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# Innovative Applications of Cold Plasma Technology in Meat and Its Products


## Abstract

The growing demand for sustainable food production and the rising consumer preference for fresh, healthy, and safe food products have been driving the need for innovative methods for processing and preserving food. In the meat industry, this demand has led to the development of new interventions aimed at extending the shelf life of meats and its products while maintaining their quality and nutritional value. Cold plasma has recently emerged as a subject of great interest in the meat industry due to its potential to enhance the microbiological safety of meat and its products. This review discusses the latest research on the possible application of cold plasma in the meat processing industry, considering its effects on various quality attributes and its potential for meat preservation and enhancement. In this regard, many studies have reported substantial antimicrobial efficacy of cold plasma technology in beef, pork, lamb and chicken, and their products with negligible changes in their physicochemical attributes. Further, the application of cold plasma in meat processing has shown promising results as a potential novel curing agent for cured meat products. Understanding the mechanisms of action and the interactions between cold plasma and food ingredients is crucial for further exploring the potential of this technology in the meat industry, ultimately leading to the development of safe and high-quality meat products using cold plasma technology.



**Keywords:** cold plasma, food safety, microbicidal efficacy, hurdles, innovative curing

## Introduction

An increase in the number of food-borne illness outbreaks caused by food-borne pathogens, including *Listeria monocytogenes*, *Staphylococcus aureus*, pathogenic *Escherichia coli*, *Clostridium perfringens*, *Campylobacter* spp., and *Vibrio* spp., has become a significant public health challenge, resulting in a substantial economic damage to many countries (Yu et al., 2021). The global consumption of meat proteins is projected to rise by 11% by 2031 compared to the average of the base period of 2019-2021, primarily driven by income and population growth (OECD/FAO, 2022). Among all commercial foods, meat is one of the most perishable, and its shelf-life is influenced by multiple factors including microbial growth, enzymatic activity, oxidation processes, package type, and the product environment, particularly at the point of sale (Cenci-Goga et al., 2020). Sustainable food production and consumers' increasing demand for fresh, nutritious, and safe food had led to of the exploration of novel processing and preservative interventions to extend the shelf life of food products (Liao et al., 2020).

Over the past two decades, non-thermal processing technologies, including high-pressure processing, ultrasound, pulsed electric field, ultraviolet light, high-intensity pulsed light, gamma irradiation, and cold plasma have gained significant interest in the meat industry for ensuring microbiological safety (Laroque et al., 2022). Plasma, the fourth state of matter, is an ionized gas generated by applying an electric current to a neutral gas (Lee et al., 2017) and has emerged as a promising technology for various applications, including non-thermal food pasteurization (Lee et al., 2017; Misra and Jo, 2017). Plasma contains reactive oxygen species (ROS), reactive nitrogen species (RNS), ultraviolet radiation (UV), free radicals, and charged particles (Laroque et al., 2022).

The application of cold plasma technology in a wide variety of food, both natural and processed, has gained significant importance in recent years. Its appealing qualities lie in its low temperature and high efficacy (Misra et al., 2015). Regarding foods and food-related materials, cold plasma treatment offers numerous options for food preparation, including surface decontamination, surface property modification, and mass transfer augmentation (Pankaj et al., 2015). The application of non-thermal plasma in different food categories has shown promising results. For instance, it has been applied to vegetables (Mahnot et al., 2020; Prasad et al., 2017; Shah et al., 2019), fruits (Misra et al., 2014; Pathak et al., 2020; Won et al., 2017; Wu et al., 2020), meat (Bauer et al., 2017; Jayasena et al., 2015; Zhuang et al., 2020), seafood (Chen et al., 2019; da Silva Campelo et al., 2019; Olatunde et al., 2019), dairy (Kim et al., 2015; Lee et al., 2012a, 2012b; Yong et al., 2015a, 2015b), grains (Lee et al., 2016b; Selcuk et al., 2008), and juices (Pankaj et al., 2017b; Rodríguez et al., 2017; Xu et al., 2017), demonstrating effective microbial inactivation, extended shelf life, reduced spoilage losses, and improved nutritional, functional, and sensory properties of food products (Nwabor et al., 2022; Starek et al., 2019). Moreover, cold plasma technology has shown successful surface sterilization of packaging materials and functional modification to achieve desired qualities (Scholtz et al. 2015).

Different plasma sources, including plasma jet, corona discharge, radiofrequency, dielectric barrier discharge, and microwave (Peng et al., 2020) are being tested for their antimicrobial efficacy in meat, such as beef, pork, lamb, and chicken and their products. Researches indicate that plasma treatments have a greater potential for the inactivation of foodborne pathogens, making them a valuable tool in microbial control (Kim et al., 2016). Cold plasma, in particular, offers advantages such as cost-effectiveness, versatility, environmental friendliness, and minimal generation of hazardous substances during the sterilization process. (Chen et al., 2020; Lee et al., 2017; Pankaj et al., 2018). It has also shown to increase the bioactivities of naturally occurring bioactive components with health benefits (Beyrer et al., 2020). Additionally, plasma technology has been recognized for its ability to protect packaged food from pathogenic microorganisms and improve food quality parameters (Jadhav and Annapure, 2021). Nevertheless, the initial installation cost, process-specific equipment requirements, need of highly trained personal, and safety measures could be listed as disadvantages of using this technology (Chen et al., 2020). Despite these challenges, this review presents a comprehensive analysis of the current knowledge on cold plasma technology and its potential applications in meat and meat products processing industry as a non-thermal pasteurization method and a novel innovative curing method.



## Plasma Technology

Plasma—the fourth state of matter—is partially or fully ionized gas composed of many different species including positive and negative ions, electrons, free radicals, gas atoms, molecules in the ground or excited state, neutral particles, and electromagnetic radiation quanta as visible light and UV photons (Akhtar et al., 2022; Nehra et al., 2008; Nwabor et al., 2022). Plasma can be created by applying energy across neutral gases in a variety of ways, such as thermal, electrical, optical (UV light), magnetic, irradiation, and microwave fields. The system may run on a mixture of noble gases, such as helium, argon, or neon, or it may use a basic gas like air or nitrogen (Pankaj et al., 2018). Mixtures of gases such as $He/O_2$, $He/N_2$, $N_2/N_2O$, $N_2/O_2$, $Ar/O_2$, and $He/O_2/H_2O$ have also been used in various plasma operations (Guo et al., 2015).

## Types of Plasma

Plasma can be classified based the thermal equilibrium and the pressure conditions. Based on the thermal equilibrium, plasma technology is divided into high-temperature (thermal equilibrium state: $10^6$ to $10^8$ $K$) and low-temperature plasma. The latter can be further subdivided into thermal plasma (quasi-equilibrium plasma; local thermal equilibrium state: 4,000 to 20,000 $K$) and non-thermal plasma (non-equilibrium plasma/cold plasma; non-equilibrium state: 300 to 1,000 $K$) (Lee et al., 2017; Nehra et al., 2008; Pankaj et al., 2018). Non-thermal plasma (cold plasma) has confirmed its effectiveness for use in heat sensitive foods including meat and meat products compared to high temperature and thermal plasmas (Akhtar et al., 2022; Lee et al., 2017; Misra et al., 2016).

According to the pressure conditions, plasma could further be subdivided into high-pressure, atmospheric pressure and low-pressure plasma (Pankaj et al., 2018). However, the requirement for a vacuum system for plasma generation at low pressure condition limited its usage and opened new avenues for plasma generation at atmospheric pressure (Lee et al., 2017; Nehra et al., 2008). Atmospheric pressure cold plasma (30-60°C) can be generated using several electrical discharges such as corona discharge, dielectric barrier discharge (DBD), gliding arc discharge, plasma needle, and plasma jets (Akhtar et al., 2022; Misra et al., 2011) with various discharge gases such as oxygen, nitrogen, helium, argon and ambient air (Lee et al., 2017; Nehra et al., 2008). However, DBD and plasma jet are considered as the most commonly used cold plasma devices (Fig. 1) in food industry including meat processing industry due to their uncomplicated designs and flexibility to be altered to meet a variety of treatment needs (Akhtar et al., 2022; Pankaj et al., 2018). Specificities for each cold plasma source suitable for food application are available in detail in the review published by Laroque et al. (2022). Besides its application in food industry, cold plasma technology has been applied in a number of manufacturing industries including medical devices, textiles, automotive, aerospace, electronics, and packaging materials (Bermudez-Aguirre, 2020; Laroque et al., 2022; Olatunde et al., 2019) (Table 1).

## Factors Affecting the Efficacy of Cold Plasma

The microbicidal efficacy of cold plasma, as depicted in Figure 2, is influenced by three main categories of factors: microbial factors, food factors, and plasma operational parameters. Therefore, a comprehensive consideration of these factors is necessary to achieve enhanced antimicrobial efficacy in food systems. The working parameters and instrumental settings of cold plasma treatment, as illustrated in Figure 2, play a crucial role in determining the concentration of reactive species, discharge characteristics, gas speciation, and overall efficiency of the cold plasma process (Pankaj et al., 2018). For instance, the effectiveness of cold plasm-mediated inhibition of *L. monocytogenes*, *E. coli*, and *S.* Typhimurium in bacon (Kim et al., 2011) and *L. monocytogenes* in chicken breast (Lee et al., 2011) was affected by the type of gas used; a mixture of helium and oxygen and a mixture of nitrogen and oxygen were more effective in reducing the microbial counts than helium and nitrogen alone, respectively. Furthermore, studies by Kim et al. (2011) and Laroussi and Leipold (2004) confirmed that an increase in input power resulted in a greater microbicidal effect. In-package (closed) plasma treatment offers advantages by preventing subsequent contamination of food systems and providing continuous pasteurization effect against microorganisms even after plasma treatment (Yong et al., 2014, Yong et al., 2017a) as compared to an open plasma system.

The formation of biofilm on food contact surfaces is a leading cause of food contamination, foodborne disease outbreaks, and recalls of finished food products. In recent years, food processors have been exploring modern green technologies as alternatives to conventional antimicrobial chemical sanitizers for the decontamination of food processing lines and facilities (Nwabor et al., 2022). Scientific studies have demonstrated that cold plasma treatment effectively disrupts and inactivates the biofilms formed by various microorganisms, including *Pseudomonas aeruginosa* (Ziuzina et al., 2014a), *Candida albicans* (He et al., 2020), *Aspergillus flavus* (Los et al., 2020), *E. coli* (Los et al., 2017; Ziuzina et al., 2015a, 2015b), *Bacillus subtilis*, *Lactobacillus* spp. (Los et al., 2017), *L. monocytogenes*, and *Staphylococcus aureus* (Ziuzina et al., 2015a). However, the anti-biofilm effectiveness of cold plasma is also influenced by several factors, such as gas composition (single gas/gas mixture), attachment surface (biotic surface, abiotic surface, roughness, hydrophilicity, hydrophobicity), type of biofilm (mono-species or mixed-species), processing parameters (power, voltage, frequency, flow rate), types of bacteria (Gram-positive/Gram-negative), individual variations in cellular properties, age of biofilm, biofilms thickness, and storage conditions (Nwabor et al., 2022; Zhu et al., 2020).

## Application of Cold Plasma in Meat Industry

Meat processing has always played the leading role of developing and implementing novel technologies in the food industry. To ensure a sanitary manufacturing environment, various technologies aimed at enhancing food safety are employed in meat processing. Due to its high nutritional value and perishable nature, meat is susceptible to microbial contamination, which poses risks to both quality and public health. Previous studies have shown that this challenge can be effectively addressed by utilizing cold plasma treatment as a non-thermal pasteurization method for meat and meat products.

### *Microbial Decontamination*

A broad range of microorganisms could be effectively inactivated by cold plasma processing which generates reactive species lethal to cells (Nicol et al., 2020; Yoo et al., 2021). The oxygen in the air forms the reactive oxygen species (ROS), which tend to react with other oxygen molecules leading to the formation of singlet oxygen, hydroxyl radical, superoxide anion, hydrogen peroxide, and ozone during the plasma generation (Han et al., 2016; Oehmigen et al., 2010; Park et al., 2018). Ozone has been shown to possess a greater microbicidal properties owing to its relatively long lifetime (Han et al., 2016; Laroussi and Leipold, 2004; Ziuzina et al., 2014b). Moreover, cold plasma generation results in RNS, including peroxynitrite, nitric oxide, and nitrite (Burlica et al., 2006; Laroussi and Leipold, 2004).

Gavahian et al. (2019) thoroughly reviewed the mechanism of inactivation of microorganisms by plasma and highlighted that the plasma-induced reactive species primarily disrupt the bacterial cell wall membrane. Free radicals present in plasma can be adsorbed on the surface of microorganisms and diffused into the cell membrane, causing damage to proteins and nucleic acids (Fernández and Thompson, 2012). Distinct microbicidal mechanisms on Gram-positive and Gram-negative bacteria have been suggested (Fig. 3). Han et al. (2016) proposed that the microbicidal effects of cold plasma treatment on Gram-positive bacteria is mainly due to oxidative damage to intracellular components, particularly DNA without cell leakage. In Gram-negative bacteria, the irreversible destruction of the cell wall via oxidative damage leads to leakage of intracellular compounds such as protein, DNA, and lipids, resulting in microbial inactivation (Han et al., 2016). Further details on microbial inactivation mechanisms can be found in other references (Akhtar et al., 2022; Nasiru et al., 2021; Nwabor et al., 2022).

Many studies have revealed the significant impact of cold plasma technology on microbial decontamination in meat and meat products. Table 2 shows the microbicidal effects of cold plasma generated using different plasma sources on common microorganisms found in chicken, pork, beef, lamb and processed meat products such as bacon, ham, and jerky. The results clearly indicated that cold plasma technology can achieve substantial log reductions in tested microbes. For instance, a reduction of 0.43 to 6.52 Log CFU/g in *L. monocytogenes* counts has been reported in inoculated meat and meat products following cold plasma treatment (Bauer et al., 2017; Choi et al., 2016; Cui et al., 2017; Jayasena et al., 2015; Kim et al., 2011, Kim et al., 2013; Lee et al., 2011, Lee et al., 2016; Yong et al., 2017a). In addition, studies conducted to improve the safety of meat and meat products found a 0.34 to 7.50 Log CFU/g reduction in *E. coli* (Bauer et al., 2017; Choi et al., 2016; Jayasena et al., 2015; Kim et al., 2011, 2013; Lee et al., 2016; Stratakos and Grant, 2018; Yong et al., 2017a), and a 0.98 to 5.30 Log CFU/g reduction in *S.* Typhimurium counts (Chaplot et al., 2019; Jayasena et al., 2015; Kang et al., 2022; Kim et al., 2011; Lee et al., 2016; Yong et al., 2017a) after cold plasma treatment. The treatment of chicken breast and Bresaola with cold atmospheric gas plasmas showed a 3.30 and 1.60 Log CFU/g reduction in *Listeria innocua* levels, respectively (Noriega et al. 2011; Rod et al., 2012). Moreover, a 1.33 to 4.00 Log CFU/g reduction in *S. aureus* counts in chicken, beef, and beef jerky (Bauer et al., 2017; Kim et al., 2014b; Royintarat et al., 2020; Sahebkar et al., 2020) and a 0.78 to 2.55 Log CFU/g reduction in *C. jejuni* counts in chicken skin and breast were reported upon cold plasma treatment (Dirks et al., 2012; Rossow et al., 2018).

Cold plasma-based hurdle technologies have emerged as innovative strategies for microbial decontamination in the food industry. These technologies combine cold plasma with other hurdles such as mild heat, chemical antimicrobials (organic acids, essential oils), ultrasound technique, biocontrol agents, and nanomaterials have recently been utilized as novel microbial decontamination strategies (Liao et al., 2020). A recent study by Lee et al. (2023) investigated the synergistic bactericidal effect of nisin and cold plasma on beef jerky and sliced ham. The hurdle treatment combining nisin and plasma demonstrated a 100% reduction rate in both *E. coli* and *L. monocytogenes* surpassing the effectiveness of individual treatment. Similarly, when atmospheric DBD plasma technology was coupled with acetic acid (i.e. plasma-activated acetic acid), it caused a reduction in *S.* Typhimurium counts more effectively than did acetic acid alone and improved the chicken meat quality (Kang et al., 2022). The hurdle treatment of cold plasma and peracetic acid applied to inactivate *S*. Typhimurium in raw poultry showed a greater log reduction (3.8 to 5.3 Log CFU/cm$^2$) compared to individual treatment with peracetic acid (0.6 to 1.3 Log CFU/cm$^2$) (Chaplot et al., 2019). Moreover, cold plasma treatment was shown to increase the inactivation of *L. monocytogenes* in pork loin when coupled with lemongrass oil (2.80 Log CFU/g) compared to application of individual cold plasma (0.96 Log CFU/g) or lemongrass oil treatment (0.59 Log CFU/g (Cui et al., 2017). It is important to note that the efficacy of these hurdle treatments may vary due to differences in plasma treatment conditions (such as power, time, and gas composition), which generate different reactive species. Additionally, other factors illustrated in Fig. 2 can also influence the effectiveness of cold plasma in microbial inactivation.

### *Effect of Cold Plasma on Physicochemical and Sensory Parameters*

Numerous studies have conducted to elucidate the effects of cold plasma technology on the physicochemical attributes of meat and meat products, but the findings have been contradictory. The color values has not been changed in chicken breast or chicken thigh skin surface as well as in pork when treated with cold plasma (Cui et al., 2017; Dirks et al., 2012; Moon et al., 2009). However, the application of plasma technology has led to a reduction in redness (a* value) of ready to eat bresaola, beef, pork, and poultry (Chaplot et al., 2019; Jayasena et al., 2015; Rod et al., 2012). According to Soffels et al. (2008), the impact of cold plasma treatment of meat on pH value is negligible. In contrast, Kim et al. (2013) reported a significant reduction in the pH of pork following the plasma treatment.

The findings of the very few studies conducted on sensory data on plasma-treated meat and meat products have shown that cold plasma has certain negative effects on some sensory parameters of meat. The application of cold plasma technology has a negative impact on sensory properties of meat such as appearance, color, odor, and acceptability (Kim et al., 2013). However, the sensory analysis on cooked pork butt and beef loin samples treated with the flexible thin-layer DBD plasma revealed no differences in the pork and beef samples with respect to appearance, color, off-flavor, general acceptability, and texture parameters such as hardness, gumminess, springiness, cohesiveness, and chewiness. The DBD plasma treatment, however, had a negative impact on consumers' preferences for the flavor of both meat samples (Jayasena et al., 2015).

Formation of radicals and ROS during plasma treatments could induce the lipid oxidation and production of related by products such as malondialdehyde (MDA) and hexanal (Kim et al., 2016). This might contribute to the variations in sensory attributes of meat and meat products upon plasma treatments, particularly in high-fat meat sources such as pork (Jayasena et al., 2015). The cold plasma treatments increased the level of lipid oxidation in beef, pork, poultry, and their products such as bresaola and beef patty (Cui et al., 2017; Gavahian et al., 2018; Huang et al., 2019; Jayasena et al., 2015; Kim et al., 2013; Rod et al., 2012; Wang et al., 2021; Yong et al., 2017a). Nevertheless, several other authors found that cold plasma treatment of meat and meat products had no impact on lipid oxidation (Jung et al., 2017b; Kim et al., 2011; Lee et al., 2016, 2018; Moutiq et al., 2020). Accordingly, it is clear that the level of lipid oxidation occurred in meat and meat products is generally influenced by plasma power, treatment time, meat type, and storage (Akhtar et al., 2022; Rod et al., 2012). In addition, scientists have proposed several strategies to limit lipid oxidation by cold plasma treatment, such as eliminating $O_2$, applying a lower voltage, using shorter treatment time, reducing fat and unsaturated fatty acid concentration in meat or meat products to be treated by plasma, and adding antioxidants (Gavahian et al., 2018). Table 3 provides an overview of recent studies examining the impact of cold plasma on the physicochemical properties of meat and meat products.

*Innovative Curing Process*

Nitrite—the most commonly used curing agent in the meat industry—contributes to the development of cured colour and flavor in meat products (Parthasarathy and Bryan, 2012; Sebranek et al., 2012). Additionally, it plays a role in inhibiting lipid oxidation and contamination by pathogenic microbes including *Clostridium botulinum* in cured meat products (Jung et al., 2017b; Sebranek et al., 2012). However, due to the increasing consumers' negative perception towards synthetic food additives, the scientists have shifted their focus on natural alternatives.

It has now been well documented that cold plasma treatment of liquids can generate nitrite (Ercan et al., 2016; Kojtari et al., 2013; Oehimigen et al., 2010). Plasma-activated water contains nitrate and nitrites, and the detailed reactions involved in the formation of nitrite and nitrate in plasma-activated water are explained in the review published by Lee et al. (2017). Since cold plasma technology contains RNS and nitrogen oxides, including $NO_2$, $NO_3$, $N_2O$, $N_3O$, and $N_2O_5$, which could form nitric and nitrous acids by reacting with water molecules and subsequently decompose into nitrate and nitrite, it could be a potential nitrite source for curing of processed meat (Jung et al., 2015a, 2015b; Lee et al., 2017). It is noteworthy that the nitrite formed by plasma under alkaline conditions can persist (Jung et al., 2015b; Lukes et al., 2014). For example, cold plasma-treated distilled water containing sodium pyrophosphate can contain up to 782 mg/L of nitrite (Jung et al., 2015b). Therefore, cold plasma has been identified as a potential novel curing agent for meat products because it can provide similar characteristics to synthetic nitrites (Jung et al., 2015b).

Comparable meat quality traits such as color, lipid oxidation, and sensory characteristics were reported in emulsion sausages and pork loin hams when they were cured using plasma-treated water and sodium nitrite. Importantly, the residual nitrite contents of the two products cured with plasma-treated water was lower than those cured with sodium nitrite (Jung et al., 2015b; Yong et al., 2017b). Moreover, Jung et al. (2017b) and Lee et al. (2018) have explored the potential use of cold plasma treatment to generate nitrite in meat batter with levels ranging from 42 to 65.96 mg/kg. Fig. 4 shows the cold plasma curing system used to treat meat batter by Jung et al. (2017b). In addition, canned ground ham prepared from meat batter treated with cold plasma exhibited similar properties in terms of color, residual nitrite content, texture, and sensory attributes compared to those cured at similar nitrite levels using sodium nitrite or celery powder (Lee et al., 2018).

Yong et al. (2018) studied the mechanism of green discoloration of myoglobin induced by cold plasma and proposed that nitroso-myoglobin, which is a major compound for desirable pink color, can be produced in the reduced meat after plasma treatment. Furthermore, Kim et al. (2021) reported an effective way of enriching nitrite level in onion powder using plasma treatment to be used as natural materials with additional meat curing ability. Interestingly, natural nitrite has been derived from *Perilla frutescens*—a plant with no original nitrate content—following cold plasma treatment. In addition, the resultant lyophilized powder following plasma treatment has shown increased antimicrobial activity against *C. perfringens* and *S.* Typhimurium as opposed to that without plasma treatment (Jung et al., 2017a).



## Limitations and Future Directives

Many authors have studied the optimal balance between plasma treatment conditions to maximize the bactericidal effects. However, the quality attributes of plasma treated meat is still less researched (Misra and Jo, 2017). The lipid oxidation might be induced in meat and meat products with high fat contents upon plasma treatment. The development of some off-flavors in meat and meat products has been reported due to rancidity development during subsequent storage (Lee et al., 2016). In addition, meat discoloration and texture deterioration in plasma-treated meat have been detected (Jayasena et al., 2015; Kim et al., 2013; Lee et al., 2016). Hence, there is a need for research to focus on retarding lipid oxidation in plasma-treated meat and meat products.

Data on the chemical residual effects and potential toxicity of plasma-treated meat and meat products are limited. Several studies reported no mutagenicity in meat and meat products treated with cold plasma (Kim et al., 2016; Lee et al., 2016) or cured with plasma-treated water (Yong et al., 2017b). However, further studies are required to fully confirm the safety of cold plasma-treated meat and meat products which would be vital in guiding decision and regulation.

The end reaction products from the reaction of plasma reactive species and other chemical agents such as essential oils are still not fully understood (Liao et al., 2020). Moreover, there is a need to investigate the precise mechanisms of chemical interactions with food ingredients and their impact on quality attributes of meat products. This will lead to the development of safe and high-quality meat products using cold plasma technology. Plasma-treated meat and its products could become microbiologically unsafe unless handled carefully post-treatment. Therefore, correct packaging methods and materials need to be applied to minimize post-treatment contamination. Therefore, further research is required for establishing cold plasma technology for meat and meat products and understanding the quality attributes of meat and its products to optimize the technology for specific applications in the meat processing industry.

## Conclusions

In the context of growing concern over foodborne pathogens, ensuring safety and quality of meat and meat products to consumers poses significant challenges for the meat industry. Recently, non-thermal food processing technologies have attracted the focus in various sectors of the food industry, including meat, and poultry processing. Cold plasma is an emerging cost-effective non-thermal technology with high microbicidal efficacy without the need for temperature abuse, making it a promising alternative to traditional meat preservation methods. The reactive oxygen and nitrogen species generated by plasma not only effectively inactivate microorganisms but also enable researchers to safely apply this technology to biological materials, including food. In addition, plasma-treated liquids have been shown to generate nitrite, which can act as a curing agent in cured meat products.

## Conflicts of Interest

The authors declare no potential conflicts of interest.

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## References

Aboubakr HA, Nisar M, Nayak G, Nagaraja KV, Collins J, Bruggeman PJ, Goyal SM. 2020. Bactericidal efficacy of a two-dimensional array of integrated, coaxial, micro hollow, dielectric barrier discharge plasma against *Salmonella enterica* serovar Heidelberg. Foodborne Pathog Dis 17(3):157–165.

Akhtar J, Abrha MG, Teklehaimanot K, Gebrekirstos G. 2022. Cold plasma technology: fundamentals and effect on quality of meat and its products. Food Agric Immunol 33(1):451-478.

Baek KH, Heo YS, Yim DG, Lee YE, Kang T, Kim HJ, Jo C. 2021. Influence of atmospheric-pressure cold plasma-induced oxidation on the structure and functional properties of egg white protein. Innov Food Sci Emerg Technol 74:102869.

Bauer A, Ni Y, Bauer S, Paulsen P, Modic M, Walsh JL, Smulders FJM. 2017. The effects of atmospheric pressure cold plasma treatment on microbiological, physical-chemical and sensory characteristics of vacuum packaged beef loin. Meat Sci 128:77–87.

Bermudez-Aguirre, D., 2020. Advances in cold plasma applications for food safety and preservation. Elsevier, Richland, WA, USA.

Beyrer M, Pina-Perez MC, Martinet D, Andlauer W. 2020. Cold plasma processing of powdered Spirulina algae for spore inactivation and preservation of bioactive compounds. Food Control 118:107378.

Bourke P, Ziuzina D, Han L, Cullen PJ, Gilmore BF. 2017. Microbiological interactions with cold plasma. J Appl Microbiol 123:308-324.

Burlica R, Kirkpatrick MJ, Locke BR. 2006. Formation of reactive species in gliding arc discharges with liquid water. J Electrostat 64:35-43.

Cenci-Goga BT, Iulietto MF, Sechi P, Borgogni E, Karama M, Grispoldi L. 2020. New trends in meat packaging. *Microbiol Res* 11(2):56-67.

Chaplot S, Yadav B, Jeon B, Roopesh M. 2019. Atmospheric cold plasma and peracetic acid–based hurdle intervention to reduce *Salmonella* on raw poultry meat. J Food Prot 82(5):878–888.

Chen G, Chen Y, Jin N, Li J, Dong S, Li S, Zhang Z, Chen Y. 2020. Zein films with porous polylactic acid coatings via cold plasma pre-treatment. Ind Crops Prod 150:112382.

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(2):685–694.

Choi SH, Jeong GH, Lee KB, Jo C, Kim TH. 2018. A green chemical oligomerization of phloroglucinol induced by plasma as novel α-glucosidase inhibitors. Biosci Biotechnol Biochem 82:2059-2063.

Chutia H, Kalita D, Mahanta CL, Ojah N, Choudhury AJ. 2019. Kinetics of inactivation of peroxidase and polyphenol oxidase in tender coconut water by dielectric barrier discharge plasma. LWT-Food Sci Technol 101:625-629.

Cui H, Wu J, Li C, Lin L. 2017. Promoting anti-listeria activity of lemongrass oil on pork loin by cold nitrogen plasma assist. J Food Saf 37(2):1–10.

da Silva Campelo MC, de Oliveira Soares Rebouças LU, de Oliveira Vitoriano J, Alves C, da Silva JBA, de Oliveira Lima P. 2019. Use of cold atmospheric plasma to preserve the quality of white shrimp (*Litopenaeus vannamei*). J Food Prot 82:1217–1223.

De Groot GJ, Hundt A, Murphy AB, Bange MP, Mai-Prochnow A. 2018. Cold plasma treatment for cotton seed germination improvement. Sci Rep 8:1–10.

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(1):22–28.

Ercan UK, Smith J, Ji HF, Brooks AD, Joshi SG. 2016. Chemical changes in nonthermal plasma-treated N-Acetylcysteine (NAC) solution and their contribution to bacterial inactivation. Sci Rep 6:20365.

Fernández A, Thompson A. 2012. The inactivation of *Salmonella* by cold atmospheric plasma treatment. Food Res Int 45:678-684.

Fröhling A, Durek J, Schnabel U, Ehlbeck J, Bolling J, Schlüter O. 2012. Indirect plasma treatment of fresh pork: Decontamination efficiency and effects on quality attributes. Innov Food Sci Emerg Technol 16:381–390.

Gao Y, Zhuang H, Yeh HY, Bowker B, Zhang J. 2019. Effect of rosemary extract on microbial growth, pH, color, and lipid oxidation in cold plasma-processed ground chicken patties. Innov Food Sci Emerg Technol 57:102168.

Gavahian M, Chu YH, Jo C. 2019. Prospective application of cold plasma for processing poultry products: Benefits, effects on quality attributes, and limitations. Compr Rev Food Sci Food Saf 18:1292-1309.

Gavahian M, Chu YH, Khaneghah AM, Barba FJ, Misra NN. 2018. A critical analysis of the cold plasma induced lipid oxidation in foods. Trends Food Sci Technol 77:32–41.

Guo J, Huang K, Wang J. 2015. Bactericidal effect of various non-thermal plasma agents and the influence of experimental conditions in microbial inactivation: A review. Food Control 50: 482–490.

Han L, Patil S, Boehm D, Milosavljevic V, Cullen PJ, Bourke P. 2016. Mechanisms of inactivation by high voltage atmospheric cold plasma differ for *Escherichia coli* and *Staphylococcus aureus*. Appl Environ Microbiol 82:450-458.

He M, Duan J, Xu J, Ma M, Chai B, He G, Gan L, Zhang S, Duan X, Lu X. 2020. *Candida albicans* biofilm inactivated by cold plasma treatment in vitro and in vivo. Plasma Process Polym 17:1900068.

Huang MM, Wang JM, Zhuang H, Yan WJ, Zhao JY, Zhang JH. 2019. Effect of in package high voltage dielectric barrier discharge on microbiological, color and oxidation properties of pork in modified atmosphere packaging during storage. Meat Sci 149:107–113.

Ibrahim NA, Eid BM. 2020. Plasma treatment technology for surface modification and functionalization of cellulosic fabrics. In Advances in functional finishing of textiles. Shahid M, Adivarekar R (eds). Springer, Singapore

Inguglia ES, Oliveira M, Burgess CM, Kerry JP, Tiwari BK. 2020. Plasma-activated water as an alternative nitrite source for the curing of beef jerky: Influence on quality and inactivation of *Listeria innocua*. Innov Food Sci Emerg Technol 59:102276.

Isbary G, Morfill G, Zimmermann J, Shimizu T, Stolz W. 2011. Cold atmospheric plasma: a successful treatment of lesions in Hailey-Hailey disease. Arch Dermatol 147:388–390.

Isbary G, Stolz W, Shimizu T, Monetti R, Bunk W, Schmidt H-U, Morfill GE, Klämpfl T, Steffes B, Thomas H. 2013. Cold atmospheric argon plasma treatment may accelerate wound healing in chronic wounds: Results of an open retrospective randomized controlled study in vivo. Clin Plasma Med 1:25–30.

Jadhav HB, Annapure U. 2021. Consequences of non-thermal cold plasma treatment on meat and dairy lipids- A review. Future Foods 4:100095.

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.

Jo K, Lee J, Lee S, Lim Y, Choi YS, Jo C, Jung S. 2020. Curing of ground ham by remote infusion of atmospheric non-thermal plasma. Food Chem 309:125643.

Jung S, Kim HJ, Park S, Yong HI, Choe JH, Jeon HJ, Choe W, Jo C. 2015a. Color developing capacity of plasma-treated water as a source of nitrite for meat curing. Korean J Food Sci Anim Resour 35(5):703-706.

Jung S, Kim HJ, Park S, Yong HI, Choe JH, Jeon HJ, Choe W, Jo C. 2015b. The use of atmospheric pressure plasma-treated water as a source of nitrite for emulsion-type sausage. Meat Sci 108:132-137.

Jung S, Lee CW, Lee J, Yong HI, Yum SJ, Jeong HG, Jo C. 2017a. Increase in nitrite content and functionality of ethanolic extracts of *Perilla frutescens* following treatment with atmospheric pressure plasma. Food Chem 237:191-197.

Jung S, Lee J, Lim Y, Choe W, Yong HI, Jo C. 2017b. Direct infusion of nitrite into meat batter by atmospheric pressure plasma treatment. Innov Food Sci Emerg Technol 39:113-118.

Kang JH, Roh SH, Min SC. 2019. Inactivation of potato polyphenol oxidase using microwave cold plasma treatment. J Food Sci 84(5):1122-1128.

Kang T, Yim D, Kim SS, Baek KH, Kim HJ, Jo C. 2022. Effect of plasma-activated acetic acid on inactivation of *Salmonella* Typhymurium and quality traits on chicken meats. Poult Sci 101:101793.

Keidar M, Shashurin A, Volotskova O, Ann Stepp M, Srinivasan P, Sandler A, Trink B. 2013. Cold atmospheric plasma in cancer therapy. Phys Plasmas 20:057101.

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(1):9-13.

Kim HJ, Jayasena DD, Yong HI, Jo C. 2016. Quality of cold plasma treated foods of animal origin. In Cold plasma in food and agriculture: Fundamentals and applications. Misra NN, Schlüter O, Cullen PJ. (ed). pp 273-291. Academic Press, San Diego, CA.

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(4):494-8.

Kim HJ, Won CH, Kim HW. 2018. Pathogen deactivation of glow discharge cold plasma while treating organic and inorganic pollutants of slaughterhouse wastewater. Water Air Soil Pollut 229:1–10.

Kim HJ, Yong HI, Park S, Choe W, Jo C. 2013. 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, Kim TH, Choe W, Jo C. 2014a. Effect of atmospheric pressure dielectric barrier discharge plasma on the biological activity of naringin. Food Chem 160:241-245.

Kim JS, Lee EJ; Choi EH, Kim YJ. 2014b. Inactivation of Staphylococcus aureus on the beef jerky by radio-frequency atmospheric pressure plasma discharge treatment. Innov Food Sci Emerg Technol 22:124–130.

Kim JW, Lee HJ, Shin DJ, Baek KH, Jung S, Jo C. 2021. Enrichment of nitrite in onion powder using atmospheric pressure plasma and egg whites for meat curing. LWT-Food Sci Technol 135:110050.

Kim TH, Lee J, Kim HJ, Jo C. 2017. Plasma-induced degradation of quercetin associated with the enhancement of biological activities. J Agric Food Chem 65:6929-6935.

Klämpfl TG, Isbary G, Shimizu T, Li Y-F, Zimmermann JL, Stolz W, Schlegel J, Morfill GE, Schmidt H-U. 2012. Cold atmospheric air plasma sterilization against spores and other microorganisms of clinical interest. Appl Environ Microbiol 78:5077–5082.

Kojtari A, Ercan UK, Smith J, Friedman G, Sensening RB, Tyagi S, Joshi SG, Ji HF, Brooks AD. 2013. Chemistry for antimicrobial properties of water treated with non-equilibrium plasma. J Nanomedicine Biotherapeutic Discov 4:1000120.

Laroque DA, Seó ST, Valencia GA, Laurindo JB, Carciofi BAM. 2022. Cold plasma in food processing: Design, mechanisms, and application. J Food Eng 312:110748.

Laroussi M, Leipold F. 2004. Evaluation of the roles of reactive species, heat, and UV radiation in the inactivation of bacterial cells by air plasmas at atmospheric pressure. Int J Mass Spectrom 233:81–86.

Lee H, Yong HI, Kim HJ, Choe W, Yoo SJ, 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(4):1189–1195.

Lee HJ, Heo Y, Kim H-J, Baek KH, Yim D-G, Sethukali AK, Park D, Jo C. 2023. Bactericidal effect of combination of atmospheric pressure plasma and nisin on meat products inoculated with *Escherichia coli* O157:H7. Food Sci Anim Resour 43(3):402-411.

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 J, Jo K, Lim Y, Jeon HJ, Choe JH, Jo C, Jung S. 2018. The use of atmospheric pressure plasma as a curing process for canned ground ham. Food Chem 240:430-436.

Lee J, Lee CW, Yong HI, Lee HJ, Jo C, Jung S. 2017. Use of atmospheric pressure cold plasma for meat industry. Korean J Food Sci Anim Resour 37(4):477-485.

Liao X, Xiang Q, Cullen PJ, Su Y, Chen S, Ye X, Liu D, Ding T. 2020. Plasma-activated water (PAW) and slightly acidic electrolyzed water (SAEW) as beef thawing media for enhancing microbiological safety. LWT-Food Sci Technol 117:108649.

Ling L, Jiangang L, Minchong S, Chunlei Z, Yuanhua D. 2015 Cold plasma treatment enhances oilseed rape seed germination under drought stress. Sci Rep 5:1–10.

Los A, Ziuzina D, Boehm D, Cullen PJ, Bourke P. 2017. The potential of atmospheric air cold plasma for control of bacterial contaminants relevant to cereal grain production. Innov Food Sci Emerg Technol 44:36–45.

Los A, Ziuzina D, Boehm D, Cullen PJ, Bourke P. 2020. Inactivation efcacies and mechanisms of gas plasma and plasma activated water against *Aspergillus flavus* spores and bioflms: A comparative study. Appl Environ Microbiol 86:e02619-e2719.

Lukes P, Dolezalova E, Sisrova I, Clupek M. 2014. Aqueous-phase chemistry and bactericidal effects from an air discharge plasma in contact with water: Evidence for the formation of peroxynitrite through a pseudo-second-order post discharge reaction of $H_2O_2$ and $HNO_2$. Plasma Sources Sci Technol 23:015019.

Misra NN, Jo C. 2017. Applications of cold plasma technology for microbiological safety in meat industry. Trends Food Sci Technol 64:74-86.

Misra NN, Schlüter O, Cullen PJ. 2016. Plasma in food and agriculture. In Cold plasma in food and agriculture: Fundamentals and applications. Misra NN, Schlüter O, Cullen PJ. (ed). pp 1-16. Academic Press, San Diego, CA.

Misra NN, Tiwari BK, Raghavarao KSMS, Cullen PJ. 2011. Nonthermal plasma inactivation of food-borne pathogens. Food Eng Rev 3:159-170.

Misra NN, Yadav B, Roopesh MS, Jo C. 2019. Cold plasma for effective fungal and mycotoxin control in foods: mechanisms, inactivation effects, and applications. Compr Rev Food Sci Food Saf 18:106–120.

Moon SY, Kim DB, Gweon B, Choe W, Song HP, Jo C. 2009. Feasibility study of the sterilization of pork and human skin surfaces by atmospheric pressure plasmas. Thin

Solid Films 517(14):4272–4275.

Moutiq R, Misra NN, Mendonça A, Keener K. 2020. In-package decontamination of chicken breast using cold plasma technology: Microbial, quality and storage studies. Meat Sci 159:107942.

Nasiru MM, Boateng EF, Muhammad U, Qian J, Mustapha AT, Yan W, Zhuang H, Zhang J. 2021. Dielectric barrier discharge cold atmospheric plasma: Influence of processing parameters on microbial inactivation in meat and meat products. Compr Rev Food Sci Food Saf 20:1–34.

Nehra V, Kumar A, Dwivedi HK. 2008. Atmospheric non-thermal plasma sources. Int J Eng 2:53-68.

Nicol MJ, Brubaker TR, Honish BJ, Simmons AN, Kazemi A, Geissel MA, Whalen CT, Siedlecki CA, Bilén SG, Knecht SD. 2020. Antibacterial effects of low-temperature plasma generated by atmospheric-pressure plasma jet are mediated by reactive oxygen species. Sci Rep 10:1–11.

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(7):1293–1300.

Nwabor OF, Onyeaka H, Miri T, Obileke K, Anumudu C, Hart A. 2022. A cold plasma technology for ensuring the microbiological safety and quality of foods. Food Eng Rev 14(4):535-554.

OECD/FAO. 2022. Meat. In OECD-FAO agricultural outlook 2022-2031. OECD Publishing, Paris. pp 189-206.

Oehmigen K, Hähnel M, Brandenburg R, Wilke C, Weltmann KD, Von Woedtke T. 2010. The role of acidification for antimicrobial activity of atmospheric pressure plasma in liquids. Plasma Process Polym 7:250-257.

Olatunde OO, Benjakul S, Vongkamjan K. 2019. High voltage cold atmospheric plasma: antibacterial properties and its effect on quality of Asian sea bass slices. Innov Food Sci Emerg Technol 52:305–312.

Pankaj S, Wan Z, Colonna W, Keener KM. 2017a. Degradation kinetics of organic dyes in water by high voltage atmospheric air and modified air cold plasma. Water Sci Technol 76:567–574.

Pankaj SK, Misra NN, Cullen PJ. 2013. Kinetics of tomato peroxidase inactivation by atmospheric pressure cold plasma based on dielectric barrier discharge. Innov Food Sci Emerg Technol 19:153-157.

Pankaj SK, Wan Z, Keener KM. 2018. Effects of cold plasma on food quality: A review. Foods 7 (1):4.

Park S, Choe W, Jo C. 2018. Interplay among ozone and nitrogen oxides in air plasmas: Rapid change in plasma chemistry. Chem Eng J 352:1014-1021.

Parthasarathy DK, Bryan NS. 2012. Sodium nitrite: The “cure” for nitric oxide insufficiency. Meat Sci 92:274-279.

Patange A, Boehm D, Bueno-Ferrer C, Cullen PJ, Bourke P. 2017. Controlling *Brochothrix thermosphacta* as a spoilage risk using in-package atmospheric cold plasma. Food Microbiol 66:48–54.

Patange A, Boehm D, Giltrap M, Lu P, Cullen P, Bourke P (2018) Assessment of the disinfection capacity and eco-toxicological impact of atmospheric cold plasma for treatment of food industry effluents. Sci Total Environ 631-632:298–307

Peng P, Chen P, Zhou N, Schiappacasse C, Cheng Y, Chen D, Addy M, Zhang Y, Anderson E, Fan L, Hatzenbeller R, Liu Y, Ruan R. 2020. Packed food and packaging materials disinfected by cold plasma. In Advances in cold plasma applications for food safety and preservation Bermudez-Aguirre D (ed). pp 269–286. Academic Press, London, United Kingdom.

Puligundla P, Lee T, Mok C. 2020. Effect of corona discharge plasma jet treatment on the degradation of aflatoxin B1 on glass slides and in spiked food commodities. LWT-Food Sci Technol 124:108333.

Punia Bangar S, Suri S, Nayi P, Phimolsiripol Y. 2022. Cold plasma for microbial safety: Principle, mechanism, and factors responsible. J Food Process Preserv 46:e16850.

Qian J, Zhuang H, Nasiru MM, Muhammad U, Zhang J, Yan W. 2019. Action of plasma-activated lactic acid on the inactivation of inoculated *Salmonella enteritidis* and quality of beef. Innov Food Sci Emerg Technol 57:102196.

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(1), 233–238.

Rossow, Marko, Martina Ludewig, and Peggy Gabriele Braun. 2018. Effect of cold atmospheric pressure plasma treatment on inactivation of *Campylobacter Jejuni* on chicken skin and breast fillet. LWT-Food Sci Technol 91:265–270.

Royintarat T, Choi EH, Boonyawan D, Seesuriyachan P, Wattanutchariya W. 2020. Chemical-free and synergistic interaction of ultrasound combined with plasma-activated water (PAW) to enhance microbial inactivation in chicken meat and skin. Sci Rep 10(1):1–14.

Sahebkar A, Hosseini M, Sharifan A. 2020. Plasma-assisted preservation of breast chicken fillets in essential oils-containing marinades. LWT-Food Sci Technol 131:109759.

Sarangapani C, Misra N, Milosavljevic V, Bourke P, O’regan F, Cullen P. 2016. Pesticide degradation in water using atmospheric air cold plasma. J Water Process Eng 9:225–232.

Sebranek JG, Jackson-Davis AL, Myers KL, Lavieri NA. 2012. Beyond celery and starter culture: Advances in natural/organic curing processes in the United States. Meat Sci 92:267-273.

Sen Y, Onal-Ulusoy B, Mutlu M. 2019. Detoxification of hazelnuts by different cold plasmas and gamma irradiation treatments. Innov Food Sci Emerg Technol. 54:252-259.

Sivachandiran L, Khacef A. 2017. Enhanced seed germination and plant growth by atmospheric pressure cold air plasma: combined effect of seed and water treatment. RSC Adv 7:1822–1832

Soffels E, Sakiyama Y, Graves DB. 2008. Cold atmospheric plasma charged species and their interactions with cells and tissues. IEEE Trans Plasma Sci 36(4):1441–1457.

Stratakos AC, Grant IR. 2018. Evaluation of the efficacy of multiple physical, biological and natural antimicrobial interventions for control of pathogenic *Escherichia coli* on beef. Food Microbiol 76:209–218.

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

Ulbin-Figlewicz N, Jarmoluk A, Marycz K. 2015b. Antimicrobial activity of low-pressure plasma treatment against selected foodborne bacteria and meat microbiota. Ann Microbiol 65(3): 1537–1546.

Van Nguyen D, Ho NM, Hoang KD, Le TV, Le VH. 2020 An investigation on treatment of groundwater with cold plasma for domestic water supply. Groundw Sustain Dev 10:100309.

Van Nguyen D, Ho PQ, Pham TV, Nguyen TV, Kim L. 2019. Treatment of surface water using cold plasma for domestic water supply. Environ Eng Res 24:412–417.

Wang J, Zhuang H, Hinton Jr A, Zhang J. 2016. Influence of in-package cold plasma treatment on microbiological shelf life and appearance of fresh chicken breast fillets. Food Microbiol 60:142–146.

Wang M-J, Chang Y-I, Poncin-Epaillard F. 2003. Effects of the addition of hydrogen in the nitrogen cold plasma: the surface modification of polystyrene. Langmuir 19:8325–8330.

Wang X, Wang Z, Zhuang H, Nasiru MM, Yuan Y, Zhang J, Yan W. 2021. Changes in color, myoglobin, and lipid oxidation in beef patties treated by dielectric barrier discharge cold plasma during storage. Meat Sci 176:1–9.

Wu Y, Cheng JH, Sun DW. 2021. Blocking and degradation of aflatoxins by cold plasma treatments: Applications and mechanisms. Trends Food Sci Technol 109:647-661.

Yadav B, Spinelli AC, Govindan BN, Tsui YY, McMullen LM, Roopesh MS. 2019. Cold plasma treatment of ready-to-eat ham: Influence of process conditions and storage on inactivation of *Listeria innocua*. Food Res Int 123:276–285.

Yong HI, Han M, Kim HJ, Suh JY, Jo C. 2018. Mechanism underlying green discolouration of myoglobin induced by atmospheric pressure plasma. Sci Rep 8:1-9.

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(8):652-657.

Yong HI, Lee H, Park S, Park J, Choe W, Jung S, Jo C. 2017a. 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.

Yong HI, Lee SH, Kim SY, Park S, Park J, Choe W, Jo C. 2019. Color development, physiochemical properties, and microbiological safety of pork jerky processed with atmospheric pressure plasma. Innov Food Sci Emerg Technol 53:78-84.

Yong HI, Park J, Kim HJ, Jung S, Park S, Lee HJ, Choe W, Jo C. 2017b. An innovative curing process with plasma-treated water for production of loin ham and for its quality and safety. Plasma Process Polym 15(2):1700050.

Yoo JH, Baek KH, Heo YS, Yong HI, Jo C. 2021. Synergistic bactericidal effect of clove oil and encapsulated atmospheric pressure plasma against *Escherichia coli* O157: H7 and *Staphylococcus aureus* and its mechanism of action. Food Microbiol 93:103611.

Yoshinari M, Matsuzaka K, Inoue T. 2011. Surface modification by cold-plasma technique for dental implants–bio-functionalization with binding pharmaceuticals. Jpn Dent Sci Rev 47:89–101.

Yu HH, Chin Y-W, Paik H-D. 2021. Application of natural preservatives for meat and meat products against food-borne pathogens and spoilage bacteria: A review. Foods 10:2418.

Zhu Y, Li C, Cui H, Lin L. 2020. Feasibility of cold plasma for the control of biofilms in food industry. Trends Food Sci Technol 99:142-151.

Zhuang H, Rothrock Jr MJ, Hiett KL, Lawrence KC, Gamble GR, Bowker BC, Keener KM. 2019. In-package air cold plasma treatment of chicken breast meat: treatment time effect. J Food Quality 2019:1837351

Ziuzina D, Boehm D, Patil S, Cullen P, Bourke P. 2015a. Cold plasma inactivation of bacterial bioflms and reduction of quorum sensing regulated virulence factors. PLoS ONE 10:e0138209.

Ziuzina D, Han L, Cullen PJ, Bourke P. 2015b. Cold plasma inactivation of internalised bacteria and bioflms for *Salmonella enterica* serovar Typhimurium, *Listeria monocytogenes* and *Escherichia coli*. Int J Food Microbiol 210:53–61.

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

Ziuzina D, Patil S, Cullen PJ, Keener KM, Bourke P. 2014b. Atmospheric cold plasma inactivation of *Escherichia coli, Salmonella enterica serovar* Typhimurium and *Listeria monocytogenes* inoculated on fresh produce. Food Microbiol 42:109-116.

## Figure captions

**Fig. 1.** Schematic diagram of cold plasma processing of meat using (a) dielectric barrier discharge device and (b) plasma jet system

**Fig. 2.** Factors influencing the microbial efficacy of cold plasma (Modified from Bourke et al., 2017; Pankaj et al., 2018; Punia Bangar et al., 2022; Laroque et al., 2022)

**Fig. 3.** Schematic diagram of cold plasma inactivation of microorganisms

**Fig. 4.** Schematic diagram of atmospheric pressure cold plasma chamber system

**Table 1.** Application of cold plasma technology in different manufacturing industries

| Sector | Application | Reference |
| --- | --- | --- |
| Medicine | Sterilization | Klampfl et al. (2012) |
| | Wound healing | Isbary et al. (2013) |
| | Disease treatment | Isbary et al. (2011); Keidar et al. (2013) |
| Agriculture | Enhance seed germination | De Groot et al. (2018); Ling et al. (2015); Sivachandiran et al. (2017) |
| Food industry | Inactivation of foodborne pathogenic and spoilage microbes | da Silva Campelo et al. (2019); Jayasena et al. (2015); Lee et al. (2023); Mahnot et al. (2020); Moutiq et al. (2020) |
| | Enzyme inactivation | Chutia et al. (2019); Kang et al. (2019); Pankaj et al. (2013) |
| | Mycotoxin degradation | Misra et al. (2019); Puligundla et al. (2020); Sen et al. (2019); Wu et al. (2021) |
| | Improvement of biological activity of natural materials | Baek et al. (2021); Choi et al. (2018); Kim et al. (2014a); Kim et al. (2017) |
| | Meat curing | Jung et al. (2015a, 2015b, 2017b) |
| Environmental management | Degradation of contaminants such as pesticides and dyes | Pankaj et al. (2017a); Sarangapani et al. (2016) |
| | Decontamination and treatment of wastewater | Kim et al. (2018); Van Nguyen et al. (2019); Patange et al. (2018); Van Nguyen et |

| | | |
|---|---|---|
| | | al. (2020) |
| Catalysis and material science | Surface modification and functionalization<br>Sterilization | Ibrahim and Eid (2020); Nwabor et al. (2022); Wang et al. (2003); Yoshinari et al. (2011) |

**Table 2. Effects of Cold Plasma Processing on Microbial Decontamination of Meat and Meat Products**

| Meat/Meat Product | Plasma Source | Processing Parameters | Microorganism | Microbial reduction ($Log_{10}$) | Reference |
|---|---|---|---|---|---|
| Beef | Atmospheric pressure plasma jet | Air, 600 W, 1 min, Plasma activated water | Total viable counts<br>Fungi and yeast | 1.62<br>1.76 | Liao et al. (2020) |
| Beef slices | Plasma activated lactic acid (PALA) | 19.2 kV, 80 s, PALA 0.2% | *Salmonella* Enteritidis | 3.52 | Qian et al. (2019) |
| Beef | DBD plasma | 20 MHz, 6 kV, 5 min | *Escherichia coli* | 1.82 | Stratakos and Grant (2018) |
| Beef loin | DBD plasma | 9 kHz, 29.9 W | *Staphylococcus aureus*<br>*Listeria monocytogenes*<br>*E. coli* | ≥ 2<br>≥ 2<br>≥ 2 | Bauer et al. (2017) |
| Beef loin | Flexible thin-layer DBD plasma | $N_2/O_2$, 100 W, 10 min | *L. monocytogenes*<br>*E. coli*<br>*Salmonella* Typhimurium | 1.90<br>2.57<br>2.58 | Jayasena et al. (2015) |

| Meat/Meat Product | Plasma Source | Processing Parameters | Microorganism | Microbial reduction ($Log_{10}$) | Reference |
|---|---|---|---|---|---|
| Beef | Low pressure plasma | He, Ar, 20 kPa, 10 min | Psychrotropes<br>Yeast and Mold | 1.48 (He)/1.32 (Ar)<br>0.98 (He)/0.50 (Ar) | Ulbin Figlewicz et al. (2015b) |
| Chicken breast and drumstick | Encapsulated atmospheric DBD plasma treated 0.8% acetic acid | Air, 2.2 kHz, 8.4 kV, 30 min | *S.* Typhimurium | 0.98 (Breast)<br>1.19 (Drumstick) | Kang et al. (2022) |
| Chicken breast fillets | Atmospheric cold plasma | Ar, 32 kHz, 10 min | *S. aureus*<br>*E. coli* | ~ 3<br>~ 4 (treatment with essential oil) | Sahebkar et al. (2020) |
| Chicken | DBD-ACP In package | Air, 100 kV, 233 W, 60 Hz, 5 | Mesophiles | 1.5 | Moutiq et al. |

| **Meat/Meat Product** | **Plasma Source** | **Processing Parameters** | **Microorganism** | **Microbial reduction ($Log_{10}$)** | **Reference** |
|---|---|---|---|---|---|
| breast | | min, 24 d storage | Psychrophiles | 1.4 | (2020) |
| | | | Enterobacteriaceae | 0.5 | |
| Chicken breast | DBD plasma | 14.5 W, 10 min | *Salmonella* | 3.7 | Aboubakr et al. (2020) |
| Chicken meat and skin | Plasma activated water and ultrasound | 1.5 MHz, 6.8 kV, 40 Hz., 60 min, 40 °C | *E. coli* | 1.12/0.86 | Royintarat et al. (2020) |
| | | | *S. aureus* | 1.33/0.83 | |
| Chicken breast | DBD-CAP | Air, 70 kV, 5 min, 5-d storage | Psychrophiles | 1.00 | Zhuang et al. (2019) |
| | | | *Campylobacter jejuni* | 0.93 | |
| | | | *S.* Typhimurium | 0.65 | |
| Chicken meat | Atmospheric cold plasma and peracetic acid (PAA) | 0 to 30 kV, 3.5 kHz, 4°C, PAA (100–200 ppm), 60 min | *S.* Typhimurium | 3.8-5.3 | Chaplot et al. (2019) |

| Meat/Meat Product | Plasma Source | Processing Parameters | Microorganism | Microbial reduction ($Log_{10}$) | Reference |
|---|---|---|---|---|---|
| Chicken skin and breast | Atmospheric pressure plasma jet | Ar or air, 1 MHz, 2-3 kV, 180 s, distance from nozzle to sample 5, 8, 12 mm | *C. jejuni* | 0.78 – 2.55 | Rossow et al. (2018) |
| Chicken breasts | Flexible thin-layer DBD plasma | Air, 100 W, 15 kHz, 10 min | Total aerobic bacteria | 3.36 | Lee et al. (2016) |
| | | | *L. monocytogenes* | 2.14 | |
| | | | *E. coli* | 2.73 | |
| | | | *S.* Typhimurium | 2.71 | |
| Chicken breast fillet | DBD plasma | 5% N2+ 30% CO2+65% O2, 80 kV, 180 s | Mesophiles | 1.0 | Wang et al. (2016) |
| | | | Psychrophiles | 0.5 | |
| | | | Pseudomonas spp | 0.9 | |
| Skinless chicken breast | DBD plasma | Air, 30 kV, 0.5 kHz, 3 min | *S. enterica* | 2.54 | Dirks et al. (2012) |
| | | | *C. jejuni* | 2.45 | |

| Meat/Meat Product | Plasma Source | Processing Parameters | Microorganism | Microbial reduction ($Log_{10}$) | Reference |
|---|---|---|---|---|---|
| Chicken breast and skin | Cold atmospheric plasma pen (CAP-Pen) | He + $O_2$, 6.5-16 kV, 23 – 38.5 kHz | *L. innocua* | 1 (8 min treatment on skin)<br>> 3 (4 min treatment on breast) | Noriega et al. (2011) |
| Cooked chicken breast | Atmospheric pressure plasma jet | He, N2, O2, 2 kV, 50 kHz, 2 min | *L. monocytogenes* | 1.37–4.73 | Lee et al. (2011) |
| Lamb meat | DBD plasma | 80 kV, 50 Hz, 5 min. | *Brochothrix thermosphacta* | 2.0 | Patange et al. (2017) |
| Pork loin | DBD plasma | $CO_2$+ $N_2$+ $O_2$, 85 kV, 60 s | Total viable aerobic count | 0.4 (20% CO2+40% N2+40% O2)<br>0.8 (20% CO2+20% N2+60% O2) | Huang et al. (2019) |

| Meat/Meat Product | Plasma Source | Processing Parameters | Microorganism | Microbial reduction ($Log_{10}$) | Reference |
|---|---|---|---|---|---|
| Pork loin | Cold nitrogen plasma and lemongrass oil | 500 W, 120 s and lemongrass oil 5 mg/mL, 30 min | *L. monocytogenes* | 2.8 | Cui et al. (2017) |
| Fresh and frozen pork | Corona discharge plasma jet | 58 kHz, 20 kV, 90–120 s | *E. coli* | 1.5 | Choi et al. (2016). |
| | | | *L. monocytogenes* | 1.0 | |
| Pork butt | Flexible thin-layer DBD plasma | $N_2/O_2$, 100 W, 10 min | *L. monocytogenes* | 2.04 | Jayasena et al. (2015) |
| | | | *E. coli* | 2.54 | |
| | | | *S.* Typhimurium | 2.68 | |
| Pork | Pulsed plasma | He, Ar, 0.8 MPa, 20–100 kHz, 1.2 kVA, 10 min | Psychrotropes | 2.70 (He)/1.20 (Ar) | Ulbin Figlewicz et al. (2015a) |
| | | | Yeast and Mold | 2.13 (He)/2.57 (Ar) | |
| Pork | Low pressure plasma | He, Ar, 20 kPa, 10 min | Psychrotropes | 1.60 (He)/1.20 (Ar) | Ulbin Figlewicz et al. |
| | | | Yeast and Mold | 1.90 (He)/0.41 (Ar) | |

| Meat/Meat Product | Plasma Source | Processing Parameters | Microorganism | Microbial reduction ($Log_{10}$) | Reference |
|---|---|---|---|---|---|
| | | | | | (2015b) |
| Pork loins | DBD plasma | He/ He + $O_2$, 3 kV, 30 kHz, 10 min, 3 mm distance between sample and DBD actuator | *L. monocytogenes*<br>*E. coli* | 0.43 (He)/0.59 (He+$O_2$)<br>0.34 (He)/0.55 (He+$O_2$) | Kim et al. (2013) |
| Beef jerky | Clove oil and encapsulated atmospheric pressure plasma | Air, 8.4 kV, 2.2 kHz, 4 min, 0.05% Clove oil concentration | *E. coli* O157:H7 | >7.5 | Yoo et al. (2021) |
| Beef jerky | Plasma beam system | $N_2$ or air, 20 kHz, 300 W, brine (sodium nitrite) solution | *L. innocua* | 0.85 | Inguglia et al. (2020) |
| Beef jerky | Encapsulated atmospheric pressure | Air, 2.2 kHz, 8.4 kV, 5 min (Beef jerky) and 9 min (Sliced | *E. coli* O157:H7 | 0.80 | Lee et al. (2023) |

| Meat/Meat Product | Plasma Source | Processing Parameters | Microorganism | Microbial reduction ($Log_{10}$) | Reference |
|---|---|---|---|---|---|
| | plasma and nisin (100 ppm) | ham) | | | |
| Beef jerky | Flexible thin-layer DBD plasma | Air, 15 kHz, 10 min | *L. monocytogenes* | 2.36 | Yong et al. (2017a) |
| | | | *E. coli* | 2.65 | |
| | | | *S.* Typhimurium | 3.03 | |
| | | | *Aspergillus flavus* | 3.18 | |
| Beef jerky | Radio-frequency atmospheric pressure plasma | Ar, 20,000 sccm, 200 W, 3 min | *S. aureus* | 3–4 | Kim et al. (2014b) |
| Pork jerky | DBD plasma | Air, 4 kHz, 3.8 kV, 40 min | *S. aureus* | ~7.00 | Yong et al. (2019) |
| | | | *Bacillus cereus* | ~6.00 | |
| Bacon | Atmospheric pressure | He/He + $O_2$; 125 W; 14 MHz, | *L. monocytogenes* | 2.06 (He)/2.60 (He+$O_2$) | Kim et al. |

| Meat/Meat Product | Plasma Source | Processing Parameters | Microorganism | Microbial reduction ($Log_{10}$) | Reference |
|---|---|---|---|---|---|
| | plasma | 90 s. | *E. coli* | 1.57 (He)/3.00 (He+$O_2$) | (2011) |
| | | | *S.* Typhimurium | 1.32 (He)/1.73 (He+$O_2$) | |
| Chicken ham | Atmospheric pressure plasma jet | He, N2, O2, 2 kV, 50 kHz, 2 min | *L. monocytogenes* | 1.94-6.52 | Lee et al. (2011) |
| Sliced ham | Encapsulated atmospheric pressure plasma and nisin (100 ppm) | Air, 2.2 kHz, 8.4 kV, 5 min (Beef jerky) and 9 min (Sliced ham) | *E. coli* O157:H7 | 1.96 | Lee et al. (2023) |
| Chicken patties | DBD plasma | 65% $O_2$+ 30% $CO_2$, 70 kV, 1% rosemary, 180 s | Total plate count | 0.55 (plasma)<br>0.80 (plasma+rosemary) | Gao et al. (2019) |
| Ready-to-eat meat product | Cold atmospheric pressure plasma | 70% Ar + 30% $O_2$, 27.8 kHz, 27 kV, 15.5, 31, and 62 W, 2- | *L. innocua* | 0.8 - 1.6 | Rod et al. (2012) |

| Meat/Meat Product | Plasma Source | Processing Parameters | Microorganism | Microbial reduction ($Log_{10}$) | Reference |
|---|---|---|---|---|---|
| (bresaola) | | 60 s | | | |

**Table 3. Effects of Cold Plasma Processing on Quality of Meat and Meat Products**

| Meat/Meat Product | Plasma Source | Processing Parameters | Key Findings | Reference |
|---|---|---|---|---|
| Beef | Atmospheric pressure plasma jet | Air, 600 W, 1 min, Plasma activated water | Comparable lipid oxidation levels in samples thawed by plasma activated water and traditional thawing methods. No detrimental effect on physicochemical and sensory quality traits by PAW thawing compared to traditional thawing methods. | Liao et al. (2020) |
| Chicken | Plasma-activated acetic acid (PAAA) | 2.2 kHz, 8.4 kVpp, 30 min, and 0.8% (v/v) acetic acid | pH, TBARS, and b* values decreased and L* values increased in PAAA-treated samples. | Kang et al. (2022) |
| Chicken breast | DBD-ACP In package | Air, 233 W, 100 kV, 60 Hz, 5 min | MDA content was comparable between untreated and treated samples. | Moutiq et al. (2020) |

| Meat/Meat Product | Plasma Source | Processing Parameters | Key Findings | Reference |
|---|---|---|---|---|
| Chicken breast | DBD-CAP | Air, 70 kV, 5 min, 5-d storage | Similar a* and b* values in control and plasma treated samples, however, plasma treatments increased the L* value. | Zhuang et al (2019) |
| Chicken breasts | Flexible thin-layer DBD plasma | Air, 100 W, 15 kHz, 10 min | Lipid oxidation was not affected by plasma treatment. However, it increased the L* and b* values and decreased the a* value. | Lee et al. (2016) |
| Pork loin | DBD plasma | $CO_2$+ $N_2$+ $O_2$, 85 kV, 60 s | Oxidation of lipids and the production of carbonyls in the oxidation of proteins were increased. | Huang et al. (2019) |
| Pork loin | Cold plasma and lemongrass oil | $N_2$, 500 W, 120 s, and lemongrass oil 5 mg/mL, 30 min | TBARS values were increased upon cold plasma treatment. | Cui et al. (2017) |
| Fresh and | Corona discharge | Air, 58 MHz, 20 kV, 90– | Plasma treatment improved the peroxide value of frozen | Choi et al. (2016) |

| Meat/Meat Product | Plasma Source | Processing Parameters | Key Findings | Reference |
|---|---|---|---|---|
| frozen pork | plasma jet | 120 s | pork. However, the lipid content of unfrozen meat was not influenced. TBARS values were not changed due to plasma treatment. | |
| Pork butt and Beef loin | Flexible thin-layer DBD plasma | $N_2/O_2$, 100 W, 15 kHz 10 min | Lipid oxidation value was increased and a* value was significantly lowered. L* value not significantly affected. | Jayasena et al. (2015) |
| Pork | Pulsed plasma | N2, He, Ar, 0.8 MPa, 20–100 kHz, 1.2 kVA, | Comparable colour parameters and pH values after cold plasma treatment. | Ulbin Figlewicz et al. (2015a) |
| Pork loins | DBD plasma | He/ He + $O_2$, 3 kV, 30 kHz, 10 min, 3 mm distance between sample and DBD actuator | Plasma treatment increased the TBARS values. The pH and L*values decreased, but a* and b* values showed no changes. | Kim et al. (2013) |

| Meat/Meat Product | Plasma Source | Processing Parameters | Key Findings | Reference |
|---|---|---|---|---|
| Fresh pork | Atmospheric pressure plasma | 2.45 GHz, 1.2 kW; process gas air | pH decreased, a* values increased and b* values decreased upon plasma treatment. | Fröhling et al. (2012) |
| Pork | Dielectric barrier discharge plasma | 0.30 W/cm$^2$ in ambient air, with a gap of 5.0 mm | Increase in L* value. Decrease in surface moisture. | Moon et al. (2009) |
| Beef jerky | Plasma beam system | $N_2$ or air, 20 kHz, 300 W, brine (sodium nitrite) solution | Comparable texture and lipid oxidation values in samples cured in plasma-activated brine as opposed to standard curing. Significantly higher a* values in samples cured in plasma-activated brine. | Inguglia et al. (2020) |
| Beef jerky | Flexible thin-layer plasma system | linear electron-beam RF accelerator (2.5 MeV, beam power 40 kW) | Plasma treatment decreased the L* value and increased the a* and ΔE values. | Yong et al. (2017a) |
| Pork jerky | DBD plasma | Air, 4 kHz, 3.8 kV, 40 min | Jerky made with plasma treatment for 40 min had similar | Yong et al. (2019) |

| Meat/Meat Product | Plasma Source | Processing Parameters | Key Findings | Reference |
|---|---|---|---|---|
| | | | color values, nitrosoheme pigment, lipid oxidation, and texture properties as opposed to jerky made with sodium nitrite (100 ppm). | |
| Bacon | Atmospheric pressure plasma (APP) | He/He + $O_2$; 125 W; 14 MHz, 90 s. | Plasma treatment increased the TBARS values in bacon after a 7-d storage L* value of the bacon surface was increased. | Kim et al. (2011) |
| Chicken patties | DBD plasma | 65% $O_2$+ 30% $CO_2$, 70 kV, 1% rosemary, 180 s | Plasma treatment increased lipid oxidation. However, MDA level decreased upon the addition of rosemary extract to the product. | Gao et al. (2019) |
| Canned ground ham | DBD plasma | Air, 600 W, 25 kHz, 30 min | Plasma treatment had no effect on lipid oxidation. | Lee et al. (2018) |
| Ground ham | Atmospheric non- | Air, 1.5 kW, 60 kHz, 30 | Temperature and residual nitrite levels increased when | Jo et al. (2020) |

| Meat/Meat Product | Plasma Source | Processing Parameters | Key Findings | Reference |
|---|---|---|---|---|
| | thermal plasma (ANP) | min | cured by remote infusion of ANP (RANP) compared to sodium nitrite. The color and MDA content of ground hams did not differ between RANP and sodium nitrite during storage. | |
| Ready to eat ham | DBD plasma | 3500 Hz,300 W, 0-28 kV | Plasma treatment had significantly induced the MDA levels, but with no changes in L* and b* values compared to untreated samples. However, a significant increase in a* values was detected. | Yadav et al. (2019) |
| Pork based batter | DBD plasma | Air, 550 W, 25 kHz, 60 s | Plasma treatment did not induce the lipid oxidation in meat batter. The redness value of cooked meat batter gradually increased. | Jung et al. (2017b) |
| Ready-to- | Cold atmospheric | 70% Ar + 30% $O_2$, 27.8 | Higher plasma power with longer treatment duration and | Rod et al. (2012) |

| Meat/Meat Product | Plasma Source | Processing Parameters | Key Findings | Reference |
|---|---|---|---|---|
| eat meat product (bresaola) | pressure plasma | kHz, 27 kV, 15.5, 31, and 62 W, 2-60 s | storage period increased the TBARS values. Significant reductions in redness value. | |

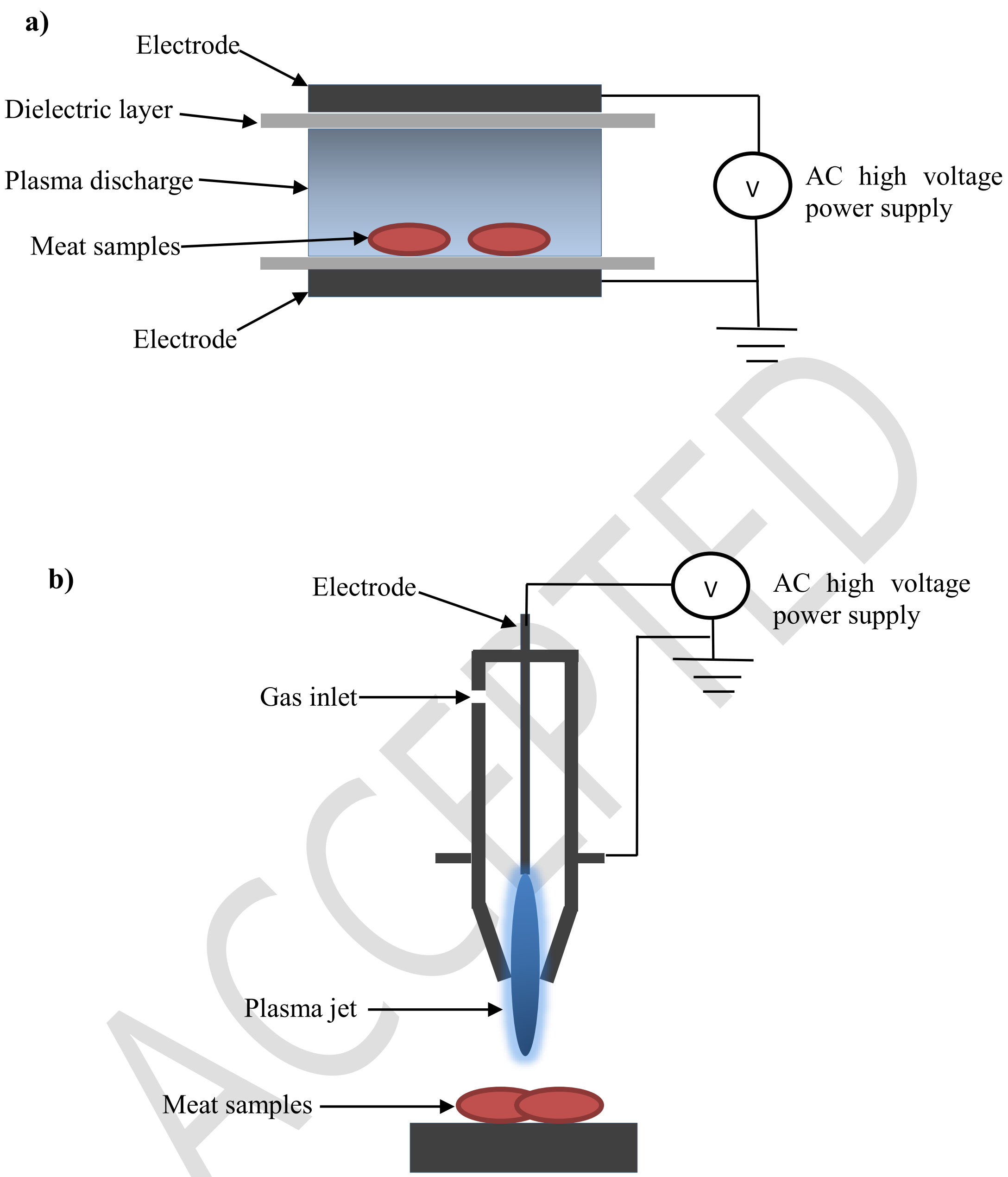
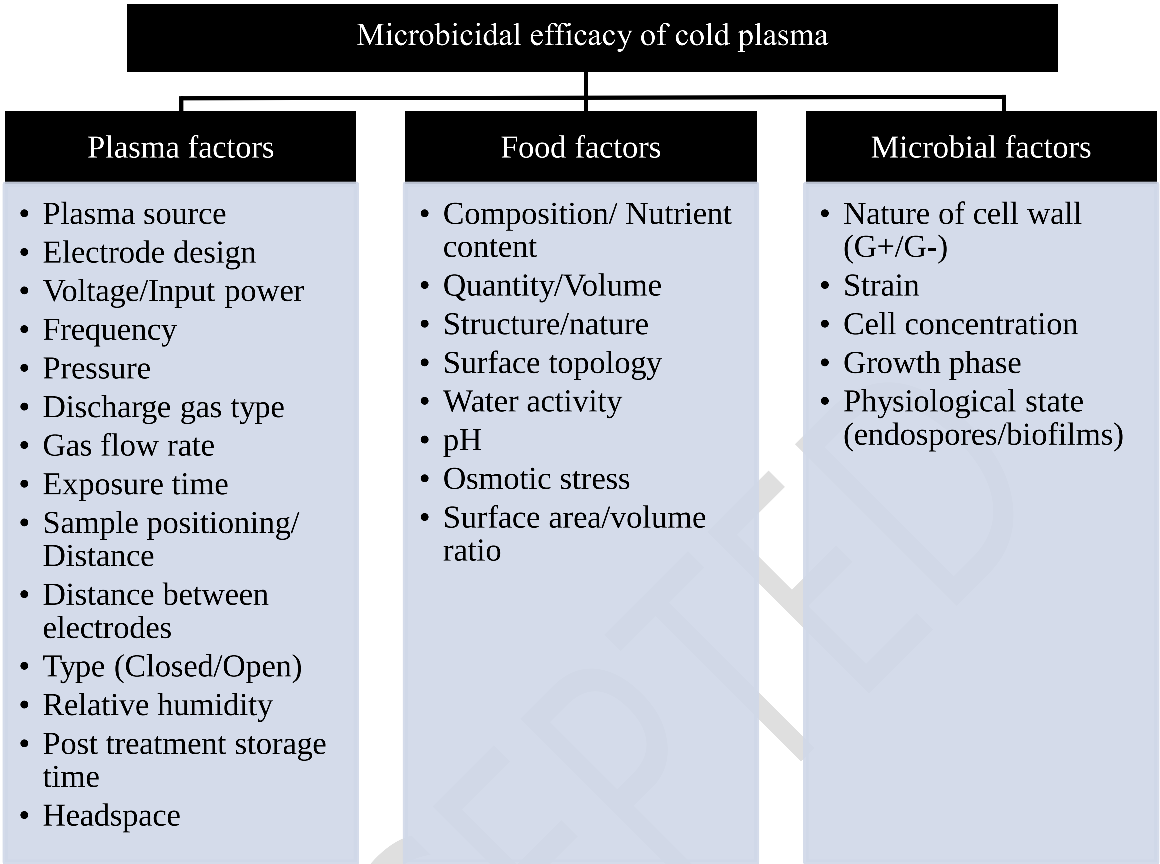
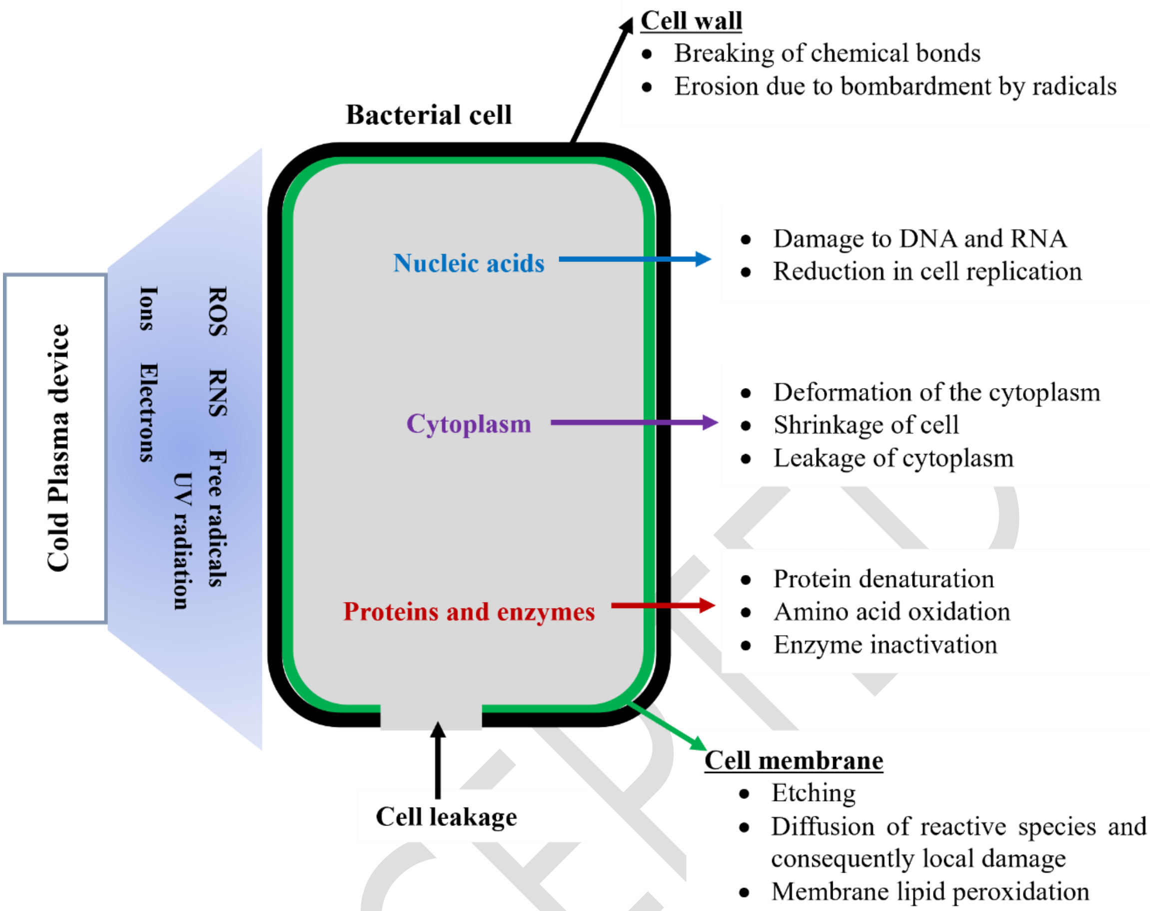

a)
Electrode
Dielectric layer
Plasma discharge
Meat samples
Electrode
V
AC high voltage power supply
b)
Electrode
V
AC high voltage power supply
Gas inlet
Plasma jet
Meat samples

**Fig. 1**



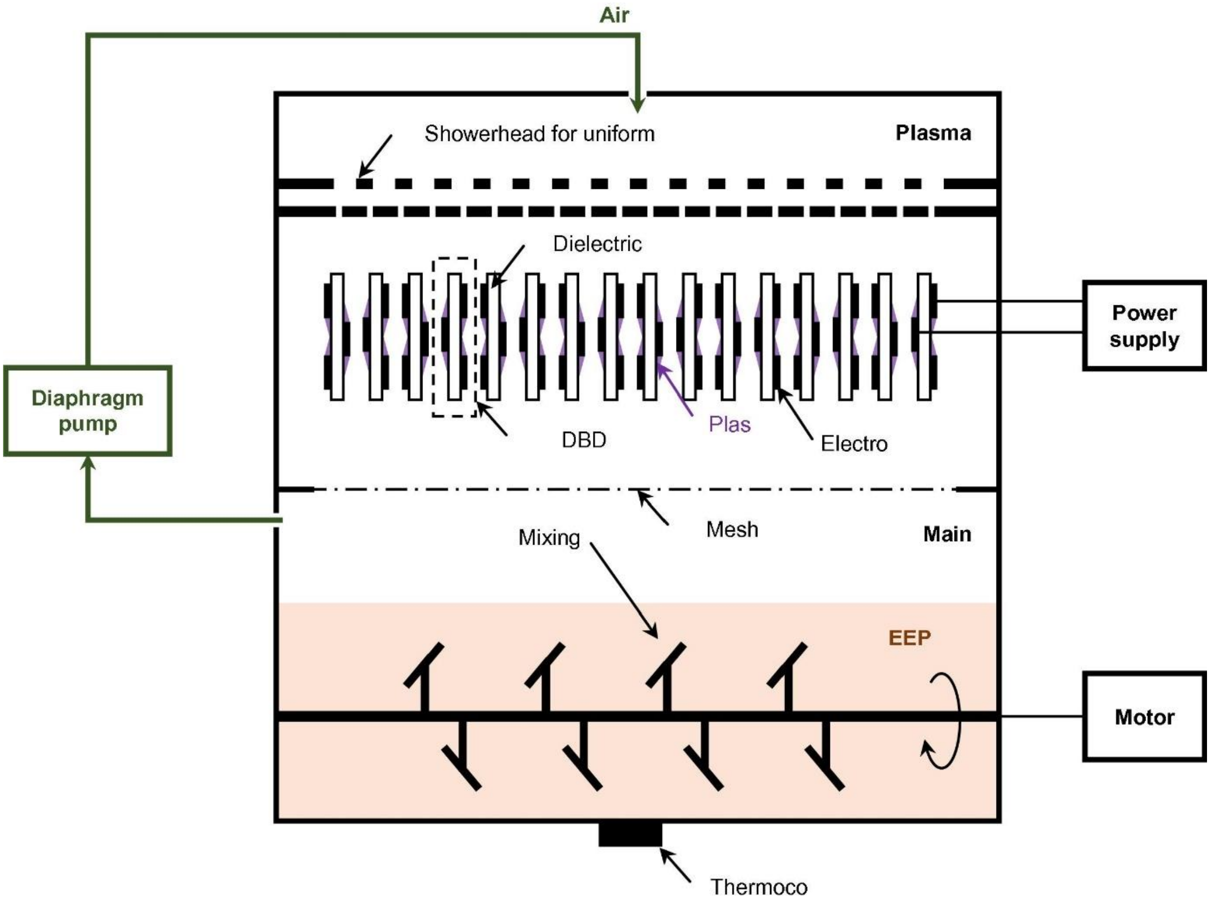
Microbicidal efficacy of cold plasma
Plasma factors
• Plasma source
• Electrode design
• Voltage/Input power
• Frequency
• Pressure
• Discharge gas type
• Gas flow rate
• Exposure time
• Sample positioning/ Distance
• Distance between electrodes
• Type (Closed/Open)
• Relative humidity
• Post treatment storage time
• Headspace
Food factors
• Composition/ Nutrient content
• Quantity/Volume
• Structure/nature
• Surface topology
• Water activity
• pH
• Osmotic stress
• Surface area/volume ratio
Microbial factors
• Nature of cell wall (G+/G-)
• Strain
• Cell concentration
• Growth phase
• Physiological state (endospores/biofilms)


**Fig. 2.**



Cell wall
Breaking of chemical bonds
Erosion due to bombardment by radicals
Bacterial cell
Cold Plasma device
ROS
RNS
Free radicals
UV radiation
Ions
Electrons
Nucleic acids
Damage to DNA and RNA
Reduction in cell replication
Cytoplasm
Deformation of the cytoplasm
Shrinkage of cell
Leakage of cytoplasm
Proteins and enzymes
Protein denaturation
Amino acid oxidation
Enzyme inactivation
Cell leakage
Cell membrane
Etching
Diffusion of reactive species and consequently local damage
Membrane lipid peroxidation


**Fig. 3.**



Air
Showerhead for uniform
Plasma
Dielectric
Power
supply
Diaphragm
pump
DBD
Plas
Electro
Mesh
Mixing
Main
EEP
Motor
Thermoco


**Fig. 4**