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Review

Inactivation mechanisms of non-thermal plasma on microbes: A review

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ABSTRACT

The increasing consumption of fresh-like food products requires the development of mild processing technologies without loss of nutritional value and sensory quality of foods. Non-thermal plasma (NTP) is an emerging and promising technology for extending the shelf-life of food products. However, the further development of a novel preservation technology should base on the adequate understandings of the effects on microbial behaviors. Therefore, the aim of this review is to provide an overview of the inactivation mechanisms of NTP technology on microbes. Topics covered are the basic introduction of NTP, the intrinsic and extrinsic factors affecting microbial inactivation effect and the probable mechanisms for microbial inactivation. Many factors, including processing parameters, environmental conditions and microbial properties have been shown to influence the bactericidal effect of NTP. According to previous research, the inhibitory activity of NTP against microbes includes biological and physical scenarios, though the exact mechanisms still remain unknown, requiring more investigations in the future.

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1. Introduction

Over the years, due to the demand for healthy lifestyles with better diets, fresh or minimally processed food products have received increasing attention from consumers (Mir, Shah, & Mir, 2016). However, the contamination of these food by pathogenic and spoilage microbes is an indispensable challenge for food industry, which may cause foodborne disease outbreaks (Sumathi, Friedman, Cohen, & Tauxe, 2004; Ziuzina, Han, Cullen, & Bourke, 2015). Currently, fresh or minimally processed products are frequently consumed raw without processing or cooking (Guo, Huang, & Wang, 2015), and the overall incidence of foodborne infections has risen over the past years. For instance, it was reported that the percentage of all foodborne outbreaks related to fresh products in USA was enhanced from 0.70% in the 1970s to 6.0% in the 1990s (Sumathi et al., 2004), and it was continuously raised from 13% during the period of 1990–2005 to 33% in 2012 (CDC, 2014; Doyle & Erickson, 2008). In order to fulfill consumers' demand, not only should the nutritious and organoleptic quality be maintained, but the microbial safety also needs to be assured without compromising (Fernandez, Noriega, & Thompson, 2013). However, conventional thermal sterilization technologies may cause serious side effects on the nutritional value and sensory qualities (taste and crunch) of fresh food products (Berk, 2008). Therefore, in recent years, several non-thermal sterilization technologies have been developed in order to satisfy consumers' requirements, such as high pressure processing (HPP), ultraviolet (UV), ultrasound, pulsed electric field (PEF), irradiation, electrolyzed water and non-thermal plasma (NTP) (Li & Farid, 2016; Li et al., 2016; Xuan et al., 2017). Among the aforementioned sterilization techniques, NTP is one of novel sterilization technologies and has huge potential in applying to food preservation due to its features of high efficiency and limited side effects. Plasma, a kind of ionized gas, is considered as the fourth state of matter. It contains plenty of charged particles (e.g. OH, H_2O^+, electrons etc.), reactive species (e.g. reactive oxygen species-ROS, OH., O_2,$^1O_{2}$-; reactive nitrogen species-RNS, NO•, ONOO•, etc.), excited molecules (e.g. excited O_2, N_2, etc.), and UV photons (e.g. vacuum UV, UVC, UVB, etc.), leading to microbial inactivation (Scholtz, Pazlarova, Souskova, Khun, & Julak, 2015). NTP sterilization enjoys advantages of relevantly low temperature, no toxic byproducts, minimal damage on food products and low cost, making it alternative to conventional sterilization technologies (Moreira et al., 2004; Ziuzina et al., 2015). The antimicrobial efficiency of NTP is incontestable and has been demonstrated by numerous literatures (Hertwig et al., 2015; Lee, Puligundla, & Mok, 2015; Perni, Shama, & Kong, 2008; Selcuk, Oksuz, & Basaran, 2008). However, there is still lack of knowledge about cellular targets and molecular mechanisms mediated by NTP inactivation due to the complexity of plasma, microbial and food system, impeding its further development and application in food industry.

In this review, firstly, a brief overview of NTP will be given. And the next part will exhibit the factors affecting microbial inactivation of NTP in detail. Finally, the inactivation mechanisms will be proposed and summarized at great length.

2. Characteristics of plasma technology

2.1. Plasma and its classification

In 1897, plasma was firstly discovered by William Crookes (Crookes, 1879). In 1929, Irving Langmuir and Tonks made first attempt to introduce the term of plasma into physics (Tonks & Langmuir, 1929). Plasma is considered as the fourth state of matter in the world. With increasing energy level, the state of matter transfers from solid to liquid, to gas, and finally to plasma (Fig. 1) (Fridman & Kennedy, 2004). Plasma is a neutral charged collection of atoms, ions, electrons, photons, and atoms in their fundamental or excited states (Misra, Tiwari, Raghavarao, & Cullen, 2011). According to the temperature of electrons, plasma can be grouped into low temperature ($T_e = 10^4$~10^5 K) and high temperature plasma ($T_e = 10^6$~10^8 K) (Fridman, Chirokov, & Gutsol, 2005). More specifically, low temperature plasma can be distinguished into thermal plasma and non-thermal plasma (NTP), on the basis of thermodynamic equilibrium (Scholtz et al., 2015). Therein, thermal plasma will reach a local equilibrium status, in which electrons temperature (T_e) is almost the same as heavy neutral particles temperature (T_n) and overall gas temperature (T_g) (Scholtz et al., 2015). The macroscopic temperature of thermal plasma can be several thousand Kelvin. In contrast, NTP shows thermodynamic non-equilibrium, where electron temperature can reach approximately 10^4 K, much higher than neutral ions temperature ($T_e \gg T_n$) and whole gas temperature ($T_e \gg T_g$). Consequently, the NTP system maintains in relatively low temperature.

2.2. Generation of NTP

Plasma can be generated by different methods, including gas discharge, photo ionization, heat radiation, radio frequencies and so on (Becker, Kogelschatz, Schoenbach, & Barker, 2004; Lieberman & Lichtenberg, 2005). Among these methods, gas discharge is the most common way to create NTP. During gas discharge processing, the energy from electric field is accumulated by electrons through collision, and only a fraction of energy will be then transferred to other particles, resulting in $T_e \gg T_n$, non-thermal state of plasma (Fridman & Kennedy, 2004). Common devices for NTP production include dielectric barrier discharge (DBD), resistive barrier discharge (RBD), corona discharge, glow discharge, radio frequency discharge (RFD), and atmospheric pressure plasma jet (APPJ) (Ehlbeck et al., 2011). For example, Misra et al. (2014) introduced a DBD system to generate cold plasma. In this system, a high voltage transformer delivered an output voltage of 60 kV at 50 Hz between two circular aluminum electrodes to make air discharge and produce adequate plasma. So far, DBD and APPJ are the most commonly and widely studied forms of plasma actuation (Fig. 2). DBD, also named silent discharge, enjoys the advantages of producing stable and uniform NTP with huge area and working at relatively low temperature under atmospheric pressure (Kang, Park, Kim, & Hong, 2003; Scholtz et al., 2015). APPJ requires auxiliary flowing gas to push the stream consisting of active particles generated by plasma in the electrode area outside (Scholtz et al., 2015).