# Chapter 16
# Future Outlooks

**Tian Ding and P. J. Cullen**

**Abstract** Cold plasma is continuing to receive growing attention from both food and plasma researchers alike, however its adoption by the food industry remains in niche areas. The advantages of cold plasma technology include its low working temperature, high antimicrobial efficacy, limited effects on food quality, and free of chemical residues. As with any emerging food processing technology, there are challenges that need to be addressed for the acceptance and adoption of plasma processes by regulatory, industry, and consumers. Such challenges include the ambiguity surrounding regulatory approval of plasma as a processing aid, the technical gaps in precisely controlling the plasma processes or dose as well as the challenges of effective scale up for industrial use. In this chapter, the aforementioned challenges in terms of regulation, precise controlling and the consumers' acceptance are discussed in detail. Only if these issues are addressed carefully can cold plasma be commercially implemented in the near future.

**Keywords** Cold plasma · Challenges · Regulatory approval · Process control · Consumer acceptance

## 16.1 Introduction

With the increase in consumer demand for minimally processed foods, food processing technologies must not only ensure food safety but also retain the food organoleptic quality (Pan et al. 2019). However, conventional thermal processing of

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food, in many cases, induces significant changes in food, such as structural modifications, nutrient losses, and changes in taste. Nonthermal technologies are therefore receiving increasing attention from the food sector due to their low operating temperatures and less compromise in food quality and nutrition. Nonthermal techniques include high pressure processing (HPP), irradiation (gamma-ray, beta-rays, electron beam), ultrasound, ozone, pulsed light, ultraviolet treatment, and pulsed electric fields (PEF) (Li and Farid 2016; Wu et al. 2020).

Cold plasma, also known as nonthermal plasma, has the advantages in practical applications due to its low treatment temperature, high antimicrobial efficacy, low cost, and ease of operation (Liao et al. 2017; Muhammad et al. 2018). During the last decade, an increasing body of literature have demonstrated the potential of cold plasma technology to reduce microbial contamination (e.g., bacteria, spores, biofilms, fungi), degrade pesticides and mycotoxins and alleviate allergens on various foods effectively as a sustainable technology with low energy input and investment (Liao et al. 2020). In order to scale up the implementation of cold plasma technology in food industry, however, some critical challenges, such as regulatory approval, effective and precise control of plasma process, and consumer acceptance, should be carefully addressed through future research.

## 16.2 Regulatory Approval

Prior to its application, a novel food processing technology generally must be reviewed and approved by the government regulatory agencies. Ozone processing technology received a Generally Recognized as Safe status as a food processing aid by the U.S. Food and Drug Administration (FDA) in 1997 (Joshi et al. 2013). In 2001, the U.S. FDA approved HPP for the commercial decontamination of juices (Koutchma 2014). In addition, the U.S. FDA allowed microwave-assisted thermal sterilization process (MATS) for food sterilization. To date, the application of cold plasma technology has not received any approval from the global regulatory agencies; however, the technology is currently being assessed by many of these bodies. The technology is however used widely for food packaging modification and has been reported for being directly used as an antibacterial agent in food. In 2019, cold plasma technology for the cancer treatment was approved by the FDA for its first-ever use in a clinical trial. The regulatory approval for cold plasma processes still requires a large amount of confirmed data and research efforts due to the complexity of plasma chemistry and the unclear effects on the products.

## 16.3 Control of Cold Plasma Processes

It is important to make the plasma processes controllable and predictable in order to achieve the maximum microbial inactivation and minimal compromise in the nutritional and sensory quality of foods. Given the complexity of cold plasma processes, a detailed understanding of the physical and chemical aspects of cold plasma is required. During plasma production, electron collisions induce hundreds of chemical reactions to produce an array of reactive species over a broad time scale from nanoseconds to hours. Consequently, diagnosis of the key plasma control parameters (e.g., frequency, power, voltage) and induced reactive species is required in order to standardize and control the process. Various technologies have been applied for the diagnostics of plasmas, such as optical emission spectroscopy (OES), optical absorption spectroscopy measurements (VUV to MIR), laser-induced fluorescence (LIF), two photons LIF (TALIF), Rayleigh-, Raman-, and Thomson scattering, mass spectrometry, gas chromatography, or electron paramagnetic resonance spectroscopy (Laroussi et al. 2017). Most of the aforementioned methods for plasma diagnostics are likely to provide the final concentrations of plasma species. In order to monitor the temporal and spatial dynamics in the reaction pathways, numerical models are generally employed for simulation (Knake et al. 2008). However, the failure in considering some specific reaction pathways might cause significant discrepancies from the simulated data and the experimental data. Furthermore, a diverse range of laboratory scale plasma systems have been developed and reported. To date, limited commercial cold plasma systems for food decontamination have been applied in the industry (Ragni et al. 2010). In 2018, a commercial plasma in-pack machine was developed by Anacail company, which could be equipped in the food production line (http://www.anacail.com/food#tabs-1). The scaled-up continuous plasma processes and devices should be designed carefully with standardization of plasma parameters (e.g., treatment time, applied power and current supply, discharge gap distance) as well as with the consideration of the health and safety issues of the operators and the work environment. During plasma production, high densities of reactive gas species (e.g., ozone, nitrogen oxides) may be produced in the gas phase. Therefore, the ventilation equipment for neutralizing the reactive species and the sensing devices for detection of gas leakage should be incorporated into the plasma machines. In addition to the reactive species in the gaseous phase, the concentrations of the plasma-induced aqueous reactive species should be accurately determined as well. So far, a lot of simple numerical simulations or experimental measurements have been conducted for the estimation of potential products from the gas-liquid-phase reaction processes (Bruggeman et al. 2016; Takeuchi 2015). However, more complex model and the associated experiments are required to be conducted for further validation of the results.

## 16.4 Consumer Acceptance

In recent years, a lot of novel food processing technologies have emerged in the food industry. However, new technologies may not be viewed positively by consumers. Foods irradiated with Gamma-rays have poor consumer acceptance in the European Union (Schweiggert et al. 2007). Fumigation of foods with ethylene oxide and propylene oxide also receives a low consumer acceptance due to the potential formation of carcinogenic by-products (Wesley et al. 1965). Consumer attitudes toward new technologies should be surveyed, ideally regionally. It is still unclear whether consumers accept cold plasma treated food products. Concerns over possible toxic by-products and potential compromise in food quality (e.g., color, texture) require further investigations. For instance, it has been reported the visible damages on the foods with soft skins (e.g., mangoes) induced by plasma treatment (Perni et al. 2008). In addition to the food quality, the cytotoxic activity of plasma-treated foods requires more investigations for the completed understanding and estimation in order to meet the regulatory criteria (Gavahian and Khaneghah 2020). It is of importance that scientists and engineers working together in the field to share their findings and unbiased opinions for cold plasma treatment of food.

## 16.5 Conclusions

As an emerging nonthermal processing technology, cold plasma technology has received growing global attention over the last decade. Abundant studies have reported the excellent performance of cold plasma technology for assuring food safety and retaining key food organoleptic qualities. Undoubtedly, the emergence of cold plasma technology presents an alternative solution to assure food safety. However, in spite of these recent progresses, there remain some challenges impeding the development of cold plasma technology, such as the lack of regulatory approval, the difficulties in plasma process controlling, and unknown consumer acceptance attitudes. Therefore, more confirmed data and research are required to deal with the aforementioned problems in order to achieve the successful implementation of cold plasma in the food sector.

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