J Food Sci Technol (March 2018) 55(3):846–857
https://doi.org/10.1007/s13197-017-3020-y

REVIEW ARTICLE

Influences of cold atmospheric plasma on microbial safety, physicochemical and sensorial qualities of meat products

Qisen Xiang[1,2] · Xiufang Liu[1,2] · Junguang Li[1,2] · Tian Ding[3] · Hua Zhang[1,2] · Xiangsheng Zhang[2] · Yanhong Bai[1,2]

Revised: 13 November 2017 / Accepted: 21 December 2017 / Published online: 30 December 2017
© Association of Food Scientists & Technologists (India) 2017

Abstract Meat and meat products can be contaminated with pathogenic microorganisms, which cause serious health problems and economic loss. Recently, numerous novel non-thermal technologies have been developed to respond to growing consumer demand for high quality and safe meat products. Cold atmospheric plasma (CAP) is a novel and emerging non-thermal technology, showing great potential for applications in the food industry. This review presents recent advances on the developments and applications of CAP in meat products, including generation and microbial inactivation effects of CAP as well as its influences on physicochemical qualities and sensory attributes of meat products. Furthermore, the safety assessment of CAP-treated meat products and challenges in industrial application of CAP are also discussed.

Keywords Cold atmospheric plasma · Inactivation · Meat products · Physicochemical qualities · Sensory attributes

✉ Yanhong Bai
baiyanhong212@163.com

[1] College of Food and Biological Engineering, Zhengzhou University of Light Industry, NO. 136, Kexue Road, Zhengzhou 450001, Henan, People's Republic of China

[2] Henan Collaborative Innovation Center of Food Production and Safety, Zhengzhou 450001, Henan, People's Republic of China

[3] Department of Food Science and Nutrition, Zhejiang Key Laboratory for Agro-Food Processing, Zhejiang University, Hangzhou 310058, Zhejiang, People's Republic of China

Introduction

As an excellent source of high-quality protein and numerous essential nutrients, meat and meat products make a significant contribution to human nutrition. As a result of unique nutrient composition, high water activity, and moderate pH (Iulietto et al. 2015), meat and meat products consequently are excellent growth media for a variety of microorganisms and are identified as frequent vehicles for foodborne diseases (Dave and Ghaly 2011). Spoilage microorganisms can cause the degradation of proteins, carbohydrates, fats, and other components, resulting in the development of off-odours, off-flavours, grayness or other discolorations, pH changes, slime formation, and texture softening (Dave and Ghaly 2011). More importantly, meat and meat products are easily contaminated with a number of foodborne pathogens, including *Salmonella* spp., *Campylobacter* spp., *Escherichia coli* O157:H7 and other *Enterohemorrhagic E. coli* (EHEC), *Listeria monocytogenes*, prions, and so on (Mor-Mur and Yuste 2010). Dietary intake of meat products contaminated with pathogenic microorganisms may cause serious foodborne illnesses or even death, leading to a great financial burden for medical care and social costs. According to Painter et al. (2013), contaminated meat products, including beef, game, pork, and poultry, were to blame for 22.2% of foodborne illnesses and 28.8% of deaths in the USA from 1998 to 2008, and these were mainly caused by bacteria. Therefore, there is an urgent need to improve the microbial safety of meat products with appropriate preservation and processing methods. With increasing consumer demand for better quality and safer meat products, some novel non-thermal food processing technologies have been developed and used in the meat industry, such as high hydrostatic pressure (Campus 2010), pulsed electric fields (Arroyo et al. 2015),

irradiation (Singh et al. 2015), modified atmosphere packaging, and so on.

In recent years, the application of cold atmospheric plasma (CAP) in the food industry is gaining more attention, including decontamination (Niemira 2012), food packaging (Pankaj et al. 2014), modification of food structure and properties (Bahrami et al. 2016), and inactivation of endogenous enzymes (Misra et al. 2016) in various food systems. On this basis, a few authors have summarized the application of CAP in the food industry (Afshari and Hosseini 2012; Mir et al. 2016; Misra et al. 2016; Niemira 2012; Pankaj et al. 2014; Thirumdas et al. 2015), but detailed descriptions on the effects of CAP on meat products are not available. Therefore, the present review summarizes the recent progress in the application of CAP on the microbial safety, physicochemical qualities, and sensory attributes of meat products. Additionally, the risk assessment of CAP-treated meat products and challenges are also discussed.

Cold plasma characteristics and sources

The existence of plasma was first discovered by William Crookes in 1879, who described it as "radiant matter" (Crookes 1879). The term "plasma" was first applied to ionized gas by Irving Langmuir in the late 1920s (Langmuir 1928). In term of physics and chemistry, plasma is a completely or partially ionized gas, that consists of a large number of different species such as ions, electrons, and uncharged particles (atoms, molecules, etc.) and radicals (Hoffmann et al. 2013). Generally, plasma is considered as the fourth state of matter besides solids, liquids, and gases, and makes up approximately 99% of the visible matter in the universe (Hoffmann et al. 2013).

Classification of plasma

In terms of the relative temperatures of the electrons, ions, and neutrals, plasmas are generally divided into two main groups: high temperature plasma and low temperature plasma (Fig. 1). High temperature plasma is also known as thermally equilibrium plasma, because all particle species exist in thermodynamic temperature equilibrium at the same temperature ($T_e \approx T_i \approx T_g$, where T_e, T_i, and T_g are the temperatures of the electron, ion, and gas molecules, respectively) (Afshari and Hosseini 2012). The gas temperature (T_p) of thermal plasma is about 10^6–10^8 K (Huang and Tang 2007). Low-temperature plasma is also called thermally non-equilibrium plasma and is further subdivided into thermal plasma (quasi-equilibrium plasma) and non-thermal plasma (non-equilibrium plasma). For quasi-equilibrium plasma, particle species are in a local thermal equilibrium state and T_g is about 2×10^4 K (Afshari and Hosseini 2012). Non-equilibrium plasma is also known as cold plasma, because of its low gas temperature of 300–1000 K (Fridman et al. 2008). Cold plasmas can be generated under low-pressure (< 1 Pa), moderate pressure ($\approx$ 100 Pa), and atmospheric pressure conditions. With versatility, low-cost operation, and user-friendly operation compared to plasmas in vacuum, cold atmospheric plasmas offer significant potential for application in food industry (Mir et al. 2016).

Generation of CAP

Plasma can be generated by supplying energy (such as thermal energy, mechanical energy, electrical energy, and nuclear energy) to gaseous medium. When molecules of the gas are given energy in excess of their ionization potential, these energies dissociate gaseous molecules into mixture of electrons, ions, charge-neutral gas molecules, photons, radicals and other species (Conrads and Schmidt 2000). The most commonly used method for generation of CAP is by applying an electric field to a neutral gas at atmospheric pressure, including dielectric barrier discharge (DBD), atmospheric pressure plasma jet (APPJ), glow discharge, corona discharge, radio frequency discharge, high voltage pulsed discharge, microwave discharge, flexible thin-layer dielectric barrier discharge (FTDBD), plasma needle, plasma pencil, and so on (Hoffmann et al. 2013). The schematic diagrams of the DBD plasma system and the APPJ system are shown in Fig. 2.

CAP induced microbial inactivation in meat products

Table 1 provides a summary of microbial inactivation in fresh meat products (such as raw pork, raw beef, and chicken breast) and processed meat products (beef jerky, bacon, and chicken ham, etc.) using various CAP applications along with the process parameters employed.

CAP induced inactivation of various microorganisms

As reviewed in Table 1, CAP can effectively kill pathogenic bacteria in pork, beef, poultry, and related products, such as *Salmonella Typhimurium* (Kim et al. 2011), *Escherichia coli* O157:H7 (Jayasena et al. 2015), *Listeria monocytogenes* (Kim et al. 2013a; Lee et al. 2011), *Listeria innocua* (Noriega et al. 2011), *Campylobacter jejuni* and *Salmonella enteric* (Dirks et al. 2012). The above mentioned bacterial strains are the most prevalent and serious pathogenic bacteria inside meat and meat products (Mormur and Yuste 2010). CAP treatments also can effectively induce the inactivation of molds (Choi et al. 2016) such as

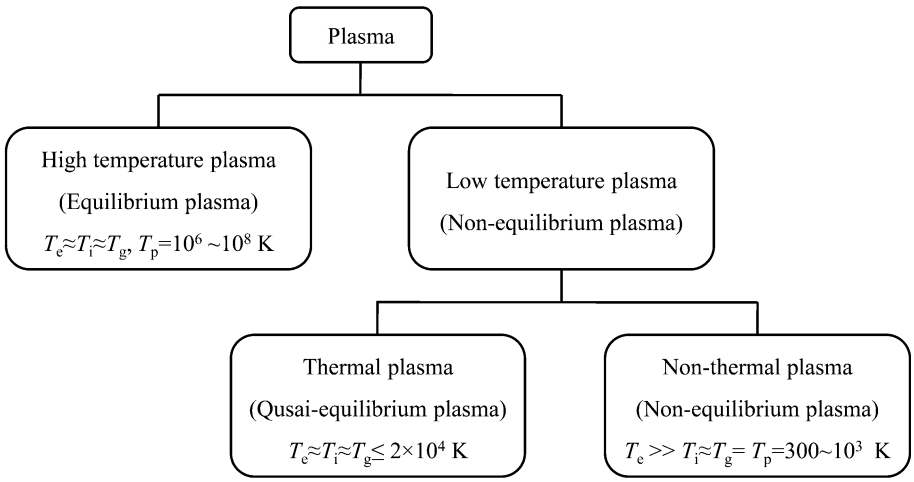

Fig. 1 Classification of plasma. *Note*: T_e, T_i, and T_g are the temperatures of electron, ion, and gas molecules, respectively

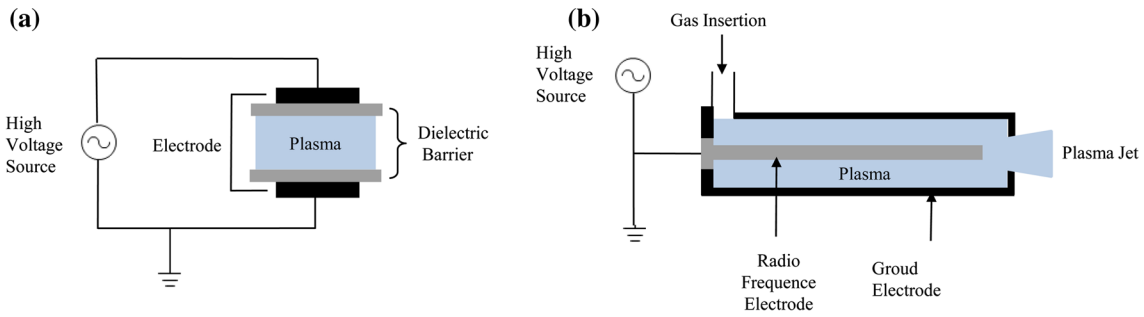

Fig. 2 Schematic diagrams of the dielectric barrier discharge plasma system (**a**) and the atmospheric pressure plasma jet (APPJ) system (**b**)

Aspergillus flavus (Yong et al. 2016), yeasts (Ulbin-Figlewicz et al. 2015), and viruses, including murine norovirus (MNV-1) and hepatitis A virus (HM-175) in meat products (Bae et al. 2015).

CAP induced inactivation of bacterial biofilms

During the last decades, biofilms formed by pathogenic and spoilage bacteria have lead to serious hygienic problems and economic losses in the meat industry (Giaouris et al. 2013). Compared with planktonic cells, biofilms and attached cells have significantly greater resistance to antimicrobial treatments and environmental stresses encountered in food production plants (Giaouris et al. 2013). Hence, it is important to assess the efficacy of CAP on inactivation of biofilms. According to Han et al. (2016a, b) and Ziuzina et al. (2015), DBD plasma effectively induced inactivation of three meat pathogens (*E. coli*, *L. monocytogenes*, and *Staphylococcus aureus*) grown as biofilms by using a meat model medium. Besides, CAP treatment also caused significant reductions of *Pseudomonas aeruginosa* quorum sensing-regulated virulence factors, such as pyocyanin and elastase (Ziuzina et al. 2015). In summary, CAP can effectively induce the direct inactivation of both planktonic cells and preformed biofilm of meat pathogens and may play an important role in attenuation of virulence of pathogenic bacteria.

Mechanism of CAP sterilization

The underlying mechanisms of microbial inactivation induced by cold plasma treatments were previously investigated in order to improve the efficiency and efficacy of such plasmas. While the mechanism of bacterial inactivation by plasma is still not well understood, it is believed that reactive species, charged particles, electrostatic disruption, and electroporation are all involved (Takamatsu et al. 2015; Liao et al. 2017). CAP operated in air is certainly known to create copious quantities of reactive species, including hydroxyl radicals, hydrogen peroxide, singlet oxygen, superoxide anion, ozone, NO, nitrites, peroxinitrite ($ONOO^-$), and so on (Shintani et al. 2010). These reactive oxygen species (ROS) and reactive nitrogen species (RNS) can cause cell injury by attacking cellular membranes, DNA, lipids, proteins, and other cell components in microorganisms, which disrupt normal metabolic functions and lead to cell death (Thirumdas et al. 2015). Moreover, charged particles generated by plasma can accumulate on the surface of bacteria and induce rupture of the outer membrane, and consequently cause the

Table 1 Overview on studies dealing with microbial inactivation by CAP in meat products

Sample	Plasma source	Microorganism	Process gas	Log reduction	References
Sliced pressed Ham	Atmospheric pressure plasma	*L.monocytogenes* (ATCC 19114, 19115, and 19111)	Power: 75, 100, 125, and 150 W Frequency:13.56 MHz Gap distance: 0.6 mm Gas and flow rate: He (10 lpm) Operation time: 60, 90, and 120 s	After 120 s APP treatments at 75, 100, and 125 W, reductions ranged from 0.25 to 1.73 log CFU/g	Song et al. (2009)
Bacon	Glow discharge plasma	*L. monocytogenes* (KCTC 3596), *E. coli* (KCTC 1682), and *S. Typhimurium* (KCTC 1925)	Power: 75, 100, and 125 W Frequency:13.56 MHz Gas and flow rate: He (10 lpm) or He (10 lpm) + O_2 (10 sccm) Operation time: 60 and 90 s	After treatments at 125 W for 90 s with He and O_2 mixture, the number of *E. coli, L. monocytogenes*, *S. Typhimurium* and total aerobic bacteria were reduced by 3.0, 2.6, 3.73, and 4.58 log CFU/g, respectively	Kim et al. (2011)
Chicken skin and breasts	Cold atmospheric plasma pen apparatus	*L. innocua* (ATCC 33090)	Power: 6.5–16 kV Frequency: 23–38.5 MHz Gas and flow rate: He (5 L/min) and O_2 (100 mL/min) Operation time: 10 s to 8 min	After treatments for 8 min or 4 min, the population of *L. innocua* was reduced by about 1 log CFU/cm^2 on skin, and > 3 CFU/cm^2 on muscle	Noriega et al. (2011)
Cooked chicken breast and ham	Atmospheric pressure plasma jet (APPJ)	*L. monocytogenes* (KCTC 3596)	Power: 2 kV Frequency: 50 kHz Gas and flow rate: He (7 L/min), N_2 (7 L/min); He (7 L/min) + O_2 (0.07 L/min), N_2 (7 L/min) + O_2 (0.07 L/min) Operation time: 2 min	2 min exposure resulted in reduction of 1.37–4.73 log CFU/g in chicken breast and 1.94-6.52 log CFU/g in ham	Lee et al. (2011)
Chicken breast and chicken thigh with skin	Dielectric barrier discharge (DBD) plasma	*S. enteric* (ATCC19214 and ATCC13076), and *C. jejuni* (ATCC700819, RM 2002, and RM1849)	Power: 30 kV Frequency: 0.5 kHz Power density: 0.15 W/cm^2 Gas: air Operation time: 0–200 s Gap distance: 1.5 mm	Inoculum levels of 10^4 CFU of *S. enteric*, 3 min treatments resulted in reduction of 2.54 log on chicken skin and 1.31 log on chicken breast, respectively. Inoculum levels of 10^4 CFU of *C. jejuni*, 3 min treatments resulted in reduction of 3.11 log on chicken skin and 2.45 log on chicken breast, respectively	Dirks et al. (2012)
Porcine *musculus longissimus dorsi* (MLD)	Microwave plasma	Total aerobic microbial	Power: 1.2 kW Frequency: 2.45 GHz Gas and flow rate: air (20 slpm) Temperature: < 20 °C Operation time: 2 × 2.5 min or 5 × 2 min	Indirect plasma treatment is able to prolong the shelf life of porcine MLD and the aerobic viable count of MLD remained between 10^2 and 10^3 CFU/g during the storage period of 20 days at 5 °C	Fröhling (2012)

Table 1 continued

Sample	Plasma source	Microorganism	Process gas	Log reduction	References
Sliced ready-to-eat meat product (bresaola)	DBD plasma	*L. innocua* (DMRI 0011)	Power: 27 kV Frequency: 27.8 kHz Gas: air Distance: 10 mm Operation time: 2, 5, and 10 min	Indirect DBD plasma treatment can reduce *L. innocua* on the surface of a ready-to-eat meat product (bresaola) inside sealed linear-low-density polyethylene bags	Rød et al. (2012)
Oval-shaped slices of pork loin	DBD plasma	*E. coli* (KCTC 1682) and *L. monocytogenes* (KCTC 3569)	Power: 3 kV Frequency:30 kHz Gas and flow rate: He (10 slpm) $+O_2$ (0.3%) Operation time: 5 or 10 min	Following a 10 min exposure with He + O_2, the population of *E. coli* and *L. monocytogenes* were reduced by 0.55 log CFU/g and 0.59 log CFU/g, respectively	Kim et al. (2013a)
Raw chicken breast and pork loin	APPJ	*S. Typhimurium* (KCTC 1925)	Power: 0.5 kW Gas and flow rate: N_2 (6 lpm) $+O_2$ (10 sccm) Distance: 20 mm	A treatment on both sides for 2.5 + 2.5 min resulted in reduction of 0.66 log CFU/g in chicken breast and 1.33 log CFU/g in pork loin, respectively	Kim et al. (2013b)
Raw chicken breasts with skins	APPJ	*E. coli* (KCTC 1682)	Power: 50 W Gas and flow rate: N_2 (6 slpm) and O_2 (10 sccm) Distance: 20 mm Operation time: 5 or 10 min	Inoculum levels of 10^4 CFU/g of *E. coli*, 5 min treatments resulted in reduction of 1.85 log CFU/g in chicken breast	Yong et al. (2014)
Beef loin, pork shoulder, and chicken breast	APPJ	Murine norovirus (MNV-1) and hepatitis A virus (strain HM-175)	Power: 3.5 kV (peak voltage) Frequency:28.5 kHz Gas and flow rate: N_2 (6 slpm) Distance: 4 cm Operation time: 0.5, 1, 3, 5, 10, and 20 min	5 min of APP jet treatment showed > 99% reduction (2 log PFU/mL) of MNV-1 titer and > 90% reduction (1 log PFU/mL) of HAV titer without concomitant changes in meat quality	Bae et al. (2015)
Pork butt and beef loin	Flexible thin-layer dielectric barrier discharge (FTDBD) plasma	*E. coli* O157:H7 (KCCM 40406), *S. Typhimurium* (KCTC 1925), and *L. monocytogenes* (KCTC 3569)	Power: 100-W peak power and 2-W average power Frequency:15 kHz Gas: air Operation time: 2.5–10 min	Following a 10-min treatment, the microbial-load reductions of *L.* monocytogenes, *E. coli* O157:H7, and *S. Typhimurium* were 2.04, 2.54, and 2.68 log CFU/g in pork-butt samples and 1.90, 2.57, and 2.58 log CFU/g in beef-loin samples, respectively	Jayasena et al. (2015)
Pork longissimus dorsi muscle	Pulsed plasma reactor	Psychrotroph bacteria, total microorganisms, yeasts, and moulds	Power: 1.2 kVA Frequency: 20–100 kHz Gas: He, Ar, and N_2 Operation time: 5 or 10 Pressure: 0.8 MPa	After the He plasma treatment for 10 min, the population of psychrotroph bacteria, total microorganisms, yeasts and moulds were reduced about 2.7, 2.96, and 3.08 log CFU/cm^2, respectively	Ulbin-Figlewicz et al. (2015)
Fresh and frozen pork slices	Corona discharge plasma jet (CDPJ)	*E. coli* O157:H7 (ATCC 43894) and *L. monocytogenes* (KCTC 3569)	Power: 20 kV Current strength: 1.50 A Frequency: 58 kHz Gas: filtered air Span length: 25 mm Operation time: 30–120 s	Following CDPJ treatment (0-120 s), the population of *E. coli* O157:H7 and *L. monocytogenes* were reduced by 1.5 log and > 1.0 log units, respectively	Choi et al. (2016)

Table 1 continued

Sample	Plasma source	Microorganism	Process gas	Log reduction	References
Beef	DBD plasma	*E.coli* NCTC 12900	Power: 1.3 KVA Frequency: 18–22 kHz Gas: He or Ar (6 L/min) Distance: 20 mm Operation time: 4, 6 or 10 min	After 10 min of exposure with argon or helium gas, the *E. coli* populations were reduced by 2.18 and 1.38 log CFU/sample, respectively	Hosseini et al. (2016)
Raw chicken breasts	FTDBD plasma	*E. coli* O157:H7 (KCCM 40406), *S. Typhimurium* (KCTC 1925), and *L. monocytogenes* (KCTC 3569)	Power: 100-W peak power and 2-W average power Frequency:15 kHz Gas: air Operation time: 2.5–10 min	Following FTDBD plasma treatment for 10 min, the numbers of total aerobic bacteria, *L. monocytogenes*, *E. coli*, and *S. Typhimurium* were reduced by 3.36, 2.14, 2.73, and 2.71 log CFU/g, respectively	Lee et al. (2016)
Beef jerky	FTDBD plasma	*L. monocytogenes* (KCTC 3569), *E. coli* O157:H7 (ATCC 43894), *S. Typhimurium* (KCTC 1925), and *A. flavus* (KCTC6905)	Power: 100-W peak power and 2-W average power Frequency:15 kHz Gas: air Operation time: 2.5–10 min	After plasma treatment for 10 min, *E.coli* O157:H7, *L. monocytogenes*, *S. Typhimurium*, and *A.flavus* populations on the beef jerky were reduced by about 2–3 log CFU/g.	Yong et al. (2016)

lpm liter per minute; *sccm* standard cubic centimeter per minutes; *slpm* standard liters per minute

inactivation of bacterial cells (Hoffmann et al. 2013; Fridman et al. 2008). Additionally, electrostatic disruption and electroporation may also contribute to the inactivation of microorganisms induced by plasma (Liao et al. 2017; Lunov et al. 2015). Ultraviolet (UV) has been demonstrated to play a very prominent role in the inactivation of microorganisms particularly when treated with vacuum plasma at very low pressure; however, the role of UV radiation for atmospheric plasmas appears to be less important (Hoffmann et al. 2013). Up to now, the sterilization mechanism of cold plasma is not well elucidated and more research is still needed.

Factors affecting the sterilization efficacy of CAP

Several factors significantly affect the microbial inactivation efficacy of CAP, such as plasma sources (Schnabel et al. 2012), input power (Kim et al. 2011; Song et al. 2009), exposure time (Bae et al. 2015; Jayasena et al. 2015; Noriega et al. 2011), the distance between plasma and surface of samples (Baier et al., 2014), gas composition (Kim et al. 2011; Lee et al. 2011; Marsili et al. 2002) and gas flow rate (Niemira and Sites 2008), relative humidity (Patil et al. 2014; Ragni et al. 2010), microbial species (Jayasena et al. 2015; Lee et al. 2016), initial concentration of microorganisms (Dirks et al. 2012; Yong et al. 2014), food microstructure (Smet et al. 2017) and so on.

Song et al. (2009) evaluated the impact of input power (75, 100, 125, and 150 W) and exposure time (60, 90, and 120 s) on atmospheric pressure plasma-induced inactivation of *L. monocytogenes* (ATCC 19114, 19115, and 19111) and a greater population reduction was achieved with elevated input power and prolonged treatment time (Song et al. 2009). These results are consistent with those of Jayasena et al. (2015), Kim et al. (2013b), and Noriega et al. (2011). The inactivation efficacy of CAP is also significantly affected by the types of carrier gasses used to generate plasma (Kim et al. 2011; Lee et al. 2011; Marsili et al. 2002; Yong et al. 2014). Compared with the use of helium alone (10 slpm), the addition of 0.3% O_2 was previously found to improve the inactivation efficiency of DBD plasma against *E. coli* and *L. monocytogenes* on pork loin (Kim et al. 2011). Lee et al. (2011) investigated the sterilization effect of atmospheric pressure plasma against *L. monocytogenes* on cooked chicken breast and ham with four kinds of carrier gases (He, He + O_2, N_2, and N_2 + O_2) and determined that the gas combination of N_2 + O_2 was the most effective. The increasing inactivation ability of plasma may be related with the increased production of ROS and RNS during the breakdown of these gases molecules (Marsili et al. 2002). Initial concentration of microorganisms is also an important factor affecting inactivation efficiency of plasma (Dirks et al. 2012; Yong et al. 2014). Yong et al. (2014) verified that the reduction rate of *E. coli* after APPJ treatment was the highest at

inoculum levels of 10^4 CFU/g in chicken breast, followed by 10^5, 10^6, and 10^7 CFU/g.

Owing to the influences of various treatment conditions on the inactivation efficiency of CAP, the process parameters (such as carrier gasses, input power, exposure time, and so on) should be optimized based on the different characteristics of meat products. Meanwhile, the impacts of the microstructure of whole-muscle meat products and the use of additives on the microbial inactivation efficacy of CAP also should be investigated in the further work.

CAP induces bacteria into VBNC state

Traditionally, the killing ability of CAP is usually assessed using plate count techniques and the results are usually expressed as colony forming units (CFUs). However, some pathogenic bacteria can enter a distinct state known as the viable but non-culturable (VBNC) state following exposure to multiple environmental stresses. The microbial cells in the VBNC state do not form colonies on most laboratory media, but retain metabolic activity and may be resuscitated back into culturable state under suitable conditions (Ramamurthy et al. 2014). Numerous research studies have revealed that many species of bacteria enter the VBNC state after CAP treatment, such as *Bacillus stratosphericus* (Cooper et al. 2010), *Chromobacterium violaceum* CV026 (Joaquin et al. 2009), and *P. aeruginosa* (Ziuzina et al. 2014). The CAP-induced VBNC bacterial cells cannot be detected by conventional plate count techniques and remain potentially pathogenic upon favourable conditions, which may contribute to further contamination and increase the risk of human exposure to contaminated water or foods. Therefore, the mechanisms underlying the induction of VBNC state mediated by CAP should be identified and technological parameters of CAP treatment should be optimized to reduce the induction of VBNC states.

Effects of CAP on the physicochemical qualities of meat products

Before the acceptance of CAP as a food decontamination process, it is necessary to determine its effects on the chemical composition and physico-chemical properties of meat products.

pH

pH value is a reliable indicator for meat quality and is often associated with dark meat color. Several recent studies have shown that CAP can significantly affect the pH of meat and meat products. For example, the pH of DBD plasma-treated pork loins was significantly lower than that of untreated meat samples (Kim et al. 2013a). CAP treatment also affects the pH of meat during storage. After storage at 5 °C for 20 d, the pH of untreated porcine meat was changed from 5.6 (3 d) to 6.0 (20 d), which might be due to the release of ammonia induced by spoilage bacteria during storage, while the pH of CAP-treated samples was maintained at 5.5 or 5.4 (Fröhling 2012). The influence of CAP treatment on the pH of meat during storage may be related its sterilization effects, because the increases in pH mainly due to the release of ammonia induced by spoilage bacteria during storage (Nychas et al. 2008).

The CAP-mediated decrease in pH can be attributed to acidogenic molecules such as NO*x*, which are normally generated in corona discharge plasma (Stoffels et al. 2008). After the treatment by corona discharge plasma, the pH of *E. coli* solution in distilled water quickly decreased from 7.5 (0 min) to about 1.2 after 20 min (Korachi et al. 2010). It is assumed that bacterial molecules and H_2O are dissociated into smaller units during prolonged plasma treatment, thus increasing the H^+ concentration and decreasing the pH value of the solution (Kim et al. 2013a; Korachi et al. 2010).

Lipid oxidation

For muscle foods, lipid oxidation is a very complex and important event, which results in decreases in flavor, color, taste, texture, shelf life, nutritional value, as well as generation of toxic compounds (Cheng 2016). Rød et al. (2012) investigated the treatment of DBD plasma on the lipid oxidation of commercial bresaola by measuring the thiobarbituric acid reactive substance (TBARS) values, which were formed as a byproduct of lipid peroxidation. After plasma treatment, the TBARS contents in sliced bresaola were significantly higher than those of control samples after 1 and 14 days of storage at 5 °C (Rød et al. 2012). After the treatment by FTDBD plasma for 10 min, the peroxide value (POV) of beef jerky and TBARS values of raw pork and beef were also significantly increased (Yong et al. 2016; Jayasena et al. 2015).

The formation of lipid oxidation products induced by DBD plasma increased with increasing power, treatment time, and storage time (Rød et al. 2012). The types of plasma sources and carrier gases (Kim et al. 2013a), and sample characteristics such as fat content and composition of meat (Bae et al. 2015; Kim et al. 2011) are important factors affecting the levels of lipid oxidation in plasma-treated meat products. For example, Bae et al. (2015) determined that chicken breast was easier to be oxidized than beef loin and pork shoulder after CAP treatment. After the treatment of DBD plasma with He + O_2, the pork loins had higher TBARS levels, which might be due to the increased formation of free radicals after the addition of O_2

(Kim et al. 2013a; Tani et al. 2012). However, Kim et al. (2011) reported that there were no significant differences in TBARS values of bacon upon the addition of O_2. The inconformity of these results may be due to variations in the fat content and fatty acid composition of different meat products as well as the different types of plasma used.

The accelerating effects of CAP on lipid oxidation in meat products may be attributed to the radicals produced by plasma, such as ROS, RNS, metastables, excited atoms and molecules, UV photons, charged particles (electrons, ions, etc.) and so on (Khelifa et al. 2016; Rehman et al. 2016). The reactive species produced in plasma, especially hydroxyl radical, superoxide anion radical, and ozone, can initiate lipid oxidation reactions in meat products and result in significant increases of TBARS values in plasma-treated meat products (Kim et al. 2013a).

Metmyoglobin content

Myoglobin is a metalloprotein composed of globin and hemes and is responsible for the color of red meat. Metmyoglobin is formed by oxidation of deoxymyoglobin or oxymyoglobin (Mancini and Hunt 2005). Several studies have indicated that the radicals formed in plasma may lead to oxidation of myoglobin to metmyoglobin, which results in higher *b* values on the Hunter Lab-system and browning (Fröhling 2012). The generated metmyoglobin can also initiate lipid oxidation in muscle and muscle-based foods (Baron and Andersen, 2002). On the other hand, the metmyoglobin contents of FTDBD plasma-treated beef jerky and low pressure plasma-treated raw pork were not changed significantly (Ulbin-Figlewicz et al. 2015; Yong et al. 2016). Therefore, the effects of various plasma sources on the chemical state of myoglobin in meat products should be investigated further.

Moisture content

Moisture content plays an important role in the quality, taste, and safety of meat and poultry (Yalçın and Şeker 2016). Bae et al. (2015) reported that after exposure to APPJ for 0.5–20 min, the moisture content of fresh beef loin, pork shoulder, and chicken breast were significantly decreased in a time-dependent way. Because of the high correlation coefficient ($r = +0.80$, $p < 0.01$) between color lightness (L^*) on the CIELAB Color Space and moisture content (Sanabria et al. 2004), the evaporation of small amounts of moisture may contribute to CAP-induced decrease of L^* value (Bae et al. 2015; Kim et al. 2011). In addition, the moisture loss may also cause decreases in meat succulence, which is one of important factors in meat palatability (Carvalho et al. 2015).

Volatile basic nitrogen

Volatile basic nitrogen (VBN) is a good index for evaluating the freshness of meat. Increasing amounts of VBN are the result of decomposition of protein during storage by microorganisms (Cai et al. 2011; Huang et al. 2014). According to Lee et al. (2012), the VBN values of cooked egg white and yolk were significantly increased after APPJ treatment. However, there were no significant changes in VBN values of unfrozen or frozen pork after corona discharge plasma treatment ($p > 0.05$), and the CAP-treated pork was considered fresh because its VBN contents were less than 15 mg/100 g (Choi et al. 2016).

Texture profile

Tenderness is one of the most important factors impacting meat quality and is also a major factor affecting the consumers' assessment of meat quality. After exposure to FTDBD-plasma for 0–10 min, the texture parameters of pork butt and beef loin samples (including hardness, springiness, cohesiveness, gumminess, and chewiness) were not changed significantly (Jayasena et al. 2015). Similar results were obtained for chicken breasts by using FTDBD plasma, except that cohesiveness was significantly increased with plasma exposure time (Lee et al. 2016). Thus, CAP may serve as a non-destructive preservation technique in terms of meat texture.

Influences of CAP on the sensory attributes of meat products

Sensory attributes of meat and meat products, such as appearance, texture, color, odor, flavor, and taste, significantly affect the consumer acceptance and decision-making process (Font-i-Furnols and Guerrero 2014). Therefore, the effects of CAP on sensory properties of meat have been widely investigated.

Surface-color values

As one of the most important quality characteristics of meat products, meat color significantly influences consumers' purchasing decisions, because consumers commonly use meat color as an indicator of meat freshness and quality (Mancini and Hunt 2005).

*L**-values

The lightness (L^*-value) of bacon (Kim et al. 2011) and pork loins (Kim et al. 2013a) were decreased after DBD plasma treatment. After the DBD plasma treatment with He or He + O_2, the L^*-values of pork loins were also

decreased when they were stored for 0 d, 3 d, and 7 d, respectively (Kim et al. 2013a). By contrast, the L^*-values of FTDBD plasma-treated pork butt and beef loin were not significantly different from those of the untreated samples (Jayasena et al. 2015). This nonconformity may be due to the types of carrier gases used (Jayasena et al. 2015; Kim et al. 2013a). The evaporation of a small amount of moisture induced by plasma treatment may also result in decreases of L^* value (Bae et al. 2015; Kim et al. 2011).

*a** and *b** values

CAP treatment also affects the redness (a^*-value) and yellowness (b^*-value) of meat products. After DBD plasma treatment, a^* values of pork and beef samples were significantly decreased with lengthening exposure time (Jayasena et al. 2015). The a^* values of plasma-treated bresaola (Rød et al. 2012), porcine *longissimus dorsi* muscle samples (Fröhling 2012), and pork loins (Kim et al. 2013a) were also significantly decreased with increasing storage time. In contrast, the a^*-value of bacon was increased at a higher input power and exposure time (Kim et al. 2011).

After the FTDBD plasma treatment for 2.5–10 min, the b^* value of beef loin was increased significantly ($p < 0.05$). By contrast, the b^* value of plasma-treated pork samples was not significantly different from those of the untreated samples (Jayasena et al. 2015). Similarly, the b^* value of DBD plasma-treated pork loins were not different from those of the untreated samples (Kim et al. 2013a). The contradictory result may be attributed to the various types of plasma sources used and the different physicochemical qualities of meat samples.

The changes of a^* and b^* values may be the results of a series of complex chemical reactions between plasma-produced reactive species and constituents of meat products. For example, the hydrogen peroxide generated in plasma can react with myoglobin and result in greener color on meat products (Jayasena et al. 2015). Furthermore, a high concentration of metmyoglobin in the meat can be formed by the oxidation of myoglobin or oxymyoglobin (Mancini and Hunt 2005), causing higher b^* values in meat samples (Fröhling 2012).

Sensory quality

The sensory characteristics of plasma-treated meat products were evaluated by trained panelists for appearance, color, taste, texture, flavor, off-flavor, and overall acceptability (Jayasena et al. 2015; Lee et al. 2016). Kim et al. (2013a) observed that DBD treatment caused significant reduction of sensory parameters (including appearance, color, odor, and acceptability) of raw pork loins ($p < 0.05$). However, though the sensory parameters (including appearance, color, flavor, odor, texture, and acceptability) of DBD plasma-treated cooked pork loins were lower than that of the untreated samples, the differences were not statistically significant (Kim et al. 2013a). As reported by Jayasena et al. (2015), the appearance, color, off-flavor, and overall acceptability of pork butt and beef loin samples were not affected by FTDBD plasma treatment, while the palatability of the meat products decreased significantly after FTDBD plasma treatment for 10 min (Jayasena et al. 2015). Lee et al. (2016) also observed that FTDBD plasma treatment did not affect most sensory parameters (appearance, color, taste, and acceptability) of cooked chicken breasts, but the flavor score of plasma-treated chicken breasts was slightly lower and the off-flavor score was higher ($p < 0.05$) (Lee et al. 2016).

Plasma-mediated lipid and protein oxidation may contribute to the sensory deterioration. Secondary oxidation products, such as alkanes, alkenes, aldehydes, and ketones, were produced during CAP treatments (Kim et al. 2013a). Several of these oxidation byproducts have unpleasant aromas, such as fishy, metallic, oxidized, and rancid and affect the sensory attributes of meat products (Ladikos and Lougovois 1990). Though the plasma-induced sensory deterioration in meat is minor, further investigations are still needed to elucidate the deterioration mechanisms and improve the sensory properties of plasma-treated fresh meat and meat products.

Safety assessment of CAP-treated meat products

Before the industrial application of CAP in food production, the scientific information and the safety assessment of CAP and CAP-treated foods should be fully established. Recent studies have investigated the mutagenic risks or genetic toxicology of plasma (Boehm et al. 2016; Boxhammer et al. 2013; Han et al. 2016a, b; Kluge et al. 2016; Lee et al. 2012; Wende et al. 2016) and cold plasma-treated meat products (Kim et al. 2016; Lee et al. 2016). Boxhammer et al. (2013) found that plasma treatment inhibited proliferation of V79 cells, but did not induce mutations at the *Hprt* locus in V79 cells. In accordance with Boxhammer et al. (2013), argon plasma has no genotoxic or mutagenic effects on human cells in vitro (Wende et al. 2016). So CAP and cold plasma bio-fluids may be considered to pose no mutagenic risks (Boehm et al. 2016; Boxhammer et al. 2013; Han et al. 2016a, b; Kluge et al. 2016; Lee et al. 2016; Wende et al. 2016). However, whether plasma treatment can result in the formation of potential toxic substances by chemical transformations of food components is still not clear. Recently, it has been reported that the ethanolic extracts of FTDBD plasma-treated chicken breast posed no mutagenic risk at doses of

up to 5000 μg/plate and there was no statistically significant difference between plasma-treated and untreated chicken breast samples (Lee et al. 2016). Furthermore, Kim et al. (2016) mentioned that the addition of plasma-treated water (PTW) had no effect on the mutagenicity of emulsion-type sausage. According to the results of serum TNF-α levels and Peyer's patches of female Balb/c mice administered with a normal diet containing emulsion sausage cured with PTW for 32 d, PTW-cured sausages also did not show immune toxicity (Kim et al. 2016).

It should be noted that each of the in vitro safety tests used in the above studies has its own limitations and disadvantages (Boehm et al. 2016; Boxhammer et al. 2013; Han et al. 2016a, b; Kluge et al. 2016; Kluge et al. 2016; Kim et al. 2016; Lee et al. 2016). For example, *S. typhimurium* is a prokaryote and consequently not a ideal model for the human body (Claxton et al. 2010). For in vitro mammalian cell genotoxicity tests, the cell function, metabolism, genetic makeup, and expression of intracellular proteins are altered in immortalized cell lines, which may provide different results from in vivo studies or false-positive results (Johnson et al. 2009). Summarily, the investigations on the potential toxic effects of CAP treatments and CAP -treated foods are relatively limited and more work is still needed in order to ensure safety of foods.

Conclusion

Recent studies have indicated that CAP can effectively kill pathogenic microorganisms in meat and related products, but also result in changes in physicochemical qualities and sensory attributes, which may influence consumers' acceptability of meat based foods. As a result, the process conditions of CAP treatments (such as generation methods, gas compositions, methods of product exposure, etc.) should be optimized in order to retain the maximum eating quality of meat products and reduce the operating costs. Secondly, the CAP equipment used in present work is mainly lab scale, the scaling up of CAP equipment from laboratory scale to commercial scale is needed for real applications in meat processing plants. Meanwhile, the innovative combination of the CAP technique with traditional food-processing methods is necessary. Finally, as a novel and emerging technology, the regulatory review approval of CAP as a food manufacturing tool is one important challenge for its widespread application in food industry. For this reason, a lot of work is also required, including the safety assessment of CAP and CAP-treated foods, the establishment of regulatory standards, and so on. During these processes, particular attention should be paid to consumer acceptance and attitudes toward CAP technology and CAP-treated foods.

In summary, CAP is a promising and effective alternative to conventional thermal processing for controlling microbial contamination of meat products. However, there are several critical issues yet to be addressed before the industrial application of CAP in meat preservation and processing.

Acknowledgements The work is financially supported by the National Key R&D Program of China (Grant No. 2016YFD0400403), the National Natural Science Foundation of China (No. 31501491), and Doctoral Scientific Research Foundation of Zhengzhou University of Light Industry (No. 2013BSJJ079).

References

Afshari R, Hosseini H (2012) Atmospheric pressure plasma technology: a new tool for food preservation. Int Conf Environ Energy Biotechnol 33:275–278

Arroyo C, Eslami S, Brunton NP, Arimi JM, Noci F, Lyng JG (2015) An assessment of the impact of pulsed electric fields processing factors on oxidation, color, texture, and sensory attributes of turkey breast meat. Poult Sci 94:1088–1095

Bae SC, Park SY, Choe W, Ha SD (2015) Inactivation of murine norovirus-1 and hepatitis A virus on fresh meats by atmospheric pressure plasma jets. Food Res Int 76:342–347

Bahrami N, Bayliss D, Chope G, Penson S, Perehinec T, Fisk ID (2016) Cold plasma: a new technology to modify wheat flour functionality. Food Chem 202:247–253

Baier M, Görgen M, Ehlbeck J, Knorr D, Herppich WB, Schlüter O (2014) Non-thermal atmospheric pressure plasma: screening for gentle process conditions and antibacterial efficiency on perishable fresh produce. Innov Food Sci Emerg Technol 22:147–157

Baron CP, Andersen HJ (2002) Myoglobin-induced lipid oxidation. A review. J Agric Food Chem 50:3887–3897

Boehm D, Heslin C, Cullen PJ, Bourke P (2016) Cytotoxic and mutagenic potential of solutions exposed to cold atmospheric plasma. Sci Rep 6:21464

Boxhammer V, Li YF, Köritzer J, Shimizu T, Maisch T, Thomas HM, Schlegel J, Morfill GE, Zimmermann JL (2013) Investigation of the mutagenic potential of cold atmospheric plasma at bactericidal dosages. Mutat Res 753:23–28

Cai JR, Chen QS, Wan XM, Zhao JW (2011) Determination of total volatile basic nitrogen (TVB-N) content and Warner–Bratzler shear force (WBSF) in pork using Fourier transform near infrared (FT-NIR) spectroscopy. Food Chem 126:1354–1360

Campus M (2010) High pressure processing of meat, meat products and seafood. Food Eng Rev 2:256–273

Carvalho VB, Leite RF, Almeida MTC, Paschoaloto JR, Carvalho EB, Lanna DPD, Perez HL, Van Cleef EHCB, Homem Junior AC, Ezequiel JMB (2015) Carcass characteristics and meat quality of lambs fed high concentrations of crude glycerin in low-starch diets. Meat Sci 110:285–292

Cheng JH (2016) Lipid oxidation in meat. J Nutr Food Sci 6:1–3

Choi S, Puligundla P, Mok C (2016) Corona discharge plasma jet for inactivation of *Escherichia coli* O157:H7 and *Listeria monocytogenes* on inoculated pork and its impact on meat quality attributes. Ann Microbiol 66:685–694

Claxton LD, Umbuzeiro Gde A, DeMarini DM (2010) The Salmonella mutagenicity assay: the stethoscope of genetic toxicology for the 21st century. Environ Health Perspect 118:1515–1522

Conrads H, Schmidt M (2000) Plasma generation and plasma sources. Plasma Sources Sci Technol 9:441–454

Cooper M, Fridman G, Fridman A, Joshi SG (2010) Biological responses of *Bacillus stratosphericus* to floating electrode-dielectric barrier discharge plasma treatment. J Appl Microbiol 109:2039–2048

Crookes W, (ed) (1879). Radiant matter: a resume of the principal lectures and papers of Prof. William Crookes on the 'fourth state of matter', Electric Spacecraft, USA

Dave D, Ghaly AE (2011) Meat spoilage mechanisms and preservation techniques: a critical review. Am J Agric Biol Sci 6:486–510

Dirks BP, Dobrynin D, Fridman G, Mukhin Y, Fridman A, Quinlan JJ (2012) Treatment of raw poultry with nonthermal dielectric barrier discharge plasma to reduce *Campylobacter jejuni* and *Salmonella enterica*. J Food Prot 75:22–28

Font-i-Furnols M, Guerrero L (2014) Consumer preference, behavior and perception about meat and meat products: an overview. Meat Sci 98:361–371

Fridman G, Friedman G, Gutsol A, Shekhter AB, Vasilets VN, Fridman A (2008) Applied plasma medicine. Plasma Process Polym 5:503–533

Fröhling A (2012) Indirect plasma treatment of fresh pork: decontamination efficiency and effects on quality attributes. Innov Food Sci Emerg Technol 16:381–390

Giaouris E, Heir E, Hébraud M, Chorianopoulos N, Langsrud S, Møretrø T, Habimana O, Desvaux M, Renier S, Nychas GJ (2013) Attachment and biofilm formation by foodborne bacteria in meat processing environments: causes, implications, role of bacterial interactions and control by alternative novel methods. Meat Sci 97:298–309

Han L, Ziuzina D, Heslin C, Boehm D, Patange A, Sango DM, Valdramidis VP, Cullen PJ, Bourke P (2016a) Controlling microbial safety challenges of meat using high voltage atmospheric cold plasma. Front Microbiol 7:977

Han SH, Suh HJ, Hong KB, Kim SY, Min SC (2016b) Oral toxicity of cold plasma-treated edible films for food coating. J Food Sci 81:T3052–T3057

Hoffmann C, Berganza C, Zhang J (2013) Cold atmospheric plasma: methods of production and application in dentistry and oncology. Med Gas Res 3:21

Hosseini AH, Sharifan A, Yousefi HR (2016) Study on effects of atmospheric cold plasma treatments on inactivation of *Escherichia coli* inoculated on beef. Int J Food Nutr Saf 7:162–169

Huang H, Tang L (2007) Treatment of organic waste using thermal plasma pyrolysis technology. Energy Convers Manag 48:1331–1337

Huang L, Zhao JW, Chen QS, Zhang YH (2014) Nondestructive measurement of total volatile basic nitrogen (TVB-N) in pork meat by integrating near infrared spectroscopy, computer vision and electronic nose techniques. Food Chem 145:228–236

Iulietto MF, Sechi P, Borgogni E, Cenci-Goga BT (2015) Meat spoilage: a critical review of a neglected alteration due to ropy slime producing bacteria. Ital J Anim Sci 14:316–326

Jayasena DD, Kim HJ, Yong HI, Park S, Kim K, Choe W, Jo C (2015) Flexible thin-layer dielectric barrier discharge plasma treatment of pork butt and beef loin: effects on pathogen inactivation and meat-quality attributes. Food Microbiol 46:51–57

Joaquin JC, Kwan C, Abramzon N, Vandervoort K, Brelles-Mariño G (2009) Is gas-discharge plasma a new solution to the old problem of biofilm inactivation? Microbiology 155:724–732

Johnson MD, Schilz J, Djordjevic MV, Rice JR, Shields PG (2009) Evaluation of in vitro assays for assessing the toxicity of cigarette smoke and smokeless tobacco. Cancer Epidemiol Biomarkers Prev 18:3263–3304

Khelifa F, Ershov S, Habibi Y, Snyders R, Dubois P (2016) Free radical-induced grafting from plasma polymer surfaces. Chem Rev 16:3975–4005

Kim B, Yun H, Jung S, Jung Y, Jung H, Choe W, Jo C (2011) Effect of atmospheric pressure plasma on inactivation of pathogens inoculated onto bacon using two different gas compositions. Food Microbiol 28:9–13

Kim HJ, Yong HI, Park S, Choe W, Jo C (2013a) Effects of dielectric barrier discharge plasma on pathogen inactivation and the physicochemical and sensory characteristics of pork loin. Curr Appl Phys 13:1420–1425

Kim HJ, Yong HI, Park S, Kim K, Bae YS, Choe W, Oh MH, Jo C (2013b) Effect of inactivating Salmonella Typhimurium in raw chicken breast and pork loin using an atmospheric pressure plasma jet. J Anim Sci Technol 55:545–549

Kim HJ, Sung NY, Yong HI, Kim H, Lim Y, Ko KH, Yun CH, Jo C (2016) Mutagenicity and immune toxicity of emulsion-type sausage cured with plasma-treated water. Korean J Food Sci Anim Resour 36:494–498

Kluge S, Bekeschus S, Bender C, Benkhai H, Sckell A, Below H, Stope MB, Kramer A (2016) Investigating the mutagenicity of a cold argon-plasma jet in an HET-MN Model. PLoS ONE 11:e0160667

Korachi M, Gurol C, Aslan N (2010) Atmospheric plasma discharge sterilization effects on whole cell fatty acid profiles of *Escherichia coli* and *Staphylococcus aureus*. Journal of Electrostat 68:508–512

Ladikos D, Lougovois V (1990) Lipid oxidation in muscle foods: a review. Food Chem 5:295–314

Langmuir I (1928) Oscillations in ionized gases. Proc Natl Acad Sci 14:627–637

Lee HJ, Jung H, Choe W, Ham JS, Lee JH, Jo C (2011) Inactivation of *Listeria monocytogenes* on agar and processed meat surfaces by atmospheric pressure plasma jets. Food Microbiol 28:1468–1471

Lee HJ, Song HP, Jung HS, Choe WH, Ham JS, Lee JH, Jo C (2012) Effect of atmospheric pressure plasma jet on inactivation of *Listeria monocytogenes*, quality, and genotoxicity of cooked egg white and yolk. Korean J Food Sci An 32:561–570

Lee H, Yong HI, Kim HJ, Choe W, Suk JY, Jang EJ, Jo C (2016) Evaluation of the microbiological safety, quality changes, and genotoxicity of chicken breast treated with flexible thin-layer dielectric barrier discharge plasma. Food Sci Biotechnol 25:1189–1195

Liao XY, Liu DH, Xiang QS, Ahn J, Chen SG, Ye XQ, Ding T (2017) Inactivation mechanisms of non-thermal plasma on microbes: a review. Food Control 75:83–91

Lunov O, Churpita O, Zablotskii V, Dejneka A (2015) Non-thermal plasma mills bacteria: scanning electron microscopy observations. Appl Phys Lett 106:053703

Mancini RA, Hunt MC (2005) Current research in meat color. Meat Sci 71:100–121

Marsili L, Espie S, Anderson JG, MacGregor SJ (2002) Plasma inactivation of food-related microorganisms in liquids. Radiat Phys Chem 65:507–513

Mir SA, Shah MA, Mir MM (2016) Understanding the role of plasma technology in food industry. Food Bioprocess Technol 9:734–750

Misra NN, Pankaj SK, Segat A, Ishikawa K (2016) Cold plasma interactions with enzymes in foods and model systems. Trends Food Sci Technol 55:39–47

Mor-Mur M, Yuste J (2010) Emerging bacterial pathogens in meat and poultry: an overview. Food Bioprocess Technol 3:24–35

Niemira BA (2012) Cold plasma decontamination of foods. Annu Rev Food Sci Technol 3:125–142

Niemira BA, Sites J (2008) Cold plasma inactivates *Salmonella Stanley* and *Escherichia coli* O157: H7 inoculated on golden delicious apples. J Food Prot 71:1357–1365

Noriega E, Shama G, Laca A, Díaz M, Kong MG (2011) Cold atmospheric gas plasma disinfection of chicken meat and chicken skin contaminated with *Listeria innocua*. Food Microbiol 28:1293–1300

Nychas GJE, Skandamis PN, Tassou CC, Koutsoumanis KP (2008) Meat spoilage during distribution. Meat Sci 78:77–89

Painter JA, Hoekstra RM, Ayers T, Tauxe RV, Braden CR, Angulo FJ, Griffin PM (2013) Attribution of foodborne illnesses, hospitalizations, and deaths to food commodities by using outbreak data, United States, 1998–2008. Emerg Infect Dis 19:407–415

Pankaj SK, Bueno-Ferrer C, Misra NN, Milosavljević V, O'Donnellb CP, Bourke P, Keenera KM, Cullena PJ (2014) Applications of cold plasma technology in food packaging. Trends Food Sci Technol 35:5–17

Patil S, Moiseev T, Misra NN, Cullen PJ, Mosnier JP, Keener KM, Bourke P (2014) Influence of high voltage atmospheric cold plasma process parameters and role of relative humidity on inactivation of *Bacillus atrophaeus* spores inside a sealed package. J Hosp Infect 88:162–169

Ragni L, Berardinelli A, Vannini L, Montanari C, Sirri F, Guerzoni ME, Guarnieri A (2010) Non-thermal atmospheric gas plasma device for surface decontamination of shell eggs. J Food Eng 100:125–132

Ramamurthy T, Ghosh A, Pazhani GP, Shinoda S (2014) Current perspectives on viable but non-culturable (VBNC) pathogenic bacteria. Front Public Health 2:103

Rehman MU, Jawaid P, Uchiyama H, Kondo T (2016) Comparison of free radicals formation induced by cold atmospheric plasma, ultrasound, and ionizing radiation. Arch Biochem Biophys 605:19–25

Rød SK, Hansen F, Leipold F, Knøchel S (2012) Cold atmospheric pressure plasma treatment of ready-to-eat meat: inactivation of *Listeria innocua* and changes in product quality. Food Microbiol 30:233–238

Sanabria C, Martín-Álvarea PJ, Carrascosa AV (2004) Colour and moisture changes during the manufacture of Iberian dry-cured ham caused by some biotics and abiotic factors. Food Sci Technol Int 10:269–275

Schnabel U, Niquet R, Krohmann U, Winter J, Schlüter O, Weltmann K-D, Ehlbeck J (2012) Decontamination of microbiologically contaminated specimen by direct and indirect plasma treatment. Plasma Process Polym 9:569–575

Shintani H, Sakudo A, Burke P, McDonnell G (2010) Gas plasma sterilization of microorganisms and mechanisms of action. Exp Ther Med 1:731–738

Singh PK, Verma AK, Ranjan R, Singh TP, Kumar D, Kumar P (2015) Non thermal preservation of meat by irradiation: a review. J Food Res Technol 3:7–13

Smet C, Noriega E, Rosier F, Walsh JL, Valdramidis VP, Van Impe JF (2017) Impact of food model (micro) structure on the microbial inactivation efficacy of cold atmospheric plasma. Int J Food Microbiol 240:47–56

Song HP, Kim B, Choe JH, Jung S, Moon SY, Choe W, Jo C (2009) Evaluation of atmospheric pressure plasma to improve the safety of sliced cheese and ham inoculated by 3-strain cocktail *Listeria monocytogenes*. Food Microbiol 26:432–436

Stoffels E, Sakiyama Y, Graves DB (2008) Cold atmospheric plasma: charged species and their interactions with cells and tissues. IEEE Trans Plasma Sci 36:1441–1457

Takamatsu T, Uehara K, Sasaki Y, Hidekazu M, Matsumura Y, Iwasawa A, Ito N, Kohno M, Azuma T, Okino A (2015) Microbial inactivation in the liquid phase induced by multigas plasma jet. PLoS ONE 10:e0132381

Tani A, OnoY Fukui S, Ikawa S, Kitano K (2012) Free radicals induced in aqueous solution by non-contact atmospheric-pressure cold plasma. Appl Phys Lett 100:254103

Thirumdas R, Sarangapani C, Annapure US (2015) Cold plasma: a novel non-thermal technology for food processing. Food Biophys 10:1–11

Ulbin-Figlewicz N, Brychcy E, Jarmoluk A (2015) Effect of low-pressure cold plasma on surface microflora of meat and quality attributes. J Food Sci Technol 52:1228–1232

Wende K, Bekeschus S, Schmidt A, Jatsch L, Hasse S, Weltmann KD, Masur K, von Woedtke T (2016) Risk assessment of a cold argon plasma jet in respect to its mutagenicity. Mutat Res Genet Toxicol Environ Mutagen 798–799:48–54

Yalçın MY, Şeker M (2016) Effect of salt and moisture content reduction on physical and microbiological properties of salted, pressed and freeze dried turkey meat. LWT-Food Sci Technol 68:153–159

Yong HI, Kim HJ, Park S, Choe W, Oh MW, Jo C (2014) Evaluation of the treatment of both sides of raw chicken breasts with an atmospheric pressure plasma jet for the inactivation of *Escherichia coli*. Foodborne Pathog Dis 11:652–657

Yong HI, Lee H, Park S, Park J, Choe W, Jung S, Jo C (2016) Flexible thin-layer plasma inactivation of bacteria and mold survival in beef jerky packaging and its effects on the meat's physicochemical properties. Meat Sci 123:151–156

Ziuzina D, Patil S, Cullen PJ, Boehm D, Bourke P (2014) Dielectric barrier discharge atmospheric cold plasma for inactivation of *Pseudomonas aeruginosa* biofilms. Plasma Med 4:137–152

Ziuzina D, Boehm D, Patil S, Cullen PJ, Bourke P (2015) Cold plasma inactivation of bacterial biofilms and reduction of quorum sensing regulated virulence gactors. PLoS ONE 10:e0138209