क्रमांक: COOP/2023/KOTA/201080/25/46

एग्रीकल्चर फ़ोरम फॉर टेक्निकल एजुकेशन ऑफ़ फार्मिंग सोसायटी

कोटा, राजस्थान

Application of Cold Plasma Technology in Food processing

संकलन

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INTRODUCTION

The food-processing sector is rapidly evolving as consumers increasingly prefer high-quality, minimally processed, and additive-free products. Traditional thermal methods like pasteurization and sterilization effectively inactivate microbes but often degrade sensory and nutritional qualities. As a result, non-thermal technologies have gained prominence, with cold plasma technology (CPT) emerging as a versatile option that ensures microbial safety while preserving food quality. Cold plasma is a partially ionized gas containing ions, electrons, radicals, and excited molecules generated at atmospheric or low pressure. Unlike thermal plasma, it operates with high-energy electrons but near-ambient temperatures, making it suitable for heat-sensitive foods. CPT is valued for its effectiveness in microbial inactivation, chemical and enzymatic decontamination, surface modification, seed stimulation, and packaging sanitation. This review outlines the principles, applications, challenges, and future potential of cold plasma for commercial food systems.

Definition and Characteristics: Cold plasma is an electrically energized, quasi-neutral gas in which a small fraction of particles are ionized, producing a mixture of electrons, ions, free radicals, UV photons, and excited species such as O*, N*, and OH*. Unlike thermal plasma, its high-energy electrons coexist with a near-ambient gas temperature, enabling safe interaction with heat-sensitive foods. This low-temperature behaviour helps preserve nutrients, sensory qualities, and structural integrity.

The reactive species formed during plasma discharge drive microbial inactivation, chemical degradation of contaminants, and functional modification of food surfaces, making cold plasma an effective non-thermal technology for enhancing food safety and quality.

Plasma Generation Techniques: Cold plasma can be generated using several electrical discharge systems, each suited to different food-processing needs. Dielectric Barrier Discharge (DBD) produces uniform atmospheric-pressure plasma ideal for surface decontamination of foods and packaging. Atmospheric Pressure Plasma Jets (APPJ) create a directed plasma plume suitable for irregular surfaces, liquids, and localized treatments.

Radio Frequency (RF) plasma, generated under low pressure, is effective for polymer modification and packaging enhancement. Glow Discharge Plasma provides uniform, controllable plasma for microbial reduction in liquid foods like milk and juices. Corona Discharge Plasma, valued for its low cost and simple design, is commonly used for seed treatment, surface cleaning, and packaging modification. Collectively, these systems offer flexible non-thermal solutions for food preservation and quality enhancement.

Chemical Interaction with Food Components: Cold plasma affects food systems through physical, chemical, and biochemical mechanisms that enhance microbial safety and quality. Its antimicrobial action mainly results from reactive oxygen and nitrogen species (ROS/RNS), which damage microbial membranes, proteins, DNA, and metabolic functions. UV photons from the plasma further disrupt DNA, enabling strong activity against resistant microbes such as spores, yeasts, and moulds. Energetic particles erode cell walls, and electrostatic effects destabilize membrane potential, causing leakage of cell contents. Beyond microbial inactivation, cold plasma can modify food components by inducing protein cross-linking, promoting lipid oxidation, and altering carbohydrates through depolymerization. It also inactivates enzymes like polyphenol oxidase, peroxidase, and pectin methylesterase, helping preserve colour, texture, and flavour. Together, these mechanisms enhance food safety while retaining nutritional and sensory quality.

Applications of Cold Plasma in Food Processing

- Microbial Decontamination: Cold plasma is a highly effective non-thermal technology for microbial decontamination, capable of reducing pathogens, spoilage organisms, and surface contaminants. It shows strong activity against major foodborne microbes such as E. coli, Salmonella, Listeria monocytogenes, Staphylococcus aureus, Bacillus spores, and toxin-producing moulds. The technology is applicable across diverse food categories: in fruits and vegetables, it provides efficient surface decontamination while maintaining colour, firmness, and freshness; in meat and poultry, it lowers pathogenic loads without affecting sensory traits; in seafood, it controls Listeria and spoilage bacteria; in grains and nuts, it reduces aflatoxins, molds, and insect eggs; and in dairy, it decreases microbial counts while preserving nutrients. Overall, cold plasma offers a versatile, safe, and quality-preserving approach to microbial control in food systems.

- **Chemical Decontamination:** Cold plasma also plays a crucial role in chemical decontamination, offering an effective non-thermal method for reducing a wide range of hazardous chemical residues present on food surfaces. It has been shown to significantly lower levels of pesticide residues, degrade various mycotoxins, and eliminate multiple chemical contaminants including nitrates, synthetic dyes, and certain allergenic compounds. The reactive oxygen and nitrogen species generated during plasma treatment initiate oxidative and reductive reactions that break down these harmful chemicals into simpler, non-toxic by-products, thereby enhancing food safety without compromising nutritional or sensory quality. This makes cold plasma a highly promising technology for ensuring cleaner, safer food while reducing reliance on traditional chemical detoxification methods.
- **Modification of Food Biopolymers:** Cold plasma can modify major food biopolymers by altering the structure and functionality of proteins, carbohydrates, and lipids. In proteins, it improves solubility, emulsifying and foaming properties, promotes useful cross-linking, and can enhance digestibility beneficial for bakery, dairy, and plant-based products. For carbohydrates, it influences starch gelatinization, retrogradation, water-binding capacity, and viscosity, improving the texture and functionality of foods such as noodles, sauces, and baked products. While cold plasma may induce some lipid oxidation, controlled conditions help minimize adverse effects and can even enhance oxidative stability. Overall, it offers strong potential for improving the functional performance of food biopolymers across various applications.
- **Cold Plasma in Food Packaging:** Cold plasma is increasingly valuable in food packaging, improving both conventional and biodegradable materials. Its main role is surface activation, which enhances adhesion, printability, sealing, and moisture- or gas-barrier properties. It also enables antimicrobial packaging through plasma-assisted deposition of antimicrobial agents, nano-coatings, or reactive species that suppress microbial growth and extend shelf-life. For biodegradable films, plasma treatment boosts hydrophobicity, mechanical strength, and durability, supporting sustainable packaging solutions. Overall, cold plasma offers a versatile and innovative method to enhance packaging performance, safety, and environmental sustainability.

- **Improvement of Food Quality Attribute:** Cold plasma enhances food quality by improving colour retention, stabilizing flavour compounds, modifying texture, and preserving essential nutrients during processing and storage. Because it is non-thermal, it avoids heat-induced degradation, helping foods retain their natural appearance, freshness, and sensory traits. Plasma-treated juices, for example, maintain higher levels of vitamins and bioactive compounds compared to heat-processed juices, while delicate flavour components in herbs and spices remain largely intact. By supporting better colour, flavour, texture, and nutritional value, cold plasma offers a promising approach for producing high-quality, minimally processed foods that align with modern consumer expectations.
- **Cold Plasma for Seed Processing and Germination:** Cold plasma is increasingly being used in seed processing and germination enhancement due to its ability to disinfect seeds, improve germination rates, boost seed vigour, and reduce the incidence of seedborne diseases. By exposing seeds to reactive plasma species, the technology effectively eliminates surface pathogens without relying on chemical treatments, thereby creating a cleaner and safer planting material. At the same time, plasma treatment can modify the seed coat, improve water uptake, and stimulate physiological responses that promote faster and more uniform germination. These combined effects contribute to healthier seedlings and improved crop establishment, ultimately enhancing agricultural productivity and supporting more sustainable cultivation practices.

Effects of Cold Plasma on Physicochemical, Nutritional, and Sensory Properties

Cold plasma treatment positively influences the physicochemical, nutritional, and sensory qualities of foods, offering clear advantages over traditional thermal processing. It causes minimal loss of vitamins, phytochemicals, and antioxidants when treatment conditions are well optimized. Sensory attributes such as colour, texture, and flavour are also better retained, as cold plasma limits enzymatic browning, prevents excessive pigment degradation, and avoids heat-induced off-flavours or protein denaturation. Fruits maintain firmness, meats preserve structural integrity, and volatile compounds remain largely stable. Overall, cold plasma provides effective microbial inactivation while maintaining the nutritional and sensory quality of foods.

Safety and Regulatory Aspects: Cold plasma is considered a safe and promising non-thermal food-processing technology, but its commercial use still requires product-specific regulatory approval in many regions. Safety assessments focus on potential toxicological risks, including chemical residues, reactive species behaviour, and any structural or compositional changes in treated foods. Regulators evaluate chemical modifications, formation of new compounds, and possible genotoxic effects to ensure consumer safety. As industrial applications grow, well-defined risk assessments, standardized safety guidelines, and transparent labelling will be essential for regulatory compliance and consumer confidence.

Limitations and Challenges: Despite its benefits, cold plasma technology faces challenges that hinder large-scale use. Its limited penetration makes it effective mainly for surface treatments, reducing suitability for foods with internal contamination or complex structures. Plasma chemistry varies with gas type, power level, and environmental conditions, making standardization difficult. Industrial-scale application is constrained by engineering limitations, the need for uniform plasma distribution, and higher operational requirements. High installation and maintenance costs further limit adoption, especially for smaller processors. Improper treatment can also accelerate lipid oxidation in some foods. Moreover, the lack of standardized protocols and clear regulatory guidelines slows approval and commercialization. Addressing these barriers is essential for wider implementation of cold plasma in food processing.

CONCLUSION

Cold plasma technology presents a revolutionary shift in food processing, driven by its non-thermal nature, energy efficiency, minimal impact on food quality, and wide applicability across microbial safety, quality enhancement, and material modification. Although challenges related to penetration depth, cost, standardization, and regulatory acceptance remain, ongoing research and technological innovations are rapidly overcoming these barriers. As the food industry moves toward safer, sustainable, and minimally processed solutions, cold plasma is poised to become a central component of next-generation food processing systems.