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Applications of electromagnetic fields for nonthermal inactivation of microorganisms in foods: An overview

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ABSTRACT

Background: Thermal processing has been widely employed in the food industry for food safety assurance. However, thermal processing may cause some undesirable changes or form by-products that negatively affect the nutritional value, flavor, color and texture of the final product. With increasing awareness of food and health, consumers prefer more naturally and minimally processed foods. Therefore, investigation of nonthermal processing technologies is important and necessary not only for its minimal impact on food but also for its extension of product shelf-life by inhibiting or inactivating microorganisms.
Scope and approach: This review presents a general perspective of nonthermal inactivation technologies based on electromagnetic fields, including pulsed electric fields, high voltage arc discharge, pulsed light, ionizing radiation, microwave and cold plasma. The inactivation mechanisms, characteristics and research progress, as well as the limitations of these technologies, are also discussed.
Key findings and conclusions: Compared to thermal treatments, nonthermal inactivation technologies have shown significant advantages with great potential. Hybrid technologies based on these methods should play a significant role in enhancing inactivation efficiency. In addition, combination of these methods with thermal treatment can lower the treatment temperature and achieve high reductions of microorganisms in foods. Despite various degrees of success in these technologies, their widespread applications in the food industry are yet to flourish. Further studies are still needed to understand these processes to provide a platform by which their limitations can be overcome.

1. Introduction

Food quality and safety are important issues for both the consumers and the food industry. Besides techniques such as drying (Cui, Sun, Chen, & Sun, 2008; Pu & Sun, 2016; Yang, Sun, & Cheng, 2017), cooling (McDonald, Sun, & Kenny, 2000; Sun, 1997; Sun & Brosnan, 1999; Sun & Hu, 2003; Sun & Wang, 2000; Wang & Sun, 2002a; Wang & Sun, 2002b; Wang & Sun, 2004; Zheng & Sun, 2004) and freezing (Cheng, Sun, & Pu, 2016; Cheng, Sun, Zhu, & Zhang, 2017; Kiani, Zhang, Delgado, & Sun, 2011; Ma et al., 2015; Pu, Sun, Ma, & Cheng, 2015; Xie, Sun, Xu, & Zhu, 2015; Xie, Sun, Zhu, & Pu, 2016) for preserving foods, processes for inactivating food microorganisms are also needed. Sterilization is the process of rendering all vegetative microorganisms as well as their spores inactivation through the application of a physical or chemical process. In food processing, sterilization is mainly achieved by applying elevated temperatures (i.e., a thermal process), however, nonthermal processes have been investigated and applied in the food industry to achieve commercial sterilization. Methods of thermal processing have been widely applied in the food industry to ensure the microbiological safety of foods at low cost (Li & Farid, 2016; Stoica, Mihalcea, Borda, & Alexe, 2013). However

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conventional thermal sterilization technologies cause negative changes in nutritional value, flavor, color or texture of the final product, or form undesirable by-products that affect food quality and safety (Li & Farid, 2016; Pereira & Vicente, 2010). With increasing awareness of food and health, consumers prefer more naturally and minimally processed foods. Therefore, in the last decade, nonthermal processing technologies have attracted attention from food scientists, technologists and engineers in academia and the food industry. Nowadays there are a number of nonthermal processing techniques available, which however are at various stages of research and development. Among them, techniques based on electromagnetic fields have been extensively studied and applied, which include pulsed electric fields (PEF), high voltage arc discharge (HVAD), pulsed light (PL), microwave, irradiation and cold plasma (CP).

Nonthermal processing techniques based on electromagnetic fields generally have the advantages of minimal impact on the nutritional and sensory properties of foods and extended product shelf-life by inhibiting or inactivating microorganisms (Chen, Yu, & Rupasinghe, 2013; Zhang, Barbosa-Canovas, Dunne, Farkas, & Yuan, 2011). Tiwari, O'Donnell, and Cullen (2009) found that the nonthermal technologies PEF and irradiation have minimal influence on anthocyanin content of fruit juices. Roselló-Soto et al. (2015) showed that when energy input was augmented, the application of high voltage electric discharge could significantly increase the aqueous and hydro-ethanolic extractions of total phenolic content. In addition, the efficiency of microorganism inactivation by nonthermal processing techniques based on electromagnetic fields are also excellent (Geveke, 2008). For example, Gayán, Serrano, Raso, Álvarez, and Condón (2012) illustrated that the combination of UV light and mild temperatures could achieve 99.99% (4D) reduction of *Salmonella enterica* subsp. *Enterica*. These technologies have the following characteristics in common: the food products are not actively heated, which means that the temperature is generally kept at low or moderate temperatures (e.g., below 60 °C).

However, some mechanisms of nonthermal inactivation are still not fully understood. Discussion on the mechanisms mainly concentrates on the change of cell morphology and structure, the endogenous key enzyme passivation of cell metabolism, the DNA damage of cellular genetic material and the change in gene expression. In addition, due to the need of expensive and specialized equipment and experienced skills, these technologies are often technically difficult for their direct applications in food production (Pereira & Vicente, 2010; Stoica et al., 2013).

In order to provide further information on the technological progress of these nonthermal processing techniques and promote their further study and application, this review presents general perspectives of pulsed electric fields (PEF), high voltage arc discharge (HVAD), pulsed light (PL), ionizing radiation, microwave and cold plasma (CP), and discuss their inactivation mechanism, characteristics and limitations. Table 1 shows the comparison of these nonthermal processing treatments. It is hoped that the review will encourage more applications of these technologies in the food industry.

2. Electric field processing technologies

2.1. Pulsed electric fields (PEF)

Among the nonthermal processing technologies, PEF is one of the most extensively researched and promising processes (Mattar et al., 2014; Zhao, Tang, Lu, Chen, & Li, 2013). It has the ability to inactivate microorganisms with minimal effects on the nutritional, flavor and functional characteristics of food products (Pereira & Vicente, 2010; Stoica et al., 2013). At present, it is generally accepted that the inactivation mechanism of PEF mainly focuses on electric breakdown and electroporation. However, in some situations, the collapse of cell membrane is reversible and thus the microorganisms cannot be inactivated completely (Elez-Martínez, Sobrino-López, Soliva-Fortuny, & Martín-Belloso, 2012; Jaeger, Balasa, & Knorr, 2009). Up to now, extensive experimentation has been carried out to prove that the PEF process could inactivate microorganisms rapidly in food, especially in liquid food. The microorganisms that can be inactivated by PEF include vegetative cells, molds and yeasts, while bacterial spores are resistant to PEF treatment, and yeasts are the most PEF sensitive microorganisms (Kuldiloke & Eshtiaghi, 2008). Table 2 summaries the effects of PEF treatments on inactivation of food-borne pathogens in liquid food. Among the studies listed in Table 2, Walkling-Ribeiro et al. (2008) found that apple juice treated with PEF (40 kV cm^{-1}, 100 μs, chamber inlet at 46 °C and outlet at 58 °C) had a higher reduction ($p < 0.05$) of *S. aureus* in comparison to conventional pasteurization (9.5 vs. 8.2 log_{10}, respectively). In addition, Altuntas, Evrendilek, Sangun, and Zhang (2010) showed that the inactivation of *Escherichia coli* O157:H7, *Staphylococcus aureus* and *Listeria monocytogenes* were significantly enhanced with the increase in electric field strength and treatment time ($p \leq 0.05$) (Fig. 1 and Table 2). However, the inactivation efficiency of microorganisms depends on many factors. Kuldiloke and Eshtiaghi (2008) agreed that electric field strength and treatment time had a significant influence on microbial inactivation. On the other hand, factors related to media such as electrical conductivity, pH and medium ionic strength and those related to the microorganism such as types, growth stage, concentration, size and shape of microbes also had significant effects on the inactivation efficiency, and thus should also be considered (Amiali & Ngadi, 2012; Stoica, Bahrim, & Cârâc, 2011). However, among the microbial parameters, the type of microorganism is a critical factor that affects the inactivation efficiency of PEF treatment (Li & Farid, 2016).

The adoption of PEF for commercial nonthermal pasteurization of fruit juices was first implemented by Genesis Juices, Oregon, USA (Clark, 2006). Today, there are several PEF companies available in the world, for example, two companies in Holland and Belgium provide PEF technology for juice processing with the purpose of microbial inactivation. However, the uptake of the technology for microbial inactivation and commercial availability are still limited. The cost of initial investment of PEF systems is high, and a gap between innovative consciousness and the innovative ability of the scientific research has been observed (Stoica et al., 2013). However, PEF has found uptake for applications other than microbial inactivation, such as increasing the yield in extraction processes, and modifying the texture of products to reduce downstream losses. For example, a company in Germany uses PEF to increase the juice yield and several companies in Australia, the US and Europe employ PEF to soften potato tissue for French fries manufacture.

Besides its use alone, PEF has been successfully combined with other nonthermal technologies such as UV irradiation, microwave, high intensity light pulses (HILP) (Fig. 2) and high hydrostatic pressure (HHP) to achieve bacterial inactivation (Caminiti et al., 2011; Stoica et al., 2013). Caminiti et al. (2011) found that when PEF treatment on apple juice was followed by HILP, *E. coli* inactivation significantly increased ($p < 0.001$), and the viable counts were below the detection level (<1 log cfu/ml) (Fig. 2). In contrast, the number of survivors was 1.85 log cfu/ml when the reverse sequence was applied. There are also reports that PEF combined with thermal treatment can achieve high reductions of microorganisms (Bermúdez-Aguirre, Dunne, & Barbosa-Cánovas, 2012; Monfort, Sagarzazu, Condón, Raso, & Álvarez, 2012).