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Commentary

Cold Plasma Technology in Food Processing: Current Advances in Microbial Safety, Quality Preservation and Future Applications

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DESCRIPTION

Cold Plasma (CP) technology has emerged as one of the most promising Non-Thermal Food Processing (NTFP) technologies improving food safety while reducing the quality losses commonly associated with conventional thermal treatments. Plasma is an ionized or partially ionized gas containing electrons, ions, excited atoms and molecules, free radicals, photons and other reactive species. In cold plasma systems, the bulk temperature can remain relatively low while energetic electrons generate chemically active species capable of interacting with microorganisms and food components. This characteristic makes CP attractive for processing foods that are sensitive to heat. Current research has expanded its application from microbial decontamination to enzyme inactivation, mycotoxin reduction, food-component modification, packaging treatment and shelf-life extension.

The antimicrobial activity of CP is primarily associated with the formation of reactive oxygen and nitrogen species. Important reactive species include ozone, singlet oxygen, hydroxyl radicals, nitric oxide, nitrogen dioxide and hydrogen peroxide. The exact composition of the plasma depends on the feed gas and operating conditions. Oxygen, nitrogen, air, argon and helium can produce different plasma chemistries and consequently different effects on microorganisms and food materials. Research indicates that voltage, frequency, treatment duration, electrode configuration, gas composition and electrode-to-food distance strongly influence processing performance.

The microbial inactivation mechanism involves several simultaneous effects. Reactive species can attack the microbial cell wall and cell membrane, alter membrane permeability, oxidize cellular proteins, damage nucleic acids and disrupt essential metabolic functions. These interactions can ultimately result in loss of cellular integrity and microbial death. Both Gram-positive and Gram-negative bacteria can be affected, although their responses may differ because of differences in cell-envelope structure. CP has also demonstrated activity against yeasts, moulds and, under suitable conditions, bacterial spores.

One major advantage of CP is its potential to reduce microorganisms without exposing foods to severe heat. Conventional pasteurization and sterilization can adversely affect thermolabile vitamins, pigments, flavor compounds and other quality attributes. CP operates at comparatively low temperatures and therefore provides an opportunity to achieve microbial control while maintaining fresh-like characteristics. Recent research has investigated CP treatment of fruits, vegetables, meat, seafood, beverages, spices, grains, dairy products and other food matrices. A 2024 review reported applications involving microbial inactivation, mycotoxin degradation, enzyme inactivation, protein modification and packaging-film treatment.

The technology is particularly promising for fresh and minimally processed foods. Fresh produce may carry pathogenic or spoilage microorganisms on its surface, while conventional heat treatments can cause undesirable softening, discoloration and nutrient losses. Surface CP treatment can provide antimicrobial action while avoiding intense heating. Its effectiveness, however, depends on surface characteristics, microbial attachment, food geometry, moisture content, roughness and treatment parameters. Irregular surfaces may shield microorganisms from direct plasma exposure, making process uniformity an important research challenge.

Food packaging represents another important research area. Plasma treatment can modify the surface characteristics of polymers by changing surface energy, wettability, adhesion and other physicochemical properties. These modifications can improve interactions between packaging materials and coatings or printing layers. CP can also be incorporated into packaging-related decontamination systems, creating opportunities for active or in-package treatment. Such approaches may be particularly valuable because the food can potentially be treated with reduced direct exposure to plasma-generated reactive species.

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CONCLUSION

Cold plasma is an important emerging technology with considerable potential for modern food processing. Its ability to generate at relatively low temperatures enables microbial decontamination and contaminant reduction while potentially preserving desirable food characteristics. Applications now extend across fresh produce, meat, seafood, beverages, grains, spices, packaging and other food systems. However, chemical modification of food components, oxidative reactions, treatment uniformity, toxicological safety, regulatory requirements, cost and industrial scalability remain important challenges. Current research increasingly supports a controlled, food-specific approach in which plasma chemistry and processing conditions are carefully optimized. With advances in process engineering, safety assessment, automation and sustainable design, CP could become an important component of next-generation food preservation and processing systems.