APPLICATION OF LIGHTS IN FOOD SAFETY

Abstract

Nowadays consumers' demand for safe, more natural and healthier food is increasing. Food safety considerations include preventing spoilage, bacterial development, and contamination. Thermal and non-thermal technologies are used for keeping food safe from pathogenic and spoilage microorganisms. Non-thermal food processing methods using light technology have been intensively studied for food decontamination. The lights of different wavelengths in UV or visible range have some antimicrobial effect and been used for surface decontamination of food. In addition, pulsed light technology is an alternative to thermal and chemical disinfection methods and used to decontaminate food and contact surfaces using high intensity pulses. Food sterilizing using UV light is referred to as irradiation, though it does not add radiation to the food or render it radioactive in any manner. Shortwave ultraviolet light (UV-C) is widely utilized in the food industry since it offers technological advantages such as low maintenance, low energy use, no undesirable effects without requirement of chemicals or pesticides. UV-C is considered as most effective method for microbial inactivation. Visible light also have emerged as new food decontamination technology as it kills surface microbes through the process of photodynamic inactivation. Pulsed light (PL) has recently gained popularity as a disinfection and preservation alternative to traditional approaches. These light technologies can be considered as eco-friendly, clean technology, chemical free, non-thermal and does not have any residual effect on food. This chapter aims to give an overview of light technology principles, applications for microbial inactivation in various food products and food contact surfaces.

Keywords: Bioactive, LED, microbes, Post-harvest, food system.

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I. INTRODUCTION

Food processing and supply chains are an established and a billion dollar industry now. At present, the international processed food market worth is about $ 7 trillion, which is rising with the increase in population and changing life style. Whereas with the rise in industries, technologies and opening up of global market is also the contributing factors to the expansion of food processing sector world-wide.

Everyday millions and millions of food products are being traded and delivered to places like hospitals, hotels, restaurants, hostels etc. Consumer's preference for ready-to eats dishes and convenient foods are increasing leading to the increased risk of microbial contamination. If not prepared with care and precautions then it may harbour microbes (bacteria, viruses, fungi) and other toxic chemicals resulting into health related issues to the consumers. According to WHO every year around 600 million people (1 in 10) get affected by food borne infections, that sometimes proves to be fatal (4.2 lakh people every year). Today food safety is one of the most critical issues that can affect not only businesses but also possess threat to human lives.

Therefore in order to maintain the brand value and to keep the legal formalities related to the food safety at bay, it has become imperative to standardise the processes and adopt all the set rules to minimise such risk. Codex Alimentarius Commission is one such international body that sets guidelines and recommends standards for food processing industry in order to ensure effective food control and hygiene Hazard Analysis and Critical Control Point (HACCP) is a management tool established by codex for controlling the processes to guarantee food safety and hygiene. It promotes consumers' confidence; prevent product loss, and boosts trade both at national and international level. It is recognized and adopted globally for eliminating food safety issues. Food safety and security are inevitably linked because unsafe food causes cycle of nutrient deficiency, sickness and diseases. For a healthy population ample quantity of balanced and safe food should be made available. Since fresh produce are highly susceptible to spoilage therefore it needs to be preserved to make quality food available.

The HACCP (hazard analysis critical control point), a quality assurance process that focuses on process and makes sure that the product or the services are introduced, implemented and produced correctly. After production efficient cold chains helps to reduce the chances for pathogenic micro-organisms to contaminate the food leading the risk of infection or toxin production. Some of the conventional preservation techniques are thermal treatments (sterilisation, pasteurisation, drying etc), chemical treatments (salt, sugar, oil, spices, preservatives etc) freezing/chilling, packaging (modified, vacuum etc) etc. In food industry non-thermal or advanced technologies are also popular because of their ability to preserve sensory and nutritious properties and retaining fresh characteristic of the food. Some of the popular technologies are irradiation, hurdle technology, pulsed electric field, HPP (high pressure processing) and use of lights.

In the recent past many work has been carried out using light to maintain and improve the quality of the harvested agricultural produce [8, 17, and 24]. It is established that the use of light in low quantities can maintain the postharvest quality of the produce. Importance of light in food processing perspective, quality of light is defined by its frequency, wavelength,

and its intensity however; other factors that determine effectiveness of light in causing microbial destruction are its intensity, exposure time, method of application.

1. **Use of Light for Food Safety:** Light has been known to cause chemical reactions in food therefore considered as important abiotic factor to control for restricting any undesirable or chemical changes in the product. Also quality of light affects the quality of the product coming out of the processing industry. Improper lighting brings about changes in the colour, rate of spoilage, flavour and smell of the commodities. Light has been shown to have bactericidal effects under certain conditions, hence playing a role in food safety Among light waves, there has been a use of different wave bands in practice for and food surfaces sanitation. Most popular of them in practice are pulsed light technology [14, 38, 50, 59], visible light [22, 30, 31, 57] and ultraviolet lights [15, 37]etc. These three sources will be discussed in detail with respect to its principle, mode of action and application.

2. **Regulations Involved With the Use of Light Source:** Food and Drug administration (FDA) is the regulating authority that regulates the enterprise/manufacturer involved in the production, relabeling, packaging of such devices medical or non-medical, through its Centre for Devices and Radiological Health [58]. There is FDA regulation applicable on the electronic components or equipment that emits any sort of radiation via Electronic Product Radiation Control Provisions (either for medical or non-medical use). The formulated radiological health regulations encompasses many activities including reporting of any accidental radiation occurrences, notification (to FDA and customers) for any defects related to radiation safety.

3. **Advantages Of Using Light Technology**
   - Longer shelf life
   - No toxic chemical release
   - Eco-friendly and easy to dispose
   - No residual effect
   - Low operating cost

II. LIGHT TECHNOLOGIES USED IN FOOD SAFETY

1. **Visible Light Technology:** The use of visible light for food safety is an emerging technology. Though visible light has been used since ages for food decontamination, recent developments have made it possible to use visible light in food safety. Microbial inactivation using visible light is termed as photodynamic inactivation (PDI) or photosensitization. PDI is a photo-physical as well as photo-chemical process which requires only three agents i.e. visible light, oxygen and photosensitizer. It does not require any harmful substance which either pollutes the environment and unsafe for humans, thus making it an eco-friendly and safe technology.

   - **Principle of Operation:** A visible light source, photosensitizer, and oxygen are the three main components of the PDI [1]. As these components united, they become toxic to the target cells. By absorbing a photon of light with a wavelength that matches the photosensitizer's absorption band, the photosensitizer dye is excited for a very short period (10^{-9} s) in the excited singlet-state [25] (Fig. 1). This singlet-state photosensitizer is then converted to a triplet state with a much longer lifespan (10^{-6} s)

by an electronic transformation (spin-flip). Because of its longer lifespan, the triplet photosensitizer thus can react with ground state oxygen through one of the two photochemical pathways: Type 1 or Type 2. The Type 1 pathway entails the passage of the electron from the excited photosensitizer to the molecular oxygen, which is then reduced to hydroxyl (·OH) radicals, hydrogen peroxide (H_2O_2) and superoxide anion (O_2^-) also called reactive oxygen species [20]. The cellular components typically consisted of lipid or fatty acids, like the cell membrane, which is severely damaged by these reactive oxygen species. The Type 2 pathway converts photosensitizer energy into triplet oxygen ($^3O_2$), which then excites singlet oxygen to convert to reactive singlet oxygen ($^1O_2$). Varieties of cytotoxic compounds produced when singlet oxygen ($^1O_2$) reacts with a wide range of biochemical elements resulting in the disruption of the DNA, cell membrane, and numerous enzymes, thus leading to fatal injury and death of the cell.

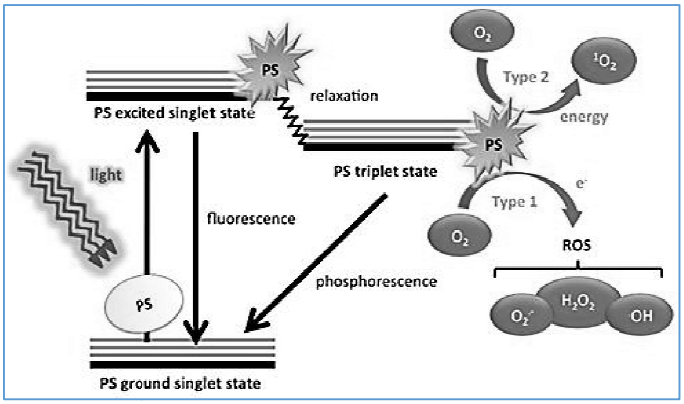

Figure 1: Principle of photodynamic inactivation

- **Light Sources:** Light plays a vital role in the photodynamic inactivation of microbes. Light of particular bandwidth which comes in the absorption band of the photosensitizer is absorbed by the photosensitizer [25]. There were different types of light sources used for photodynamic inactivation. Incandescent lamps like tungsten or tungsten-halogen lamps; gaseous discharge lamps like xenon lamps or metal halide lamps, lasers, light emitting diodes were used for PDI [13]. All these light sources have some drawbacks like most of them have broad spectrum and need filters to narrow down their bandwidth. These filters may be long-pass; short-pass or narrow band filters [10]. Halogen lamps have heating problems so need extra filters to avoid heating effect. The life expectancy of these lamps is also shorter. Although lasers are monochromatic sources of light but they are coherent also which limits their application to food products. However, LEDs don't have any such limitations and are most suitable light source for PDI as they are monochromatic, have no heating effect, mechanically robust, flexible and have longer life expectancy.

- **Advantages:** This technology is eco-friendly as well as safe as it has lower photon energy, doesn't generate any chemical residues or any radiations like gamma rays. It does not require high pressure (high pressure processing), high temperature (thermal processing) or frequency (ultrasonic treatment) for disinfection. Also, it does not require any pre-treatment for activation. There is also minimal effect on the sensory

characteristics (colour, odour and taste) of food products. This technology is simple and doesn't require any protocol to be followed.

- **Limitations:** The major limitation of this technology is that it can only be used for surface decontamination. Also, the antibacterial efficacy of visible light is not as high as that of UV light.

III. APPLICATIONS

The use of visible light for food surface decontamination has been used nowadays. Though there are limited studies on the effect of visible light on food surface. There are different food products on which its effect has been evaluated.

1. **Fruits and Vegetables:** Fruits and vegetables usually consume fresh or minimally processed which makes them more prone to contamination since they are not processed. Therefore, they need to be decontaminated before consumption. Different wavelengths of visible region have shown detrimental effect on various microorganisms present on food surface. A study was conducted using 456 and 630 nm LEDs for the surface decontamination of tangerines infected by *Penicilliumdigitatum*[2]. At 456 nm, opposed to constant dark conditions, interchanging periods of 12 h light/ 12 h dark greatly decreased fungal colonisation in tangerines. As compared to constant blue light, white light and dark treatment, the diameter of the lesions in the 12 h light/12 h dark therapy was around threefold less after six days. The effect of 405 nm LED on *B. cinerea* in tomato leaves was elucidated [31]. When compared to white light treatment and the dark, the mycelial development of *B. cinerea* was consistently inhibited after 24 hours of 405-nm. The effect of 435 nm LED on S. aureus in cucumber was investigated using curcumin (50 and 100 µmol) as photosensitizer (57). In comparison to control samples, a mean reduction of 2.6 log was obtained. The log reduction using 50 µmol photosensitizer was 2.84 immediately after illumination, 2.96 after 24 h and 3.02 after 48 h compared to untreated control samples.

   The impact of various LED light wavelengths on tomato resistance to *B. cinerea*was investigated [30]. It was postulated that purple (400 to 410 nm) and blue (450 to 460 nm) light irradiation substantially inhibited *B. cinerea* mycelium formation, with inhibition rates of 22.3 and 15.16 %, respectively, and purple light had a stronger inhibitory effect than blue light. However, red and yellow LEDs had shown 0% inhibition. The antibacterial effect of 405 nm LEDs was observed on the surface of fresh cut mango infected with pathogens (*E. coli*, *Salmonella species* and *L. monocytogenes*) [35]. Inoculated mango was kept at 4.5 cm distance under 405 nm LEDs at 20 mW/cm^2 irradiance for 24 to 48 h at 4, 10 and 20 °C temperature levels. After 36 h at 10 and 4 ° C, *Salmonella spp.* and *E. coli* were inactivated to below the detection level (1.0 log). The bacterial population i.e. *E. coli*, *Salmonella species* and *L. monocytogenes* of non-illuminated samples increased to 4.6, 4.3 and 7.3 log_{10} CFU/cm^2 after 24 h at 20 °C, while for illuminated samples it was significantly lower than non-illuminated samples. In a similar work used same 405 nm LED for illuminating bacteria (*Salmonella enterica*sarovars i.e. *S. Agona, S. Saintpaul, S. Newport,* and *S. Typhimurium*) on fresh cut papaya (34). The papaya samples were placed at 4.5 cm below LED (10 mW/cm^2) for 24 to 48 h at 4, 10 and 20 °C temperature levels. During LED illumination at 4 °C, all

*Salmonella*serovars population were substantially ($p<0.05$) decreased by 1-1.2 log_{10} CFU/cm^2, while no substantial change was observed in colonies on non-illuminated papaya for 48 hours. For 36 hours at 10 °C, non-illuminated cells population on papaya developed to 4.3, 4.6, 3.8 and 4.0 log_{10} CFU/cm^2 for *S. Newport, S. Agona, S. Typhimurium* and *S. Saintpaul,* respectively. In contrast, for *S. Newport, S. Typhimurium* and *S. Saintpaul*, LED lighting resulted in 0.3, 1.3 and 0.6 log_{10} reductions, respectively, while the LED lighting inhibited the development of *S. Agona* population for 36 hours at 10 °C. During a 24-hour cycle, the number of LED treated colonies reached 6.7, 6.3, 7.0, and 6.8 log CFU/cm^2, respectively, at 20 °C which was lower than the non-illuminated population, indicating that LED illumination slowed *Salmonella* cell development on fresh cut papaya at room temperature. At varying irradiances (254.7, 147.7 and 92 mW/cm^2) and temperatures (25, 16, and 7 °C), the influence of 460 nm LED treatment on the viability of *Salmonella species* (*S. enterica, S. Gaminara, S. Montevideo, S. Saintpaul,S. Typhimurium* and *S. Newport*) on fresh cut pineapples was determined (22). At 7 °C, the maximum antibacterial effects were 0.68 log_{10} CFU/g at 92 mW/cm^2, 1 log_{10} CFU/g at 147.7mW/cm^2, and 0.64 log_{10} CFU/g at 254.7mW/cm^2. However, at 16 °C, the maximum antibacterial effect (1.2 log_{10} CFU/cm^2) was observed at 92 mW/cm^2. Thus, the effect was bactericidal at both 16 and 7 °C, but at 25 °C the effect was inhibition of bacteria instead of inactivation.

2. **Liquid Products:** The bactericidal effect of 460 nm LED's irradiance (254.7, 147.7 and 92 mW/cm^2) and temperature (20, 12 and 4 °C) on *Salmonella* inoculated in orange juice was studied (23). *Salmonella* inactivation was found to be a function of temperature and irradiance (at constant dosage) both. At 4°C, the lower irradiance level (92 mW/cm^2 for 13.58 h) have shown more reduction (3.3 log CFU/ml) while the higher irradiance level (254.7 mW/cm^2 for 4.91 h) have observed less reduction (2.1 log CFU/ml) in *Salmonella.* Similar results were obtained at 12 and 20 °C; however 20°C have shown maximum reduction compared to other temperatures.

   A research to comprehend the effect of LED treatment on *E.coli* inactivation in milk [55]. 405 nm, 430 nm and 460 nm LEDs were used for study. From this study it was observed that increasing the wavelength reduced the inactivation of *E. coli* at all temperatures. At higher temperature i.e. 15 °C the inactivation was higher whereas lower temperature showed minimum reduction. The decimal reduction time (D-value) was also determined and it was elucidated that 405 nm at 15 °C had lowest D-value. In comparison to regular pasteurised milk, LED-treated milk had a longer shelf life.

3. **Meat Products:** The susceptibility of *C. jejuni* to a high power near-UV/visible 395 LED and its efficacy in decontaminating raw chicken was elucidated by [26]. The inoculated chicken fillet (skinless) and chicken skin were illuminated with 395 nm LED at distances of 30, 120 and 230 mm, for a period of 10, 5 and 1 min. The total viable count (TVC) and *Enterobacteriaceae* (ENT) were also detected on chicken fillet (skinless) and chicken skin. On raw chicken fillet (skinless), improved exposure times and reduced distances from LED resulted in the maximum log_{10} reductions in *C. jejuni*. The reductions of 1.23 and 2.17 logs CFU/g found after 5 and 10 min treatments, respectively at a distance of 30 mm which differed significantly from untreated controls for TVC. After 5 and 10 minutes of exposure, substantial reductions of 2.86 and 1.23 log_{10} CFU/g were achieved for ENT at the 30 mm distance, respectively. On chicken skin, similar results were obtained

at 30 mm distance; however the temperature of chicken skin reached to 65 °C within 5 min of exposure thus the microbial inactivation might be due to elevation in temperature. In another study, the effect of 435 nm LED on *S. aureus* in chicken meat was investigated using curcumin (50 and 100 µmol) as photosensitizer [57].

The *S. aureus* population for control sample was 7.2 log CFU, for photosensitizer treated sample was 6.99 log CFU, for LED treated sample was 7.18 log CFU whereas for combination of LED and 50 and 100 µmol photosensitizer was 5.48 and 5.51 log CFU, respectively. This showed that photosensitizer has specific role for PDI.

The antibacterial effect of a 460 nm LED (58, 31 and 15 mW/cm^2) in conjunction with riboflavin (100, 50 and 25 µM) on smoked salmon inoculated with *L. monocytogenes* was investigated at 4°C and 12°C [32]. Using lowest irradiance and highest riboflavin concentration, the inactivation levels were 1.2 log_{10} CFU/cm^2 at 4°C and 1.1 log_{10} CFU/cm^2 at 12°C. Higher irradiances with high concentration of riboflavin were proved to be beneficial as 90 % reduction achieved. In ready-to-eat fresh salmon, the anti-biofilm effect of 405-nm (26 mW/cm^2) against *L. monocytogenes* was assessed at varying temperatures (4 – 25 °C) for 8 h storage [41]. The biofilm was formed on stainless steel (SS) and acrylic (AC) coupons using fresh salmon exudate. At the time of biofilm formation and LED illumination for 8 hours, the populations of *L. monocytogenes* cells on SS coupons and AC coupons were substantially decreased, resulting in 2.4 and 2.8 log reduction at 4°C, 2.4 and 2.4 log_{10} reductions at 15°C and 1.9 and 2.4 log_{10} reductions at 25°C, respectively.

In preformed biofilms the detached *L. monocytogenes* cells were 5 to 5.4 log_{10} CFU/ml. These cells were illuminated with LEDs. After 6 hours of LED illumination, the detached cells were dramatically decreased at 4 C, but there were no substantial changes in the planktonic cells number at 15 or 25 °C, while the non-illuminated cells increased in population. This indicates that the proliferation of detached cells may be effectively prevented by LED illumination.

4. **Grains and Seeds:** In a study conducted by [62],*Fusariumoxysporum*and *E. coli* were incubated separately with chlorophyllin (0.5 mmol) in wheat seeds for 60 minutes before LED illumination (405 nm). The mesophilic count of bacteria was also determined and it was observed that mesophilic bacteria were present in large amounts (6 log_{10} CFU/g) in wheat seeds. After PDI with chlorophyllin and light, the mesophillic count decreased by 2.5 log_{10} CFU/g on wheat surface. On the other hand, the *E. coli* population was inactivated by 1.5 log_{10} CFU/g. There was also reduction in *Fusariumoxysporum* by 1.5 log_{10} CFU/g.

Light activated chlorophyllin-chitosan complex was tested against food pathogens and fungi on the surface of germinated wheat seeds [11]. *L.monocytogenous* was incubated with chlorophyllin-chitosan complex on wheat surface for 1 h and then LED illumination (405 nm) was given to incubated seeds. After 60 min of incubation and 2.9 J/cm^2 of illumination, the *L. monocytogenous* population was reduced by 8 logs.

IV. ULTRAVIOLET LIGHTS

1. **Ultraviolet Light (Introduction):** Ultraviolet (UV) light occupies spectral range of 100nm to 400nm wavelength in the non-ionising region of the electromagnetic spectrum, falling between X-rays and visible radiations. However wavelengths between 250 and 280 nm has a proven germicidal effect, this effect decreases with the increase in wavelength particularly above 300 nm.

   Broadly based on the germicidal potential UV spectrum is divided into three regions:
   - UVA (320 to 400nm) is a long-wave
   - UVB (280 to 320 nm) is a medium-wave
   - UVC (200 to 280 nm) is a short-wave

   Ultraviolet light can be used to inactivate many types of organisms, including viruses. Since these wavelengths are readily absorbed by most proteins (amino group) and nucleic acids causing structural transformation leading to cell destruction. UV light radiation has been used for many years in medical, pharmaceutical, aquaculture, and food industries as a disinfecting medium.

   UV treatments are used extensively in the food processing industries for producing microbiologically safe food. For sterilizing products like food &contact material surfaces, air spaces, and liquids/water etc.The usage of UV light in food processing sector is for shelf life enhancement and reducing (pathogenic) microbial load. It has been tested on products like fruit juices, drinks and other processed meat and horticultural products. The penetration capacity of UV light is affected by the distance as well as the medium in which it is applied. The germicidal effect of UV lights decreases exponentially with the increase in distance between source and the object, as it affects the penetration capacity, whereas the germicidal effect on bacteria in water is more than in air. Precaution is suggested to limit its exposure to humans as it may damage the eyes and skin causing conjunctivitis or skin cancer depending upon the dose [37].

   US FDA and USDA (US Department of Agriculture) has recommended the UV irradiation as safe for the use in foods like fresh and vegetable juices based on the criteria of 5 log reduction (US FDA, 2000).

   - **Principle of Operation:** The photo-chemical reactive process mediated by UV radiation is a physical method where in the structure and morphology of the pathogenic cell is altered showing germicidal effect. It is chemical free and safe and not reported to produce any undesirable by-products on the exposed material [15]like sensory characteristics of the food.

     Exposure of UV radiation on to the object for the desired period of time penetrates inside the cell and alters the genetic constituents of the cell. Changes in the genetic material lead to mutations and permanent cell damage. Since shorter wavelengths have greater penetration power for this reason UVC (254) nm has greater germicidal effect than longer UV radiations. UVC has been used for disinfecting surfaces, materials, water, and some food products.

This germicidal effect is because of the photo mediated chemical reactions that degrades the biomolecules inside the microbial cell resulting into inactivation or death. At molecular level, UV radiations causes the changes in pyrimidine (thymine) bases i.e. fusion or bonding of the two adjacent thymine bases located on the same DNA strands () thereby affecting structure and morphology of the microbial DNA. This dimerization of the nitrogenous bases inhibits the replication procedure (transcription) of the microbial DNA. If the doses of UV radiations are high, causing more damage and loss of repairing capability through photo-reactivation of the cell and cell finally dies.

However longer wavelengths damages the cells in a different manner. UVA affects the cell membrane of the microbes and produces reactive oxygen that causes oxidative changes in protein, membranes and other molecules also results in indirect damage to DNA molecule. Whereas UVB alters the DNA backbone and has been reported to cause lesions and oxidative reactions but their effect is intermediate between UVA and UVC. Therefore, UV light is being used for disinfection and sterilisation without generating any residue. Compared to other sterilisation processes is simple and low lost method.

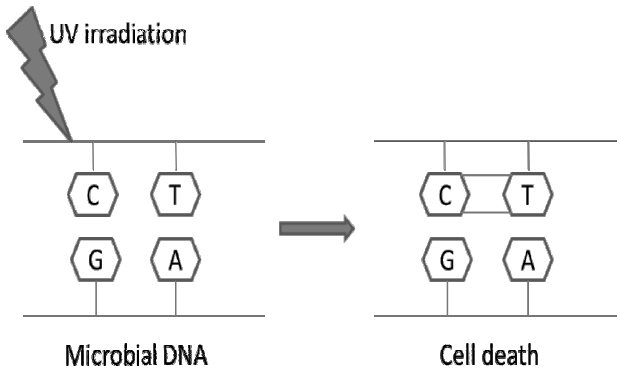

Figure: Nucleic acid of a microbial before and after UV exposure

- **Sources of Radiation:** Various sources of ultraviolet radiations are available that includes the sun, LEDs, lasers, lamps, tanning beds, and numerous instruments such as dental equipment. This can be categorised into natural and artificial sources.

The Sun is the natural and strongest source of UV radiations emitting wide range of wavelengths. Radiation in the range of 100nm to 400nm falls under ultraviolet radiation. The three UV regions UVA, UVB and UVC differ in their potency of bacterial disinfection [53]. UV radiation before reaching the earth's surface undergoes absorption and scattering by the atmosphere.

Among these radiations UVC is most affected and UVA is least. Most percentage of UV radiations are absorbed by ozone layer present in the earth’s atmosphere before it reaches the surface while apart of UVB and majority of UVA reaches the earth’s surface.

- **Artificial Sources:** Various artificial sources are available

  - UVA lamps (for long-wave): mercury lamps are more common for producing UV lights. For emitting specific wavelength range filters are used over the mercury vapour lamp. Filters allow only UVA lights to pass while removing other radiations from the spectrum.
  - UVB lamps (for medium-wave): For producing lights of UVB range pressure is changed in the mercury lamps with the use of glass bulbs.
  - UVC lamps (for short-wave): low pressure mercury lamps (LPM) are most common for emitting lethal UVC lights (254nm). These are similar to fluorescent lamps with the exception of phosphor coating and the use of glass for UVC transmission. Few lamps that emit UVC radiations are medium pressure mercury lamp (MPM), Far-UVC lamps (excimer lamps with peak of 222nm), and mercury free amalgam lamp, Xenon lamps, metal halide etc. LMP are most commonly used for food applications.
  - There are also other lamps that emit wider range of UV & visible radiations like high-intensity discharge (HID) lighting, including high-pressure sodium (HPS), metal halide, xenon lamps as well as fluorescent and incandescent lamps. These lamps have been used as an irradiation source food production and preservation. Such systems are used for broad spectral emission, with lesser control over the emissions of specific wavelengths (UV).

- **Light-emitting diodes (LEDs):** Recently Light-emitting diodes (LEDs) producing UV lights are becoming more popular. The unique properties of LEDs allow better control over radiant intensity, spectral characteristics over the produced radiation [9]. UV LEDs available in the market produces light having a peak of 265 nm, 273 nm, and 280 nm respectively, among others. It eliminates the use of mercury. However, it is reported that the germicidal effect of LEDs is lower because of the smaller surface area and higher directionality.

2. **Advantages and Limitations:** Among the advantages that it offers as source for disinfecting food production system are listed here:

- Inactivation of pathogenic and spoilage microorganisms
- Chemical-free process so no residue/toxins and protects from its potentially harmful effects
- Maintenance of nutritional and physicochemical properties as no heat generation
- Minimal degradation of sensory characteristics of the food
- Can easily be combined with other disinfecting techniques to add extra layer of protection
- Environment friendly
- Low maintenance, installation and operational costs

It is proven that the efficacy of 99.9% in killing most of the harmful foodborne infection causing microorganisms eg. Salmonella, E. coli, and also some viruses (norovirus).

V. APPLICATION OF UV LIGHTS IN FOOD SAFETY

Application of UV light is well known in reducing the number of pathogenic microorganism and increase the shelf life of foods. The food products that have been reported with good results in increasing the shelf life through UV light are fruit juices, various drinks, milk and milk products, vegetables, fruits, meat, poultry and seafood products. On the other hand, interest to focus is on the photo degradation of composition of food upon UV treatments. The concern is if there is any negative impact of the UV treatment of the food other than the advantageous achieved. Vitamins with a high structural diversity are of particular interest, most of them being potentially sensitive to UV light by virtue of their structure [37]. However, the results provided by various researchers reported that UV treatment has more advantageous compare to the conventional method. The application of UV radiation lies not only for food materials but also for packaging materials and storage of food grains. Table no. 1. Provides the various applications of UV radiation in different foods products and processing operations.

Table 1: Applications of UV radiation on different food products

Food products	UV types/ doses	Applications/ target	Remarks	References
Goat's Milk	15.8 mJ/cm^2 of cumulative UV radiation	Treatment on the food microorganism, Listeria monocytogenes	Amount of the microbes decreased by 5-log10	[19]
Cow's milk	UV treatment- 15 kJ/litre	Treatment on the food microorganism	Reduced the number of coliform bacteria by three orders of magnitude, but there was no significant decrease in the case of spores	
Naturally contaminated maize	both UV-A and UV-C radiation	Fungal toxin	Deoxynivalenol (DON)-decreasing effect; underlined that the change is not consistent, maybe due to the uneven toxin Distribution; UV-A more effective than UV-C.	
Orange juice	UV light of 100 mJ/cm2	Pasteurization	The loss of Vitamin C was around 17%, just similar with that of the loss on heat treatment pasteurization.	

Apple juice	UV treatment	Pasteurization	Total phenolic components significantly decreased but slighter decrease compared to a heat treatment of similar efficiency.	
Disinfection of surfaces				
Packaging materials for aseptic yoghurt flling, eg plastic cups and aluminium foil lids,	UVC lamps at 100-200mW/cm2,	UV sterilization	Shelf-life of fruit yoghurt packaged in containers sterilized by UVC lamps was extended by about 2 weeks at 5±7°C	[5]
Surface of food in thin layers of sugar and the surface of meat.	Short-wave UV	To control food spoilage micro-organisms Bacillus stearothermophilus and Pseudomonas spp	Meat that has been exposed directly to UV light sometimes develops off-flavours,	
Fresh fish	UVC irradiation	Pseudomonas spp,	Effectiveness in reducing initial bacterial counts, in prolonging the storage life of fish	
Surface of egg shell	UVC radiation	Salmonella typhimurium	Effective in reducing the total aerobic and mould counts, along with, on the surfaces of egg shells	
Carrots	Pre-storage treatment of carrots with UVC radiation	Fungicides for the control of post-harvest diseases	induces the accumulation of the phytoalexin 6-methoxymellein (an isocoumarin), and this change increases tissue resistance to fungal pathogens.	
Disinfection of liquids				

Water used in brewing industry	UV doses -300 to 600Jm^{-2} Compared with 200 to 300Jm^{-2} for the treatment of potable water.	Disinfection	Ensure the absence of any spoilage problems during the early stages of the brewing process.	
Fruit juices	UVC, turbulent flow of the juice below 5°C and applying a rigorous HACCP programme.	Kill the pathogen	'Light-processed' juice retains its levels of vitamins A, B, C and E.	
Wheat	UV radiation- 3.6 MJ/t.	Sterilization Effect on microorganisms adhering to grain.	The amount of UV energy supplied reduced microorganisms by 90%; little influence on wheat quality in this energy range.	[27]

VI. PULSED LIGHT (PL)

1. **Introduction of Pl:** The ever growing concern for food safety and nutrition has led to the development of non-thermal technologies that provide safe and healthy foods with adequate amount of nutrients but devoid of any chemical preservatives and deleterious effect of thermal technologies. One such non-thermal technology that has potential to replace thermal technologies to some extent is pulsed light (PL) technology. PL is a non-thermal technology used for industrial food applications with light of intense broad spectrum (200-1100 nm). PL is the application of a series of high intensity in the range 0.01-50 J/cm^2 and short time (1 μs-0.1 s) pulses of broad-spectrum light [43; 44]. This broad spectrum includes ultraviolet (200-400 nm), visible (400-700 nm), and infrared (700-1100 nm) (Fig. 1) with peak emission in the wavelength range 400-500 nm [48]. PL is known by different nomenclatures such as pulsed UV light, pulsed white light, high intensity broad-spectrum pulsed light, intense light pulse, and high-intensity pulsed UV light [44]. The US Food and Drug Administration approved PL as a safe technology for food products with maximum fluence of 12 J/cm^2 [58].

2. **Sources of Pl:** PL treatment is carried out with the help of a light source based on inert gas flash lamps or silica fibers doped with ytterbium ions (Yb^{3+}) [51] which can produce pulses with ultrashort durations (picoseconds and femtoseconds) and has very high energy. The xenon flash lamps are commonly used for commercial PL equipments and are more environmentally friendly than mercury lamps. Xenon flash lamps used for PL system are designed to emit radiation in the wavelength range of 200-1100 nm which includes ultraviolet (UV), visible, and infrared spectra. Flashes at the rate of about 1-20 pulses per second are deliver with duration of each pulse being few hundred microseconds [33]. Other inert gases used for generation of PL are argon, krypton or mixtures of inert gases [42]. Two types of lamp are available for PL generation, the flash lamp and the surface discharge lamp [6]. In case of flash lamp, pulses are produced by the gas present in between two electrodes which are confined in an envelope.

The efficiency of UV and intensity of a flash lamp is about 9% and 600 Wcm^{-2} [36]. The lifetime of pulsed xenon lamp is about one month. On the other hand, plasma in surface discharge lamp is produced due to high power electrical discharge that occur along the surface of the dielectric substrate usually fused silica tube containing xenon gas inside an envelope [54] Surface discharge lamp has higher UV efficiency and intensity of about 17% and 30,000 Wcm^{-2} [33]. Surface discharge lamp has longer lifetime due to larger diameter of the envelope as compared to flash lamp.

PL system with multiple xenon lamps are also manufactured by the PL equipment manufacturing company Claranor (France).

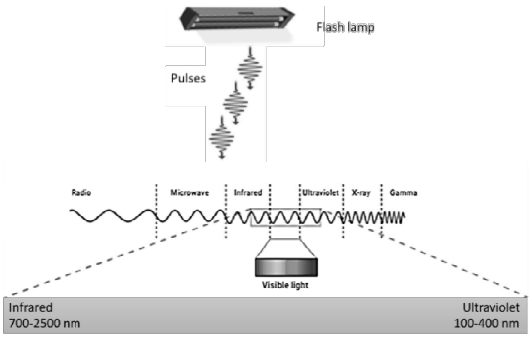

Figure 3: Electromagnetic spectrum covered in PL irradiation.

- **Principle of Pulsed Light**

  - **PL System:** The PL system consists of the following components mentioned in the table below.

Table 2: Components of PL system with their functions.

Components	Functions
• Flash lamp	source of pulsed light
• High-voltage power supply	electrical power supply to the capacitor
• Storage capacitor	temporary storage of electrical energy
• Pulse forming network	decides wavelength and pulse width
• Trigger signal	releases electrical energy to the flash lamp

The flash lamp consists of a light electrode surrounded by 1 mm thick quartz tube (Fig. 2). The quartz tube is filled with inert gas (xenon or krypton). Xenon gas is commonly used for the flash lamp of PL as 45-50% of the electrical energy is converted into pulsed energy. The electrical power supply to the capacitor is high-voltage DC power obtained from low-voltage AC power. The light electrode connected to the high-voltage capacitor, provides electrical energy to the xenon gas. In the pulse forming network, the energy is concentrated from the power supply unit in the charge cycle and

release that during the discharge cycle, thereby generating high electrical current. The pulse forming network is connected to high-power handling switches that perform on/off cycles of very short time that convert the continuous low-electrical power into a pulsed high-electrical power. The continuous bombardment action of high-voltage pulses excites electrons surrounding the gas atoms and then emits photons of the desired wavelength of the PL. The flash lamp emitted light with the spectral distribution of UV (25%), visible light (45%) and infrared (30%) [3]. The flashes of high energy pulses vary from 1-20 flashes per second.

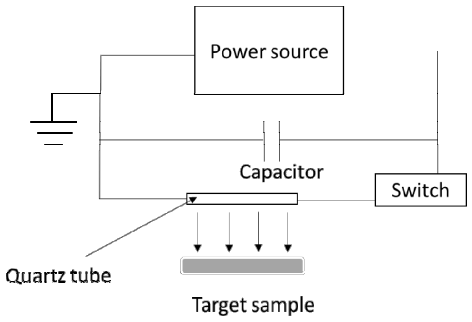

Figure 4: Pulsed light generation system

The parameters of PL system for surface decontamination includes fluence, number of pulses, exposure time, frequency, pulse width, and peak power [45].

The dose of PL can be calculated by using the light intensity, time of treatment [7], and number of pulses per second.

$$Dose = Intensity \times Time \times No.\ of\ pulses/second$$

- **PL Equipment:** Parameters that influenced the efficiency of PL treatment include dimensions of treatment unit, degree of microbial inactivation, and surface area of food product. PL treatment can be done either in batch or continuous mode. The batch mode of treatment is carried out in the system that consists of a treatment chamber having quartz tube loaded with inert gas, a flash lamp, a control panel and a tray for food. The continuous mode of PL treatment is applied in decontamination of liquid foods such as milk and fruit juices.

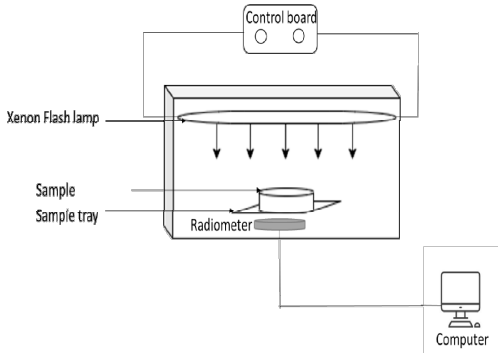

Figure 5: **Batch type pulsed light system**

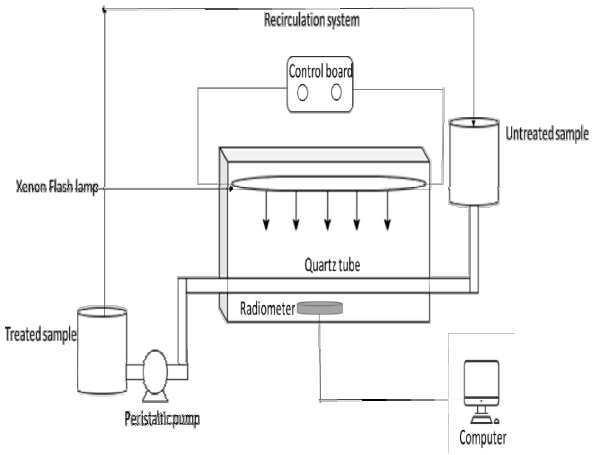

Figure 6: **Continuous type pulsed light system**

The PL equipment for treatment of liquid foods consists of a feed tank, pulsed light treatment chamber, radiometer, quartz tube, PL source, and control panel (Fig. 4). The quartz tube is fixed horizontally connected from the stainless steel pipeline, at the centre of the treatment chamber. The quartz tube allows 90% of the PL transmittance. The source of PL that is commonly used is xenon flash lamp and is placed above the quartz tube. The lamp is provided with provisions to adjust its height from the quartz tube. For quantifying the intensity of light, radiometer is placed beneath the tube.

The pulsed UV light system was first patented for microbial inactivation during 1970s by Hiramoto [28]. [21] Patented pulsed UV system for sterilization of food and packaging materials [21]. Since then, Purepulse Technologies Inc., San Diego, California, a subsidiary of Xenon Corporation is the major organization for decontamination of food and drinking water [4] and later on commercial PL equipments are manufactured under the name PureBright^{TM} [12]. The leading companies that manufacture PL systems at commercial level are Claranor (France), Xenon Corporation (USA) and SteriBeam system (Germany), Wek-tec Systems (Germany), and Solaris Disinfection Inc. (Canada).

VII. APPLICATIONS OF PL ON FOOD

PL as a non-thermal technology can be used not only to decontaminate but also for preservation or enhancement of the nutritional and sensorial quality of food. The effect of PL is mainly responsible with photochemical mechanism, however, photothermal and photo-physical effects are also contributed with its efficacy. The microbial cell inactivation with PL treatment is due to damage of DNA by photochemical, photothermal and photophysical effect [38]. Application of PL can intensify reactions or cause overheating which result in the degradation of phenolic compounds and/or the enzymes that ultimately leads to appearance of browning, discoloration, and oxidation. PL application on fresh fruits and vegetables improves the phytochemicals content.

In food industry, PL is commonly used to decontaminate the surfaces of solid and liquid foods, packaging material and equipment [59]. Applications of PL technology has been studied for decontamination of solid products including fruits, vegetables, seeds, food

powders, and dairy foods; liquid foods including fruit juices (apple, orange, mulberry and turnip) [50]. PL has been commercially successful for the liquid foods specifically juices, however clarity, penetration depth and turbidity are important factors to be considered.

PL treatment can modify the phenolic compounds present in fruits and vegetables.PL technology can be used to inactivate *E. coli* MTCC 433 in liquid foods with dose of 95.2 J/cm^2 [50].

Intense PL could rapidly inactivate polyphenol oxidase (PPO) present in mushroom by destroying the secondary and tertiary structure of polyphenol oxidase [61]. The results of this study showed that the lower the concentration of PPO, the lower the required intensity and fluence for inactivating 90% of PPO. The effect of PL on numerous quality characteristics of pineapple juice was studied and found PL treatments with 2.4 kV and either 94 or 187 pulses (757/ 1479 J/cm^2), a 5-log reduction in aerobic mesophiles, yeast and mould counts [60]. In the same study, peroxidase was more resistant to PL than polyphenol oxidase, with complete retention of bromelain activity in all PL-treated juices. The PL treatment of gooseberry at 2.9 kV for 5 min (at fluence of 3,012 J/cm^2) was the optimum conditions to produce enzymatically stable amla juice with 61, 45, and 54% more retention in vitamin C, total phenolics, and antioxidants content, respectively than the thermally pasteurized gooseberry juice [14].

Table 3: Applications of PL on different liquid and solid foods

Food	Targeted Microorganism/enzyme	PL dose (J/cm^2)	Log reduction/ effect	Reference
Liquid food				
Fruit juices (Orange, Pineapple and Coconut)	*E. coli* (MTCC 433)	95.2	5.33	[50]
Pineapple juice	Aerobic mesophiles, yeast and mould	757-1479	5	[60]
Gooseberry juice	polyphenol oxidase (PPO), and peroxidase (POD)	3,012	Complete inactivation of PPO and POD	[14]
Solid foods				
Cilantro, mesclun lettuce, spinach, and tomato	*Cryptosporidium parvum*oocyst	0.0675-0.0680	2.2, 4.3, 2.5, and 2.2 respectively	[18]
Mushroom	Polyphenol oxidase (PPO)	0.13, 0.40, and 0.66	PL effectively inactivates PPO by destroying the secondary and tertiary structure	[61]
Red bell pepper fresh-cuts	Yeast and molds	16	1.59–2.13	[52]

VIII. SYNERGISTIC PL TREATMENT WITH OTHER TECHNOLOGY

The impact of combined treatment of PL with other technologies is shown in Table 2. The combined treatment of PL with H_2O_2 can be an alternative to chlorine washing for inactivation of *Salmonella* on tomatoes than treatment with PL alone [29]. Another study of combination treatment of PL and gamma radiation on inactivation of *B. cereus* on mesquite flour showed that 1.69 logs reduction of B. cereus spore for 28s- catalytic intense pulsed light and 8 kGy gamma resulted in 3.51 logs reduction [16]. This study shows that combination of PL with gamma radiation has the potential to treat powdered foods effectively and safely. The study on combined treatment of the effect of ultrasonication (28 kHz, 60 W, 15 min) and pulsed light (1.213 $Jcm^{-2}pulse^{-1}$, 360 μs, 3 Hz, 4 s) on the phenolics concentration and antioxidant activities of lactic-acid-fermented mulberry juice was carried out by [39]. This combined treatment significantly improved the total phenolic concentration, total flavonoids concentration total anthocyanin concentration, and antiradical activity in all the PL-ultrasonication treated fermented juice compared to the control sample. In another study of PL with cold plasma technology on red pepper powder showed effective inactivation of indigenous aerobic bacteria and no effect on the red pepper powder colour, vitamin C, capsaicin, and antioxidant activity [40]. The surface decontamination methods of fresh-cut cucumber slices inoculated with *E. coli* with combined treatment of PL on chitosan coating containing carvacrolnanoemulsion induced up to 4 log cycles [56].

Table 4: Synergistic Effect of PL with Other Technology on Foods

Food product	Combination of technologies	Observation	Reference
Tomato	PL-H_2O_2 treatment	Reduction of *Salmonella* in turbid wash water below the detection limit of 2 CFU/mL	[29]
Mesquite flour	PL-Gamma radiation	Inactivation of *B. cereus* spore upto 3.51 log_{10}CFU/g was achieved with 8 kGy of gamma radiation, and up to 1.69 log_{10}CFU/g was reduced after 28s of catalytic PL exposure	[16]
Mulberry juice	PL-ultrasonication	Use of pulsed light after sonication improve antioxidant activities flavonoids concentration of the juice	[39]
Red pepper powder	PL-cold plasma	Yielded the highest inactivation 2.9 log CFU/g of indigenous bacteria	[40]
Fresh-cut cucumber	PL-chitosan coating	Combined treatment reduced up to 4 log cycles of *E. coli*	[56]

IX. ADVANTAGES AND LIMITATIONS OF PL

The associated greater and instantaneous energy impact of PL treatment has been reported to be more effective as compared to the conventional UV light treatment. The germicidal action of PL is attributed to the combined effect of the broad spectrum of UV as well as infrared (IR) which is responsible for the formation of lethal thymine dimers within

the bacterial DNA, leading to blockage of DNA transcription and replication, and ultimately causing cell death. The localized temperature elevation due to absorption of UV and IR radiations contribute to bacterial disruption. The various advantages associated with energy released during the ultrashort emission of PL include denaturation of protein structures and cellular membranes, nucleic acid destruction, and dimer formation [49]. These advantages have proven for the reduction of pathogens in food matrices that have an impact on the shelf life and quality of many food products, and health and safety demand intended for human consumption.

PL has two major limitations in food decontamination process, one is sample heating that depends on the intensity and time of PL treatment, and another limitation is limited penetration depth on opaque foods [47]. Food products with good optical properties can be treated with PL [12]. Food composition also plays an important role in effective PL treatment efficacy. Solid foods and packaging materials must be clear having smooth surface and absence of roughness, and grooves which could give shadow to the microorganisms during PL treatment. The desired inactivation cannot be obtained in case of proteinaceous and fat-rich food matrixes such as meat and fish treatment due to lack of full coverage of the samples under flashlight (Ohlsson and Bengtsson, 2002). In case of herb and leafy green vegetables, PL treatment for more than 10 s at a dose range of 0.0675-0.0680 J/cm^2 resulted in wilting [18].

X. CONCLUSION

With the growing public concern over the safety and chemical free foods, light shows evidently a great promise for the use in food processing industries. Offering a chemical free physical preservation method, where broad range of light, varying from visible, ultraviolet to pulsed or continuous light, can be used for achieving the desired result. Violet-blue range is most effective among other visible wavelengths for decontaminating food surfaces without affecting its quality. It can also be used for inactivating microbes of food contact surfaces.It is not harmful as UV light as well as can work intermittently or continuously both.
Among ultraviolet lights UVC range is famous for sanitising the food products and its surfaces along with maintaining its nutritional and sensory properties. It adds to extra protection layer for achieving complete sanitisation. Though offers many benefits but has some limitations related to its penetration depth in case of liquid dairy products. However more extensive studies are required in this field.

PL technology is a novel non-thermal technology that has potential to be employed for decontaminating food, food-contact surfaces, and packaging materials. PL can employ in the food industry for enhancement of keeping quality or extending shelf life of food products by inactivating microorganisms within a few seconds. PL is one such technology, which has the capacity to reduce the undesirable effects of conventional thermal processing methods. However, PL cannot be used to sterilize food products having non-uniform surfaces and opacity such as grains and spices due to the shadow effect to the microorganisms present.

REFERENCES

[1] Abdel-Kader, M. H. (2014). History of photodynamic therapy. In Photodynamic Therapy (pp. 3-22). Springer, Berlin, Heidelberg.
[2] Alferez, F., Liao, H. L., & Burns, J. K. (2012). Blue light alters infection by Penicilliumdigitatum in tangerines. Postharvest biology and technology, 63(1), 11-15.
[3] Bhalerao, P., Dhar, R., & Chakraborty, S. (2021). 5 Pulsed Light Technology. Food Processing: Advances in Non-Thermal Technologies, 91.
[4] Bhavya, M. L., &UmeshHebbar, H. (2017). Pulsed light processing of foods for microbial safety. Food Quality and Safety, 1(3), 187-202.
[5] Bintsis, T., Litopoulou-Tzanetaki, E., & Robinson, R. K. (2000). Existing and potential applications of ultraviolet light in the food industry–a critical review. Journal of the Science of Food and Agriculture, 80(6), 637-645.
[6] Bohrerova, Z., Shemer, H., Lantis, R., Impellitteri, C. A., & Linden, K. G. (2008). Comparative disinfection efficiency of pulsed and continuous-wave UV irradiation technologies. Water research, 42(12), 2975-2982.
[7] Bolton, J. R., & Linden, K. G. (2003). Standardization of methods for fluence (UV dose) determination in bench-scale UV experiments. Journal of environmental engineering, 129(3), 209-215.
[8] Braidot, E, Petrussa, E., Peresson, C., Patui, S., Bertolini, A.,Tubaro, F., Wahlby, U., Coan, M., Vianello, A. &Zancani, M. (2014). Low-intensity light cycles improve the quality of lamb's lettuce (Valerianellaolitoria[L.] Pollich) during storage at low temperature. Postharvest Biol Technol. 90:15–23.
[9] Branas, C., Azcondo, F. J., & Alonso, J. M. (2013). Solid-state lighting: A system review. IEEE Industrial Electronics Magazine, 7(4), 6-14.
[10] Brancaleon, L., & Moseley, H. (2002). Laser and non-laser light sources for photodynamic therapy. Lasers in medical science, 17(3), 173-186.
[11] Buchovec, I., &Lukšienė, Ž. (2015). Novel approach to control microbial contamination of germinated wheat sprouts: photoactivatedchlorophillin–chitosan complex. International journal of food processing technology, 2, 26-30.
[12] Cacace, D., & Palmieri, L. (2014). High-intensity pulsed light technology. In Emerging Technologies for Food Processing (pp. 239-258). Academic Press.
[13] Calin, M. A., &Parasca, S. V. (2009). Light sources for photodynamic inactivation of bacteria. Lasers in medical science, 24(3), 453-460.
[14] Chakraborty, S., Ghag, S., Bhalerao, P. P., &Gokhale, J. S. (2020). The potential of pulsed light treatment to produce enzymatically stable Indian gooseberry (EmblicaofficinalisGaertn.) juice with maximal retention in total phenolics and vitamin C. Journal of Food Processing and Preservation, 44(12), e14932.
[15] Chang, J. Ch, Susan F. Ossoff, David C. Lobe, Mark H. Dorfman, Constance M. Dumais, Robert G. Qualls, & J. Donald Johnson. (1985). "UV inactivation of pathogenic and indicator microorganisms." Applied and environmental microbiology 49 (6): 1361-1365.
[16] Chen, D., Mosher, W., Wiertzema, J., Peng, P., Min, M., Cheng, Y., ...& Chen, R. R. (2021). Effects of intense pulsed light and gamma irradiation on Bacillus cereus spores in mesquite pod flour. Food Chemistry, 344, 128675.
[17] Costa L, Millan Montano Y, Carri´ on C, Rolny N. &Guiamet J. J. (2013). Application of low-intensity light pulses to delay postharvest senescence of Ocimumbasilicum leaves. Postharvest BiolTechnol 86:181–91.
[18] Craighead, S., Huang, R., Chen, H., &Kniel, K. E. (2021). The use of pulsed light to inactivate Cryptosporidium parvumoocysts on high-risk commodities (Cilantro, mesclun lettuce, spinach, and tomatoes). Food Control, 126, 107965.
[19] Csapó, J., Prokisch, J., Albert, C., & Sipos, P. (2019). Effect of UV light on food quality and safety. Acta Univ. Sapientiae, 12, 21-41.
[20] D'Souza, C., Yuk, H. G., Khoo, G. H., & Zhou, W. (2015). Application of light-emitting diodes in food production, postharvest preservation, and microbiological food safety. Comprehensive Reviews in Food Science and Food Safety, 14(6), 719-740.
[21] Dunn, J.E.; Clark, R.W.; Asmus, J.F.; Pearlman, J.S.; Boyer, K.; Painchaud, F.; Hofmann, G.A. (1989). Methods for Preservation of Foodstuffs. U.S. Patent 4,871,559.
[22] Ghate, V., Kumar, A., Kim, M. J., Bang, W. S., Zhou, W., & Yuk, H. G. (2017). Effect of 460 nm light emitting diode illumination on survival of Salmonella spp. on fresh-cut pineapples at different irradiances and temperatures. Journal of food engineering, 196, 130-138.

[23] Ghate, V., Kumar, A., Zhou, W., & Yuk, H. G. (2016). Irradiance and temperature influence the bactericidal effect of 460-nanometer light-emitting diodes on Salmonella in orange juice. Journal of food protection, 79(4), 553-560.
[24] Glowacz, M, Mogren, L. M, Reade, J. P. H, Cobb, A. H. & Monaghan, J. M. (2014). High-but not low-intensity light leads to oxidative stress and quality loss of cold-stored baby leaf spinach. J Sci Food Agric 95(9):1821–9.
[25] Hamblin, M. R. (2016). Antimicrobial photodynamic inactivation: a bright new technique to kill resistant microbes. Current opinion in microbiology, 33, 67-73.
[26] Haughton, P. N., Grau, E. G., Lyng, J., Cronin, D., Fanning, S., & Whyte, P. (2012). Susceptibility of Campylobacter to high intensity near ultraviolet/visible 395±5 nm light and its effectiveness for the decontamination of raw chicken and contact surfaces. International Journal of Food Microbiology, 159(3), 267-273.
[27] Hidaka, Y., and Kubota, K. (2006). Study on the Sterilization of Grain Surface Using UV Radiation—Development and Evaluation of UV Irradiation Equipment—. Japan Agricultural Research Quarterly: JARQ, 40(2), 157-161.
[28] Hiramoto, T. (1984). Method of Sterilization. U.S. Patent 4,464,336.
[29] Huang, R., & Chen, H. (2019). Sanitation of tomatoes based on a combined approach of washing process and pulsed light in conjunction with selected disinfectants. Food Research International, 116, 778-785.
[30] Hui, X. U., FU, Y. N., LI, T. L., &Rui, W. A. N. G. (2017). Effects of different LED light wavelengths on the resistance of tomato against Botrytis cinerea and the corresponding physiological mechanisms. Journal of integrative agriculture, 16(1), 106-114.
[31] Imada, K., Tanaka, S., Ibaraki, Y., Yoshimura, K., & Ito, S. (2014). Antifungal effect of 405-nm light on B otrytiscinerea. Letters in applied microbiology, 59(6), 670-676.
[32] Josewin, S. W., Ghate, V., Kim, M. J., & Yuk, H. G. (2018). Antibacterial effect of 460 nm light-emitting diode in combination with riboflavin against Listeria monocytogenes on smoked salmon. Food Control, 84, 354-361.
[33] Keklik, N. M., Krishnamurthy, K., &Demirci, A. (2012). Microbial decontamination of food by ultraviolet (UV) and pulsed UV light. In Microbial decontamination in the food industry (pp. 344-369). Woodhead Publishing.
[34] Kim, M. J., Bang, W. S., & Yuk, H. G. (2017). 405±5 nm light emitting diode illumination causes photodynamic inactivation of Salmonella spp. on fresh-cut papaya without deterioration. Food microbiology, 62, 124-132.
[35] Kim, M. J., Tang, C. H., Bang, W. S., & Yuk, H. G. (2017). Antibacterial effect of 405±5 nm light emitting diode illumination against Escherichia coli O157: H7, Listeria monocytogenes, and Salmonella on the surface of fresh-cut mango and its influence on fruit quality. International journal of food microbiology, 244, 82-89.
[36] Koutchma, T. (2019). Ultraviolet light in food technology: principles and applications (Vol. 2). CRC press.
[37] Koutchma, T. N. Forney, L. J. and Moraru, C. I. (2009).Ultraviolet light in food technology. Principles and applications. CRC Press, Taylor and Francis Group, Boca Raton.
[38] Krishnamurthy, K., Tewari, J. C., Irudayaraj, J., &Demirci, A. (2010). Microscopic and spectroscopic evaluation of inactivation of Staphylococcus aureus by pulsed UV light and infrared heating. Food and Bioprocess Technology, 3(1), 93-104.
[39] Kwaw, E., Ma, Y., Tchabo, W., Apaliya, M. T., Sackey, A. S., Wu, M., & Xiao, L. (2018). Impact of ultrasonication and pulsed light treatments on phenolics concentration and antioxidant activities of lactic-acid-fermented mulberry juice. LWT, 92, 61-66.
[40] Lee, H. S., Park, H. H., & Min, S. C. (2020). Microbial decontamination of red pepper powder using pulsed light plasma. Journal of Food Engineering, 284, 110075.
[41] Li, X., Kim, M. J., Bang, W. S., & Yuk, H. G. (2018). Anti-biofilm effect of 405-nm LEDs against Listeria monocytogenes in simulated ready-to-eat fresh salmon storage conditions. Food Control, 84, 513-521.
[42] Linden, K. G., &Mofidi, A. A. (2004). Disinfection efficiency and dose measurement of polychromatic UV light. IWA Publishing.
[43] Mahendran, R., Ramanan, K. R., Barba, F. J., Lorenzo, J. M., López-Fernández, O., Munekata, P. E., ...& Tiwari, B. K. (2019). Recent advances in the application of pulsed light processing for improving food safety and increasing shelf life. Trends in food science & technology, 88, 67-79.
[44] Mandal, R., Mohammadi, X., Wiktor, A., Singh, A., &Pratap Singh, A. (2020). Applications of pulsed light decontamination technology in food processing: an overview. Applied Sciences, 10(10), 3606.

[45] Marangoni Junior, L., Cristianini, M., &Anjos, C. A. R. (2020). Packaging aspects for processing and quality of foods treated by pulsed light. Journal of Food Processing and Preservation, 44(11), e14902.
[46] Nelson, K. L., Boehm, A. B., Davies-Colley, R. J., Dodd, M. C., Kohn, T., & Linden, K. G. (2018). Sunlight-mediated inactivation of health-relevant microorganisms in water: A review of mechanisms and modeling approaches. Environmental Sciences: Processes Impacts, 20, 1089-1122.
[47] Oms-Oliu, G., Martín-Belloso, O., &Soliva-Fortuny, R. (2010). Pulsed light treatments for food preservation. A review. Food and Bioprocess Technology, 3(1), 13-23.
[48] Pinela, J., & Ferreira, I. C. (2017). Nonthermal physical technologies to decontaminate and extend the shelf-life of fruits and vegetables: Trends aiming at quality and safety. Critical Reviews in Food Science and Nutrition, 57(10), 2095-2111.
[49] Pollock, A. M., Singh, A. P., Ramaswamy, H. S., &Ngadi, M. O. (2017). Pulsed light destruction kinetics of L. monocytogenes. LWT, 84, 114-121.
[50] Preetha, P., Pandiselvam, R., Varadharaju, N., Kennedy, Z. J., 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.
[51] Richardson, D. J., Nilsson, L. J. A., Lefort, L., Price, J. H. V., Malinowski, A., & Ibsen, M. (2005). U.S. Patent No. 6,917,631. Washington, DC: U.S. Patent and Trademark Office.
[52] Rybak, K., Wiktor, A., Pobiega, K., Witrowa-Rajchert, D., &Nowacka, M. (2021). Impact of pulsed light treatment on the quality properties and microbiological aspects of red bell pepper fresh-cuts. LWT, 111906.
[53] Santos, A. L., Oliveira, V., Baptista, I., Henriques, I., Gomes, N. C. M., & Almeida, A., (2013). Wavelength dependence of biological damage induced by UV radiation on bacteria. Archives of Microbiology, 195,63-74.
[54] Schaefer, R., Grapperhaus, M., Schaefer, I., & Linden, K. (2007). Pulsed UV lamp performance and comparison with UV mercury lamps. Journal of Environmental Engineering and Science , 6 (3), 303-310.
[55] Srimagal, A., Ramesh, T., &Sahu, J. K. (2016). Effect of light emitting diode treatment on inactivation of Escherichia coli in milk. LWT-Food Science and Technology, 71, 378-385.
[56] Taştan, Ö.,Pataro, G., Donsì, F., Ferrari, G., &Baysal, T. (2017). Decontamination of fresh-cut cucumber slices by a combination of a modified chitosan coating containing carvacrolnanoemulsions and pulsed light. International journal of food microbiology, 260, 75-80.
[57] Tortik, N., Spaeth, A., &Plaetzer, K. (2014). Photodynamic decontamination of foodstuff from Staphylococcus aureus based on novel formulations of curcumin. Photochemical &Photobiological Sciences, 13(10), 1402-1409.
[58] U. S. Food and Drug Administration. (2001). 21 CFR Part 179. Irradiation in the production, processing and handling of food. Federal Register, 65: 71056-71058.
[59] Vargas-Ramella, M., Pateiro, M., Gavahian, M., Franco, D., Zhang, W., Khaneghah, A. M., ...& Lorenzo, J. M. (2021). Impact of pulsed light processing technology on phenolic compounds of fruits and vegetables. Trends in Food Science & Technology.
[60] Vollmer, K., Chakraborty, S., Bhalerao, P. P., Carle, R., Frank, J., &Steingass, C. B. (2020). Effect of pulsed light treatment on natural microbiota, enzyme activity, and phytochemical composition of pineapple (Ananascomosus [L.] Merr.) juice. Food and Bioprocess Technology, 13, 1095-1109.
[61] Zhang, J., Yu, X., Xu, B., Yagoub, A. E. A., Mustapha, A. T., & Zhou, C. (2021). Effect of intensive pulsed light on the activity, structure, physico-chemical properties and surface topography of polyphenol oxidase from mushroom. Innovative Food Science & Emerging Technologies, 102741.
[62] Žudytė, B., &Lukšienė, Ž. (2019). Toward better microbial safety of wheat sprouts: chlorophyllin-based photosensitization of seeds. Photochemical &Photobiological Sciences, 18(10), 2521-2530.

