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REVIEW

Use of Atmospheric Pressure Cold Plasma for Meat Industry

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Abstract

Novel, effective methods to control and prevent spoilage and contamination by pathogenic microorganisms in meat and meat products are in constant demand. Non-thermal pasteurization is an ideal method for the preservation of meat and meat products because it does not use heat during the pasteurization process. Atmospheric pressure cold plasma (APCP) is a new technology for the non-thermal pasteurization of meat and meat products. Several recent studies have shown that APCP treatment reduces the number of pathogenic microorganisms in meat and meat products. Furthermore, APCP treatment can be used to generate nitrite, which is an essential component of the curing process. Here, we introduce the effectiveness of APCP treatment as a pasteurization method and/or curing process for use in the meat and meat product processing industry.

Keywords atmospheric pressure cold plasma, meat, meat products, pasteurization, nitrite

Introduction

Food is not only an essential source of nourishment but also a source of pleasure, especially when it comes to meat. Meat contains several essential nutrients, including proteins, lipids, vitamins, and minerals (Biesalski, 2005). Several factors can influence meat quality during processing and storage and controlling these factors is important in the meat industry in order to ensure optimal quality and consumer satisfaction. Of the many quality properties of meat, those related to safety, particularly to pathogenic microorganism contamination, are of utmost concern. The high moisture content and abundance of nutrients found in meat results in favorable growth conditions for microorganisms (Alahakoon *et al.*, 2015; Biesalski, 2005; Jayasena *et al.*, 2015). While heat pasteurization is an effective way to kill these microorganisms in fresh meat, the high temperature results in undesirable changes in the meat's quality, including changes in its appearance, texture, and nutritional content (Awuah *et al.*, 2007; Deng *et al.*, 2007). Therefore, various technologies have been developed for pasteurization for raw meats. Irradiation is one common non-thermal pasteurization method. It uses a linear accelerator for electron beam irradiation and cobalt 60 for gamma irradiation (Ahn *et al.*, 2016)

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and has outstanding efficacy (Kim *et al*., 2015). However, the construction and operation of irradiation facilities is costly, and it has been reported that irradiation can generate an off-flavor in the meat (Brewer, 2009). High pressure processing (HPP) technology is another effective non-thermal pasteurization method (Zhang and Mittal, 2008), but, HPP causes discoloration in fresh red meat and can alter its physiochemical, morphological, structural, and textural characteristics (Cheftel, 1995; Kim *et al*., 2007).

Plasma, especially cold plasma, is a relatively new method of non-thermal pasteurization under investigation for use in the food industry. Plasma is a form of ionized gas that is generated by applying an electric current to a neutral gas (Conrads and Schmidt, 2000). Plasma contains reactive oxygen species (ROS) and reactive nitrogen species (RNS) that cause oxidative damage to the outer membranes and DNA of microorganisms resulting in cell death (Afshari and Hosseini, 2014). Based on the properties of ROS and RNS in plasma, the microbicidal effects of plasma treatment in meat and meat products have been widely studied and reviewed (Mir *et al*., 2016; Misra and Jo, 2017). Recently, plasma has been shown to have the potential to be a source of nitrite, which is an important additive in the production of cured meat products (Jung *et al*., 2015b). In this review, we explore the potential applications of plasma for use in the meat and meat product processing industry as a non-thermal pasteurization method. Furthermore, the roles of plasma treatment as a curing for meat products are reviewed.

Atmospheric Pressure Cold Plasma

Plasma, which has been described as the fourth state of matter, is partially or fully ionized gas composed of positive and negative ions, electrons, free radicals, and neutral particles (Nehra *et al*., 2008). It is generated by applying an electric current across neutral gases, which results in the dissociation of the gaseous molecules (Conrads and Schmidt, 2000; Nehra *et al*., 2008). Plasma can be divided into two types based on temperature: high temperature plasma and low temperature plasma. High temperature plasma exists in a thermal equilibrium state in the range of 10^6 to 10^8 K (Fig. 1; Nehra *et al*., 2008). Low temperature plasma can be further divided into thermal or non-thermal plasma. Thermal plasma exists in a local thermal equilibrium state with temperatures ranging from 4000 to 20,000 K (Bogaerts *et al*., 2002; Schluter *et al*., 2013). Non-thermal plasma, also known as cold plasma, exists in a non-equilibrium state with a temperature range of 300 to 1000 K (Nehra *et al.,* 2008). High temperature and thermal plasmas are not suitable for use on heat sensitive foods because the heat transfer from the plasma to the food causes deterioration in the food's quality. Therefore, non-thermal plasma methods of pasteurization are of considerable interest to the meat industry.

Plasma can be generated over a wide range of pressures depending on the plasma source. In early studies, plasma was generated at low pressures (Napartovich, 2001). However, a vacuum system was required for plasma generation, and consequently, the applicability of low pressure discharge plasma is limited. For this reason, various other plasma sources, including dielectric barrier discharge (DBD), corona discharge, and atmospheric plasma jet, have been developed for plasma generation at atmospheric pressure (Nehra *et al*., 2008). DBD plasma generators are comprised of two electrodes; a high voltage electrode and a ground electrode. The gas in the gap between these electrodes undergoes electrical breakdown when a high-voltage electric current is applied (Kogelschatz, 2003).

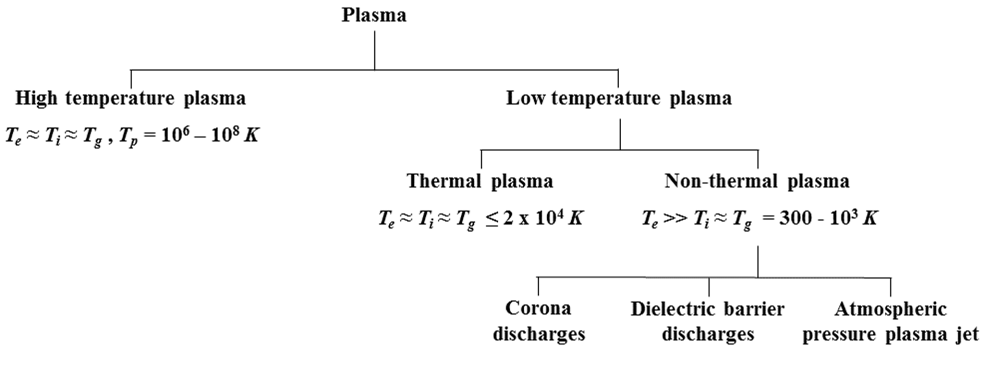

Fig. 1. Plasma classification (Nehra *et al*., 2008).

Furthermore, DBD plasma can easily be produced at scale in laboratory or industry (Kogelschatz, 2003).

Atmospheric pressure cold plasma (APCP) is the plasma generated at atmospheric pressure and its temperature is around 30-60°C (Misra *et al*., 2011). It can be produced with various plasma sources such as DBD, corona discharges, and atmospheric plasma jet, with various discharge gas such as nitrogen, oxygen, helium, and argon as well as ambient air (Nehra *et al*., 2008). Recently, APCP generated using a DBD system is of particular interest to the meat industry.

Application of Atmospheric Pressure Cold Plasma in the Meat Industry

Pasteurization of meat and meat products

Meat provides a favorable environment for the growth of pathogenic and spoilage microorganisms because of its high moisture content and abundance of nutrients (Alahakoon *et al*., 2015; Biesalski, 2005). Therefore, the elimination of pathogenic microorganisms from meat and meat products is important for consumer safety. Furthermore, increasing shelf life via the elimination of spoilage microorganisms in meat and meat products is important for food security and the economic viability of the meat industry. Non-thermal pasteurization is regarded as an ideal pasteurization method for meat and meat products because chemical pasteurization methods with chlorine, organic acids, peroxyacetic acid, and phosphate can leave behind harmful substances or deteriorate meat quality and thermal pasteurization results in a deterioration of meat quality (Chen *et al*., 2011).

Many previous studies have examined the applicability of APCP treatment as a technique for the non-thermal pasteurization of foods. ROS and RNS are produced via the dissociation of gaseous molecules during the plasma generation (Conrads and Schmidt, 2000; Han *et al*., 2016). ROS, including singlet oxygen, hydroxyl radical, superoxide anion, hydrogen peroxide, and ozone, in plasma have microbicidal properties, with ozone of particular importance because of its relatively long life time (Han *et al*., 2016; Laroussi and Leipold, 2004; Ziuzina *et al*., 2014). The ROS in APCP act via different microbicidal mechanisms on Gram-positive and Gram-negative bacteria. Gram-positive bacteria have a thick cell wall composed of peptidoglycans. Exposure of *Listeria monocytogenes* and *Staphylococcus aureus* to APCP causes cell shrinkage but little damage to the cell wall (Cullen *et al*., 2014; Han *et al*., 2016). Furthermore, intracellular ROS levels have been shown to increase in *L. monocytogenes* and *S. aureus* with prolonged exposure to APCP (Han *et al*., 2016; Ziuzina *et al*., 2015). It has also been reported that the ROS generated by DBD plasma can penetrate the cell membrane and lead to cell apoptosis via intracellular DNA damage (Sensenig *et al*., 2011). Therefore, the microbicidal effects of APCP on Gram-positive bacteria appear to be mainly the result of oxidative damage to intracellular components, particularly DNA (Han *et al*., 2016). The cell walls of Gram-negative bacteria consist of an outer membrane of lipopolysaccharide and a thin layer of peptidoglycan. Following APCP treatment, visible morphological changes, including cell breakage, have been observed along with an increase in cell leakage in *Escherichia coli* (Han *et al*., 2016). Previous studies have found that ROS attack and destroy the cell walls of Gram-negative bacteria by cleaving the C-O, C-N, and C-C bonds of the peptidoglycans and oxidizing the lipids in the lipopolysaccharides (Dobrynin *et al*., 2009; Han *et al*., 2016; Yusupov *et al*., 2013). While an increase in intracellular ROS level was found in *E. coli* following APCP treatment, this increase was less than in *L. monocytogenes* and *S. aureus* (Han *et al*., 2016; Ziuzina *et al*., 2015). Furthermore, the extent of DNA damage was less in *E. coli* than *S. aureus* (Han *et al*., 2016). Therefore, Han *et al*. (2016) proposed that the microbicidal effects of APCP treatment in Gram-negative bacteria is mainly caused by the destruction of the cell wall via oxidative damage.

The microbicidal effects of APCP generated using DBD on various microorganisms in meat and meat products have also been investigated (Table 1). Previous studies have shown than the levels of *L. monocytogenes* in inoculated meat and meat products were reduced as much as 0.59 to 6.52 Log CFU/g after plasma treatment (Jayasena *et al.,* 2015; Kim *et al.,* 2011; Kim *et al*., 2013; Lee *et al*., 2011; Yong *et al.,* 2017a). Noriega *et al.* (2011) reported a 3.30 Log CFU/g reduction in *L. innocua* levels in inoculated chicken breast following plasma treatment. A 0.35 to 3.00 Log CFU/g reduction in *E. coli* and a 1.70 to 3.03 Log CFU/g reduction in *S.* Typhimurium levels in inoculated meat and meat products were also found after plasma treatment (Jayasena *et al.,* 2015; Kim *et al.,* 2011; Kim *et al*., 2013; Yong *et al.,* 2017a). Furthermore, a 2.54 Log CFU/g reduction in *S. enterica* and a 2.45 Log CFU/g reduction in *C. jejuni* levels in chicken breast were found following plasma treatment (Dirks *et al.,* 2012).

Several factors influence the microbicidal efficacy of

Table 1. Inactivation of microorganism in meat and meat products by atmospheric pressure cold plasma with dielectric barrier discharge

Microbes	Reduction rate (Log CFU/g) / Substrate	Discharge gas	Power / Frequency	Exposure time	Type / Distance	Reference
Gram-positive						
L. monocytogenes	6.52 / ham	Nitrogen / oxygen	2 kV / 50 kHz	2 min	Closed / -	Lee *et al*., 2011
L. monocytogenes	4.73 / chicken breast	Nitrogen / oxygen	2 kV / 50 kHz	2 min	Closed / -	Lee *et al*., 2011
L. monocytogenes	2.60 / bacon	Helium / oxygen	125 W	90 s	Open / 3 mm	Kim *et al*., 2011
L. monocytogenes	0.59 / pork loin	Helium / oxygen	3 kV / 30 kHz	10 min	Open / 3 mm	Kim *et al*., 2013
L. monocytogenes	2.04 / pork butt	Nitrogen / oxygen	100 W / 15 kHz	10 min	Closed / -	Jayasena *et al*., 2015
L. monocytogenes	1.90 / beef loin	Nitrogen / oxygen	100 W/15 kHz	10 min	Closed / -	Jayasena *et al*., 2015
L. monocytogenes	2.36 / beef jerky	Ambient air	15 kHz	10 min	Closed / -	Yong *et al*., 2017a
L. innocua	3.30 / chicken breast	Oxygen / helium	16 kV / 30 kHz	8 min	Open / 1 cm	Noriega *et al*., 2011
Gram-negative						
E. coli	3.00 / bacon	Helium / oxygen	125 W	90 s	Open / 3 mm	Kim *et al*., 2011
E. coli	0.35 / pork loin	Helium / oxygen	3 kV / 30 kHz	10 min	Open / 3 mm	Kim *et al*., 2013
E. coli	2.54 / pork butt	Nitrogen / oxygen	100 W / 15 kHz	10 min	Closed / -	Jayasena *et al*., 2015
E. coli	2.57 / beef loin	Nitrogen / oxygen	100 W / 15 kHz	10 min	Closed / -	Jayasena *et al*., 2015
E. coli	2.65 / beef jerky	Ambient air	15 kHz	10 min	Closed / -	Yong *et al*., 2017a
S. Typhimurium	1.7 / bacon	Helium / oxygen	125 W	90 s	Open / 3 mm	Kim *et al*., 2011
S. Typhimurium	2.68 / pork butt	Nitrogen / oxygen	100 W / 15 kHz	10 min	Closed / -	Jayasena *et al*., 2015
S. Typhimurium	2.28 / beef loin	Nitrogen / oxygen	100 W / 15 kHz	10 min	Closed / -	Jayasena *et al*., 2015
S. Typhimurium	3.03 / beef jerky	Ambient air	15 kHz	10 min	Closed / -	Yong *et al*., 2017a
S. enterica	2.54 / chicken breast	Ambient air	30 kV / 0.5 kHz	3 min	Open / 2 mm	Dirks *et al*., 2012
C. jejuni	2.45 / chicken breast	Ambient air	30 kV / 0.5 kHz	3 min	Open / 2 mm	Dirks *et al*., 2012

plasma treatment. APCP can be generated by DBD from nitrogen, oxygen, helium, and argon, as well as from ambient air. Of the ROS found in plasma, ozone is the major microbicidal species. Ozone concentrations in the gas phase discharge is related to the oxygen concentration of the discharge gas (Eliasson and Kogelschatz, 1991). Kovačević *et al*. (2017) showed that ozone is the dominant species produced in gas phase discharges composed of oxygen alone as compared to those with air, nitrogen, helium, or argon, and RNS are dominant in the gas phase discharges composed of air or nitrogen. Kim *et al*. (2011) found a large reduction in *L. monocytogenes*, *E. coli*, and *S.* Typhimurium levels in bacon when it was treated with plasma with a discharge gas consisting of helium and oxygen as compared to a discharge gas composed of helium alone. Furthermore, treatment with a mixture of nitrogen and oxygen was more effective in reducing the levels of *L. monocytogenes* in chicken breast than with nitrogen alone (Lee *et al*., 2011). Input power is another important factor in the microbicidal efficacy of plasma. Kim *et al*. (2011) found that the microbicidal effects of plasma treatment on *L. monocytogenes*, *E. coli*, and *S.* Typhimurium in inoculated bacon increased with an increase in input power from 75 to 125 W. Furthermore, Laroussi and Leipold (2004) found that an increase in the input power from 1.5 to 10 W increased the concentration of hydroxyl radicals and ozone in DBD plasma generated from atmospheric air.

Recently, the interest in *In-package* (closed) plasma treatment has increased. *In-package* plasma treatment is conducted using a flexible thin-layer electrode inside the sealed package and it has several benefits (Yong *et al*., 2017a). At first, subsequent contamination by microorganisms is prevented because the pasteurized food is transported in the sealed package to the consumer. Secondly, the long-lived reactive species, particularly ozone and hydrogen peroxide, generated in the sealed package pasteurize microorganisms continuously after plasma treatment (Yong *et al*., 2014).

Jayasena *et al*. (2015) reported 2.04, 2.54, and 2.68 Log CFU/g reductions in *L. monocytogenes*, *E. coli*, and *S.* Typhimurium levels, respectively, in inoculated pork shoulder after plasma treatment for 10 min in the package with a gas mixture of nitrogen and oxygen. Furthermore, *L. monocytogenes*, *E. coli*, and *S.* Typhimurium levels in beef jerky were reduced to as much as 2.36, 2.65, and 3.03 Log CFU/g, respectively, with *In package* plasma treatment for 10 min using ambient air (Yong *et al*., 2017a).

However, previous studies have also reported that an increase in the discharge gas humidity from water vapor decreases ozone production (Kovačević *et al.,* 2017; Ono and Oda, 2003). Kovačević *et al*. (2017) reported that plasma treatment heats the liquid, thereby increasing the humidity via the vaporization of water. Jung *et al.* (2017b) reported the temperature of meat batter increased from 0.2 to 10°C after plasma treatment for 30 min. Therefore, ozone production may be reduced when using *In-package* plasma treatment because the humidity in the package can be increased via the vaporization of moisture in samples.

Curing of meat products

Nitrite is a multifunctional curing additive used in the production of cured meat products. The addition of nitrite results in the development of a cured color and flavor (Parthasarathy and Bryan, 2012; Sebranek *et al*., 2012). Furthermore, it can prevent contamination by pathogenic microorganisms, including *Clostridium botulinum* (Jung *et al*., 2017b; Sebranek *et al*., 2012). Synthetic and natural nitrite sources, including sodium nitrite, potassium nitrite, and vegetable juice powder, are widely used in the meat product industry (Alahakoon *et al*., 2015; Parthasarathy and Bryan, 2012; Sebranek *et al*., 2012).

Several studies have shown that APCP treatment of liquids can result in the generation of nitrite (Ercan *et al*., 2016; Kojtari *et al*., 2013; Oehimigen *et al*., 2010). Plasma contains various RNS and nitrogen oxides, including NO_2, NO_3, N_2O, N_2O_3, and N_2O_5, which are relatively stable species (Sakiyama *et al*., 2012). Nitrogen oxides in the gas-phase discharges diffuse and dissolve in liquids after plasma treatment. The dissolved nitrogen oxides then form nitric and nitrous acids via reactions with water molecules, and subsequently decompose into nitrate and nitrite, respectively (1-4) (Lukes *et al*, 2014; Rayson *et al*., 2012; Thomas and Vanderschuren, 2000).

$$NO+NO_2+H_2O \rightarrow 2HNO_2 \leftrightarrow 2NO_2^- + 2H^+ \tag{1}$$

$$2NO_2+H_2O \rightarrow HNO_2+HNO_3 \leftrightarrow NO_2^- + NO_3^- + 2H^+ \tag{2}$$

$$N_2O_3+H_2O \rightarrow 2HNO_2 \leftrightarrow 2NO_2^- + 2H^+ \tag{3}$$

$$N_2O_4+H_2O \rightarrow HNO_2+HNO_3 \leftrightarrow NO_2^- + NO_3^- + 2H^+ \tag{4}$$

The nitrite concentration in plasma-treated liquids decreases with the increase in plasma treatment time (Ercan *et al*., 2016; Kojtari *et al*., 2013; Oehimigen *et al*., 2010). The generation of nitrite is also accompanied by the release of hydrogen ions which can decrease the pH of the liquid from 7 to 2 (Jung *et al*., 2015). Nitrite is unstable under acidic conditions and forms nitrous acid. It subsequently decomposes into nitrate and nitrogen oxide (5-7) (Rayson *et al*., 2012; Thomas and Vanderschuren, 2000).

$$HNO_2+H^+ \rightarrow H_2NO_2^+ \rightarrow NO^+ + H_2O \tag{5}$$

$$2HNO_2 \rightarrow NO+NO_2+H_2O \tag{6}$$

$$3HNO_2 \leftrightarrow H^+ + NO_3^- + 2NO+H_2O \tag{7}$$

However, under alkaline conditions the nitrite generated by plasma persists (Jung *et al*., 2015; Lukes *et al*., 2014). Furthermore, Jung *et al*. (2015) showed that plasma treated water can contain up to 782 mg L^{-1} of nitrite when distilled water containing sodium pyrophosphate is exposed to APCP for 120 min.

The nitrite content of products treated with APCP is shown in Table 2. Emulsion sausages cured using plasma treated water containing nitrite had similar properties in terms of color, lipid oxidation, and sensory characteristics as those cured with sodium nitrite (Jung *et al.,* 2015). Furthermore, Yong *et al*. (2017b) found that pork loin hams manufactured using brine injections consisting of plasma treated water or sodium nitrite had similar color, nitrosoheme pigment content, and lipid oxidation. However, the residual nitrite content of the emulsion sausage and pork loin ham cured with plasma treated water was lower than for those cured with sodium nitrite (Jung *et al*., 2015; Yong *et al*., 2017b). Natural nitrite sources are produced from vegetables containing nitrate which is subsequently converted into nitrite by nitrate reductase (Parthasarathy and Bryan, 2012). Therefore, vegetables that do not contain nitrate cannot be candidates of natural nitrite sources although it has high antioxidative and antimicrobial activities. However, natural nitrite has been derived from *Perilla frutescens,* which does not contain nitrate (Jung *et al*., 2017a). Jung *et al*. (2017a) found that the nitrite content of ethanolic extracts from *P. frutescens* increased following APCP treatment. Lyophilized *P. frutescens* powder extracts following APCP treatment contained nitrite at a concentration of 3.74 mg g^{-1}, and exhibited increased antimicrobial activity against *C. perfringens* and *S.* Typhimurium when compared with those without APCP treatment (Jung *et al*., 2017a).

The direct curing effects of APCP treatment are shown

Table 2. The development of new nitrite sources and the direct curing of meat products by atmospheric pressure cold plasma with dielectric barrier discharge

Substrate	Discharge gas	Power / Frequency	Exposure time	Nitrite content	Reference
Distilled water	Ambient air	200 W / 15 kHz	120 min	782 mg L^{-1}	Jung *et al*., 2015 Yong *et al*., 2017b
Red perilla extract	Ambient air	550 W / 25 kHz	60 min	3.74 g kg^{-1}	Jung *et al*., 2017a
Meat batter	Ambient air	550 W / 25 kHz	30 min	65.96 mg kg^{-1}	Jung *et al*., 2017b
Meat batter	Ambient air	600 W / 25 kHz	30 min	42 mg kg^{-1}	Lee *et al*., 2018

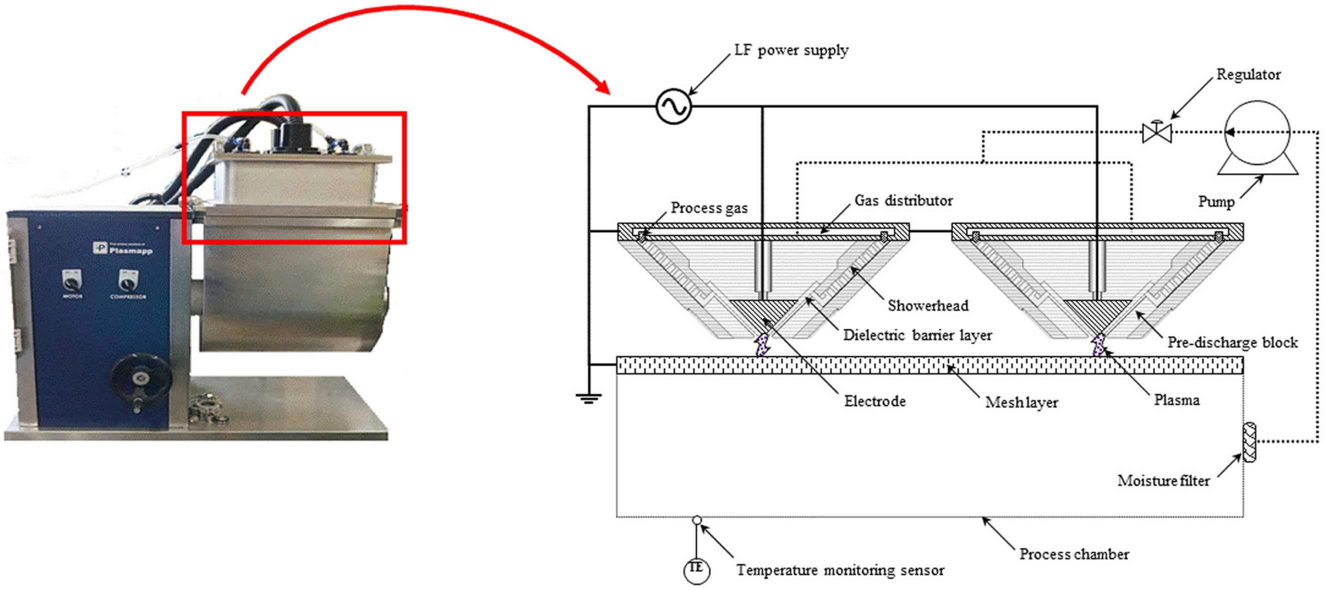

Fig. 2. Plasma curing system (Lee *et al*., 2018).

in Table 2. APCP treatment of meat batter resulted in the generation of nitrite (Jung *et al*., 2017b; Lee *et al*., 2018) and the meat batter was found to contain 65.96 mg kg^{-1} nitrite after APCP treatment for 30 min and it developed a cured color after cooking (Jung *et al*., 2017a). Lee *et al*. (2018) found 42 mg kg^{-1} nitrite in meat batter cured in the developed plasma curing mixer treated with APCP for 30 min while mixing (Fig 2). Furthermore, canned ground ham manufactured from meat batter treated with APCP for 30 min showed no difference in color, residual nitrite content, texture, or sensorial properties as compared to ground ham cured at same nitrite level of 42 mg kg^{-1} by addition of sodium nitrite or celery powder (Lee *et al*., 2018).

Considerations

The ROS found in plasma are important for the inhibition of microorganism growth. However, ROS, especially free radicals, can catalyze lipid and protein oxidation that can cause deterioration in the quality of meat and meat products (Armenteros *et al*. 2016; Lund *et al*., 2011). While some studies have found increased lipid oxidation in pork, beef, and bacon after APCP treatment (Jayasena *et al*., 2015; Kim *et al*., 2011), contrary findings have also been reported. Jung *et al*. (2017b) found no increase in lipid oxidation in meat batters after APCP treatment for 30 min. Furthermore, no differences in lipid and protein oxidation levels were found in ground hams cured by APCP treatment for 30 min, sodium nitrite, or celery powder at same nitrite level of 42 mg kg^{-1} (Lee *et al*., 2018). The temperature of APCP is similar to that of room temperature (Nehra *et al*., 2008). Jung *et al*. (2017b) reported an increase in the temperature of meat batter from 0.2 to 10°C during APCP treatment for 30 min, while Lee *et al*. (2018) found a temperature change from 1.0 to 8.9°C in meat batter under the same treatment conditions. Therefore, while APCP does raise the temperature of meat batter, this increase is small.

RNS in plasma generates nitrite in a treated substrate via reactions with water molecules (Jung *et al*., 2017b; Lee *et al*., 2018). Although Bauer *et al*. (2017) found that APCP treatment of beef loin did not increase nitrite levels, it is possible that APCP treatment of fresh meat forms nitrite, even though nitrite is usually only used for cured meat products. Previous studies have reported that the dominant reactive species in plasma are related to discharge gas composition. The dominant species are ROS in plasma generated with oxygen and RNS in plasma generated with air and nitrogen (Kovačević *et al*., 2017). Furthermore, an increase in input power results in an increase in RNS and a decrease in ozone concentrations (Bauer *et al*., 2017). Therefore, operating conditions must be taken into account depending on the objective of the APCP treatment.

Lee *et al*. (2016) reported no mutagenicity in chicken breast treated with APCP. Kim *et al*. (2016) found no mutagenicity in emulsion sausage cured by plasma treated water and no immune toxicity, based on tumor necrosis factor-α levels in mice fed emulsion sausage for 32 d. In addition, no mutagenicity in pork loin ham cured by plasma treated water has been reported (Yong *et al*., 2017b). However, there are limited data that fully confirm the safety of meat and meat products treated with APCP, therefore, further testing is necessary to satisfy consumers and the authorities.

Conclusion

APCP has been deemed to be an eco-friendly technology because it does not produce residues or toxic molecules. APCP treatment can effectively increase the shelf life and safety of meat and meat products via pasteurization of spoilage and pathogenic microorganisms without thermal damage. Furthermore, APCP is unique in that it can be used to produce nitrite and directly cure the meat products. It may seem obvious that the ROS, especially ozone, are important substances for the microbicidal effect of APCP treatment, and the RNS are main substances for the curing effect of APCP treatment. However, the generation of ROS and RNS in APCP can be influenced by several factors. Therefore, optimal operation conditions, including discharge gas composition, input power, and type (open or closed), must be optimized in accordance with the objective of the APCP treatment. In addition, the present studies of APCP treatment in meat and meat products have been conducted at the laboratory scale. Therefore, the efficiency of APCP treatment has to be evaluated at the industrial scale for the increase in the industrial applicability. Nonetheless, we conclude that APCP is a promising technology for use in the meat and meat product industry as a non-thermal pasteurization and curing methods.

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