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Pulsed light sterilization of packaging materials

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ABSTRACT

Pulsed light (PL) technology is an emerging processing method that utilizes short duration pulses of intense, broad-spectrum light for the sterilization of surface. Compared to other sterilization methods, such as heat or chemical disinfectant treatment, PL treatment has several advantages; it is faster and leaves no residues. This review discusses the sterilization principles behind PL and its applications for surface sterilization, in especially the decontamination of food packaging materials. The efficacy of PL treatment can be affected by several factors, including the low penetration ability of PL, the shadowing effect of microorganisms, and the composition and properties of the surfaces. The mechanism of microbial inactivation by PL are also summarized. To increase the efficacy of sterilization, PL treatment in combination with chemicals or other decontamination techniques and their applications are also discussed. A complete understanding of the mechanisms of microbial decontamination and the hermetic effects of PL would provide clues on how to increase the efficiency and benefits of this technology for food industry applications.

1. Introduction

Nonthermal food-processing technologies are emerging sterilization techniques for extending the shelf life of food products. Although the traditional thermal sterilization technologies and equipment are highly developed, such heat treatments cause inevitable damage to food ingredients and flavor. Consequently, to preserve the sensory properties and nutritional value of food ingredients, nonthermal food sterilization technologies that use physical methods have attracted increasing attention. Nonthermal food-processing technologies that have been developed include, active packaging, high pressure processing, pulsed electric fields, pulsed light (PL) disinfection, electron beam irradiation, high intensity ultrasounds and cold plasma (Muredzi, 2012; Vanderroost, Ragaert, Devlieghere, & De Meulenaer, 2014). These nonthermal food-processing technologies are expected to have wide commercial usage in the improvement of food and agricultural product quality, and in reducing the risk of microbial hazards.

PL sterilization can achieve rapid inactivation of microorganisms on food surfaces, equipment, and food packaging materials using high-intensity light with a wide range of optical wavelengths. PL lamps produce broad spectrum light at wavelengths ranging from ultraviolet (UV) to near infrared (NIR, 100–1000 nm; UV [100–400 nm], visible light [380–780 nm], and infrared [700–1100 nm]). The light used for food processing applications typically pulsed at 1–20 flashes per second and an energy density in the range of 0.01–50 J/cm^2 at the surface (Condón, Álvarez, & Gayán, 2014). PL sterilization technology possesses the characteristics of easy operation and short irradiation duration. This technology can reduce or replace traditional chemical sanitizers used for sterilizing

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surfaces (e.g., hydrogen peroxide and peracetic acid). The Food and Drug Administration has approved the use of PL technology for food production, processing, and handling (Code of Federal Regulation, CFR: 21CFR179.41). Microbes exhibit variations in PL susceptibility, and exhibit the following trend (in decreasing order): Gram-negative bacteria, Gram-positive bacteria, fungal spores and bacterial spore (Levy, Aubert, Bornard, & Carlin, 2012; Oms-Oliu, Martín-Belloso, & Soliva-Fortuny, 2010). Esbelin, Mallea, Ram, and Carlin (2013) also reported that the color of the fungal spores can play a significant role in susceptibility, and *Aspergillus niger* spores are more resistant than *Fusarium culmorum* spores. The extent of the fungal spore resistance of *A. niger* could be attributed to the presence of protective dark pigments in the wall layers that surround the spore form. This might be because the pigment in *A. niger* spores absorbs more light in the UV-C region than the pigment in *F. culmorum* spores, which protect *A. niger* spores. Inactivation by PL is commonly attributed to DNA damage caused by UV irradiation. Turtoi and Nicolau (2007) also reported spore color seems to play some role in spore resistance to light pulses, the dark colored fialospores produced by *A. niger* (black) and *A. cinnamomeus* (brown) are easier destroyed than those of *A. repens* (green). The absorbance scan of pigment extracts from the fungus over the range 240–480 nm indicated that the pigments of *A. niger* absorb strongly in the UV range. Takeshita et al. (2003) observed that the DNA damage in *Saccharomyces cerevisiae* cells was slight higher after continuous UV light treatment than after PL treatment. However, protein elution from the yeast cells was higher after PL irradiation than after UV irradiation when the fluence was increased. Krishnamurthy, Irudayaraj, Demiric, and Yang (2008) also reported photophysical effects of PL treatment for 5 s on *S. aureus* in phosphate buffer based on transmission electron microscopy and Fourier transform infrared spectroscopy observations, which included cell wall damage, cytoplasmic membrane shrinkage, cellular content leakage, and mesosome disintegration. In bacterial spores, UV-C treatment mainly results in the formation of the ''spore photoproduct'' 5-thyminyl-5,6-dihydrothymine, and single-strand breaks, double-strand breaks, and cyclobutane pyrimidine dimers (Demirci & Krishnamurthy, 2011). Ringus and Moraru (2013) hypothesized that the physical properties of the surfaces to be treated, including surface topography and reflectivity, affect the efficacy of PL inactivation. Surface roughness and crevices have been suggested to shield microbial cells during treatment; and surface hydrophobicity may influence the distribution of bacterial contaminants on surfaces, as liquid droplets may contain hydrophilic organisms.

Because of the optical and physical limitations of this technology, PL is non-chemical and non-ionizing, and is primarily employed for sterilizing the surfaces of items, such as foods, packaging materials, and processing equipment, and medical equipment. This paper describes the processing technologies and application range for PL sterilization of food packaging materials surfaces (Keklik & Demirci, 2014). Packaging increases the convenience of food storage, transportation, retailing, consumption, and most importantly shelf life. Various materials are currently used in food packaging including glass, metal, paper, paperboard, and plastics (Marsh & Bugusu, 2007). However, from manufacture to usage in food production, packaging materials might be exposed to various contaminants that may include microorganisms. This could post a potential threat to food production, especially in aseptic or hygienic packaging processes, and may cause food safety issues. Currently, the packaging materials used in these two processes are mainly treated with chemical sterilants such as peracetic acid, and hydrogen peroxide at concentrations of up to 30% and at temperatures up to 80 °C (Ansari & Datta, 2003). However, possible residues from these sterilants in the final product and heat sensitive packaging materials have increased interest in developing a new technique for sterilizing packaging materials.

2. The characteristics and mechanisms of PL sterilization

In 1970, Japanese scientists discovered that pulsed flash lamps could be used for sterilization, and they submitted a patent application for this technology in 1984. By using short-duration flashes (1 μs to 0.1 s) of intense light, PL sterilizes and inhibits enzymatic activity. This PL is emitted over a wide wavelength range in the UV and near-NIR spectrums (Demirci & Keklik, 2012). In addition, PL is suitable for mass production because of its high operational efficiency. PL technology involves exposing an object intended for sterilization to intense pulses of light. The surface of the object is irradiated using the PL one or more times (Gómez-López, Ragaert, Debevere, & Devlieghere, 2007).

The wavelength range of the PL spectrum includes the solar spectrum wavelengths as well as light at 180 nm–300 nm. Sunlight at these wavelengths (180 nm–300 nm) is blocked by the atmospheric layer above earth. When PL at wavelengths under 300 nm is blocked, the overall effectiveness of sterilization decreases considerable. This indicates that the sterilization function of PL is primarily dependent on light in the UV range. Compared with the UV rays produced by UV lamps, PL releases increased instantaneous energy peaks, but consumes less overall power and provides enhanced sterilization effectiveness. PL is believed to be four to six times more effective for inactivating microorganisms than continuous UV light (Krishnamurthy, Tewari, Irudayaraj, & Demiric, 2010).

The pulsed-light sterilization mechanism primarily depends on the following two photoreactions (Demirci & Keklik, 2012).

(1) Photothermal effects: a portion of the PL is in visible and NIR range. This portion conveys heat, which is transmitted to the surfaces of the objects. This heat instantly increases surface temperatures up to 50–150 °C. In addition, this heating process only affects the surface of objects (to approximately 10 μm thick) without considerably increasing the internal temperature of the irradiated objects.
(2) Photochemical effects: UV photon energies can be absorbed by protein, DNA, and RNA, thereby causing photochemical damage, which kills microorganisms. Levy et al. (2012) determined the damage caused by PL treatment in *Bacillus subtilis* and *A. niger* spores by using SEM (Fig. 1). Treatment with PL resulted in severe damage to the microbial cells, and cell wall damage, cytoplasmic membrane shrinkage,