 log after 15 days of refrigeration. 12 and 28 Joule/ cm^2 treatment affected the texture due to thermal damage by treatment. It induced enzymatic browning due to increase in polyphenoloxidase activity. Some phenolic compounds and vitamin C content were found to be reduced. But 4.8 Joule/cm^2 increased shelf-life without affecting the texture and antioxidant properties.

Application of pulsed light on food processing equipment

Rajkovic *et al*. [60] investigated the effectiveness of pulsed ultraviolet (UV) light therapy in removing *Listeria monocytogenes* and *Escherichia coli* O157:H7 from stainless steel surfaces that come into contact with meat. A four lamp batch scale apparatus which generated 3 Joule/cm^2 with an input voltage of 3000 Volts was used. The study was performed on stainless steel slicing knife. The type of meat product in contact with the treatment surface and the time between contamination and intense pulse treatment decide the effectiveness of the microbial inactivation. When the knife surface was in contact with meat product containing lower fat and protein content and the time between contamination and treatment was 60 seconds, highest effectiveness of inactivation of 6.5 log colony forming units (CFU)/side of knife was achieved. It was also observed that even though the number of flashes was increased to compensate for the extended time between contamination and treatment, the lost effectiveness of microbial inactivation could not be restored.

Future challenges, Trends and Scope

The commercialization of PL is possible only when the system is economical and affordable. Scaling-up will be made simpler by enhancing the crucial processing parameters to achieve the needed log reduction level for specific food applications without compromising quality. Future attempts to develop the PL process must be optimised based on the U.S. The preliminary recommendations from Food and Drug Administration, i.e. total cumulative treatment, in terms of total fluence shall not exceed 12 J/cm^2, duration of pulses is less than 2 ms, and pulse frequencies used in range of 1 to 20 pulses per second.

Currently, several difficulties exist in PL applications. The reflection coefficient of the product surface should be low for an efficient PL treatment for microbial inactivation. The optical properties of food products should be suitable for PL treatment [12]. Food composition is a significant factor in PL effectiveness. Excellent solid food and packaging materials should be transparent, smooth, and devoid of holes, grooves, or roughness that can 'shroud' the microorganisms from the light. Even extremely smooth surfaces can reflect light, making PL ineffectual. The adverse effects of overheating, which have complicated the treatment of carrots, alfalfa seeds, and raw salmon fillets, have made these issues more challenging [11]. An important challenge that must be addressed is how to maximise the desired photo-thermal based decontamination impact without unnecessarily overheating the product.

Chung *et al*. [61] revealed that the PL technique has potential to minimize peanut allergen levels as well as those in other food items. While PL can be useful for treating smooth surfaces like those found in packaging, one area of study focuses on developing PL for solid foods with rough surfaces and granular substances like grains, seeds, and spices. In the future, PL may be investigated further to combat allergies to other foods. The application of microbial load reduction in foods based on photosensitization needs more study. A future study might be fascinating in improving phytochemicals in foods other than mushrooms.

Significant efforts are required to meet the engineering problem of equipment development for innovative PL applications, such as conveyor systems for the treatment of solid meals and continuous flow-through systems for liquid foods. It is necessary to investigate the feasibility of 'thin profile PL treatment' of liquid foods [62]. It appears that PL equipment with good penetration in the future will be possible, such as fluidized beds for treating granular meals and multi-directional lamps for uniform surface exposure [63]. When sterilizing packing films in aseptic packaging systems, PL may be used as an alternative to H_2O_2 or UV lights. PL systems can also be used in conjunction with other food preservation techniques like HHP or PEF. Product heating issues could be resolved using PL equipment with cooling systems [11].

Credit author statement

Ashok Kumar: Conceptualization, Writing-original draft, methodology, Investigation and data Analysis, Satish Kumar: Data Validation, Reviewing and Editing, Sanoj Kumar: Conceptualization, Supervision, Review and Editing.

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