

Cold Plasma Technology Harnessing Reactive Species for Safer Meat Preservation

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Abstract: -

Meat preservation requires effective control of microbial contamination while maintaining desirable quality and freshness. Cold plasma technology has emerged as a promising non-thermal approach that can provide microbial control without the use of conventional heat treatment. The technology generates a mixture of reactive oxygen and nitrogen species, charged particles and other active components that interact with microbial cells, disrupting their membranes and damaging essential cellular components. In meat preservation, cold plasma has been investigated for surface decontamination, reduction of foodborne pathogens and spoilage microorganisms, shelf-life extension, biofilm control and in-package treatment. Its application offers the potential to improve microbial safety while minimizing the thermal effects associated with conventional processing. However, excessive treatment may promote lipid and protein oxidation and affect meat colour and other quality attributes. Therefore, careful optimization of plasma conditions is necessary to achieve effective microbial inactivation while preserving the physicochemical and sensory quality of meat.

Keywords: Cold plasma technology; meat preservation; microbial control; non-thermal processing; shelf life; meat quality etc.

Introduction:

Maintaining the safety and quality of meat from processing to consumption remains a major challenge for the meat industry. Microbial contamination can occur during slaughter, cutting, handling and packaging, while oxidation and other biochemical changes can progressively affect colour, flavour, texture and shelf life. Conventional preservation methods are effective in controlling deterioration, but some treatments

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may alter desirable characteristics of meat.

The growing interest in fresh and minimally processed meat has encouraged the development of non-thermal preservation technologies. Among these, cold plasma technology has attracted attention as an alternative approach for controlling microorganisms while avoiding conventional high-temperature processing.

Cold Plasma Technology

Plasma is commonly described as the fourth state of matter. It is generated when sufficient energy is supplied to a gas, producing electrons, ions, excited molecules and reactive species.

In cold plasma, the treatment is performed under conditions that maintain relatively low overall temperatures. Depending on the system and operating conditions, plasma may contain reactive oxygen species, reactive nitrogen species, charged particles and ultraviolet radiation. These active components are largely responsible for its antimicrobial effects.

Different plasma systems have been investigated for meat processing, including dielectric barrier discharge, atmospheric-pressure plasma jets and corona discharge. Dielectric barrier discharge and atmospheric-pressure plasma jets are particularly relevant to meat processing because of their adaptability

to different treatment requirements (Akhtar *et al.*, 2022).

How Cold Plasma Works

The antimicrobial activity of cold plasma results mainly from the interaction of reactive species with microbial cells. These species can attack the cell envelope, causing oxidation of membrane components and disruption of membrane integrity.

Plasma-generated reactive species can also cause oxidative damage to proteins, enzymes and genetic material. Thus, several cellular targets may be affected simultaneously, ultimately interfering with microbial functions and leading to cell inactivation (Nwabor *et al.*, 2022).

Applications in Meat Preservation

The major application of cold plasma technology in meat is microbial decontamination. It has been investigated for reducing important foodborne pathogens and spoilage microorganisms in beef, pork, poultry and other meat products. By reducing the initial microbial load, cold plasma treatment can contribute to improved microbiological stability and extended shelf life.

Cold plasma has also attracted attention for biofilm control in meat-processing environments. Biofilms allow microorganisms to persist on processing surfaces and can become a continuous source of contamination.

Plasma-based treatments therefore offer potential for reducing bacterial contamination and biofilm formation.

Another promising application is in-package treatment, in which meat is exposed to plasma within a packaging environment. This approach can provide microbial treatment while limiting the possibility of contamination after processing. These applications demonstrate the potential of cold plasma as a flexible technology for improving the safety and storage stability of meat and meat products (Oliulla *et al.*, 2024).

Effect on Meat Quality

Microbial inactivation must be achieved without compromising meat quality. Cold plasma treatment can influence colour, pH, lipid oxidation, protein characteristics and sensory properties.

The same reactive species responsible for microbial inactivation can also interact with meat components. Excessive treatment may accelerate lipid oxidation and affect colour, while protein oxidation can alter certain physicochemical properties. However, the extent of these changes depends on treatment intensity, exposure time, plasma composition and the characteristics of the meat product (Akhtar *et al.*, 2022)

Challenges in Meat Application

The application of cold plasma to meat requires careful control of plasma power,

treatment time, working gas, electrode configuration and treatment geometry. Differences in meat composition, moisture and surface characteristics can also influence treatment effectiveness.

A major challenge is achieving sufficient microbial inactivation without excessive oxidation or other quality changes. Treatment conditions therefore need to be optimized for individual meat products rather than applying a single condition universally.

Commercial implementation also requires attention to treatment uniformity, process standardization, equipment scalability, cost and food-safety considerations. The technology remains largely at the developmental stage for many meat applications, requiring further validation under industrial conditions (Zhang *et al.*, 2025).

Future Directions

Future research is moving towards optimized and product-specific cold plasma treatments that provide effective microbial control while maintaining meat quality. Combining cold plasma with other preservation technologies may provide additional opportunities for improving microbial safety and storage stability.

Development of scalable plasma systems, improved control of reactive species and better understanding of plasma–meat interactions will be important for commercial

application. Further research should also focus on treatment standardization, long-term quality, safety and the economic feasibility of integrating cold plasma into meat-processing operations.

Conclusion

Cold plasma technology offers a promising non-thermal approach to meat preservation. Its reactive species can target microorganisms through membrane disruption and cellular damage, creating opportunities for microbial decontamination, shelf-life extension, biofilm control and in-package treatment. However, excessive treatment can affect meat components through oxidative reactions. Achieving the right balance between microbial inactivation and quality preservation is therefore essential. With optimized processing conditions and further technological development, cold plasma technology has considerable potential for improving the safety and storage stability of meat and meat products.

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