Cold Atmospheric Plasma: A Breakthrough in Non-Thermal Food Processing

Vasu Devarapalli[1] *, Dr. Sandip Gangil[2], Dr. Ravi Kumar Sahu[3], Rahul[1] and Maneesh Sonkar[1]

[1]Research Scholar, Department of processing and food engineering, ICAR - Central Institute of Agricultural Engineering, Bhopal

[2]Principal Scientist, Agricultural Energy and Power Division, ICAR - Central Institute of Agricultural Engineering, Bhopal

[3]Senior Research Fellow, Agricultural Energy and Power Division, ICAR - Central Institute of Agricultural Engineering, Bhopal

Corresponding Email: vasu455422@gmail.com

Introduction

Most of us are familiar with three states of matter—solid, liquid, and gas. However, science tells us that there is a fourth state of matter called plasma, which is far more energetic and dynamic than the others. Plasma is formed when energy is added to a gas, causing its atoms to break apart into charged particles such as ions, electrons, and reactive species. Though it sounds futuristic, plasma is not uncommon in daily life—it exists naturally in lightning, flames, the aurora borealis, and even in the sun.

In food processing, heat has long been the primary tool for ensuring safety and extending shelf life. Techniques such as pasteurization, sterilization, and canning rely on high temperatures to destroy harmful microorganisms. While effective, these thermal methods often come with a cost. Excessive heat can degrade heat-sensitive vitamins, alter natural colour, reduce antioxidant content, and diminish fresh flavours and textures. As consumers increasingly demand foods that are not only safe but also fresh-like, nutritious, and minimally processed, the limitations of heat-based processing have become more apparent.

This challenge has led scientists to explore innovative, non-thermal alternatives, and one of the most exciting among them is Cold Atmospheric Plasma (CAP). Unlike conventional plasma, which is extremely hot, cold plasma can be generated at or near room temperature. Despite its mild thermal nature, CAP is highly reactive, producing a rich mix of charged particles, ultraviolet photons, and reactive oxygen and nitrogen species capable of inactivating microorganisms. In essence, it delivers the power of lightning without the heat, making it an ideal technology for food preservation.

By bridging the gap between food safety and quality retention, cold atmospheric plasma represents a breakthrough in modern food processing, offering a way to protect foods while preserving their natural taste, appearance, and nutritional value.

The Science: How Cold Plasma Works

At first glance, cold atmospheric plasma may seem like something out of science fiction, but the science behind it is both fascinating and practical. The power of cold plasma lies not in heat, but in carefully controlled electrical energy that transforms ordinary air into a highly reactive tool for food safety.

The process begins with generating the spark. Cold plasma is produced using electrical discharge systems that operate at atmospheric pressure, meaning no vacuum is required. Two of the most commonly used technologies are Dielectric Barrier Discharge (DBD) and plasma jets. In DBD systems, an electrical voltage is applied across two electrodes separated by an insulating barrier, creating a uniform plasma field over the food surface. Plasma jets, on the other hand, generate a focused stream of plasma that can be directed precisely onto complex or irregular food surfaces. Both methods allow plasma to be generated at room temperature, making them suitable for delicate, heat-sensitive foods.

Once the plasma is formed, it creates what can be described as a "chemical cocktail". This cocktail consists of highly reactive oxygen and nitrogen species, commonly known as RONS. These include molecules such as ozone, hydrogen peroxide, nitric oxide, and superoxide radicals. While these species are short-lived, they are extremely effective. They carry the antimicrobial power of plasma, enabling it to attack microorganisms rapidly and efficiently without leaving chemical residues.

The mechanism of action of cold plasma is fundamentally different from thermal processing. Instead of "cooking" the food to kill microbes, plasma works by physically and chemically disrupting microbial cells. The reactive species interact with bacterial cell walls and membranes, causing microscopic damage often described as "etching." This leads to leakage of cellular contents, disruption of vital metabolic processes, and ultimately cell death. Because the energy is concentrated on the microorganisms rather than the food matrix, the overall temperature of the product remains low. As a result, cold plasma achieves microbial inactivation while preserving the food's natural texture, flavour, color, and nutritional quality. Through this unique combination of electrical energy and reactive chemistry, cold atmospheric plasma offers a powerful, non-thermal approach to food processing, one that ensures safety without sacrificing quality.

Key Benefits: Why It's a Food Industry Game-Changer

Preserving the "Fresh" Factor

One of the most compelling advantages of cold atmospheric plasma (CAP) is its ability to preserve the fresh-like quality of foods. Because the treatment operates at near-room temperature, heat-sensitive nutrients such as vitamins, antioxidants, and bioactive compounds are largely retained. Unlike conventional thermal processes, CAP does not cause softening of tissues, discoloration, or loss of natural aroma. As a result, fruits, vegetables, and minimally processed foods maintain their original texture, color, and sensory attributes, closely resembling freshly harvested produce.

Eco-Friendly and Chemical-Free Processing

Cold atmospheric plasma offers a sustainable alternative to traditional sanitation methods that depend heavily on water and chemical disinfectants such as chlorine. CAP significantly reduces water consumption and eliminates the need for chemical agents, thereby avoiding the formation of harmful residues and by-products. Since plasma is generated using electricity and ambient air, the process is environmentally friendly and aligns well with the growing emphasis on green and sustainable food processing technologies.

Energy-Efficient Operation

Another key benefit of CAP is its energy efficiency. Conventional thermal processing requires substantial energy to heat food products and maintain high temperatures for extended periods. In contrast, cold plasma uses energy primarily to generate reactive species that inactivate microorganisms without heating the entire product. This targeted energy use results in lower power consumption, shorter processing times, and reduced operational costs, making CAP an economically attractive option for modern food industries.

Together, these advantages position cold atmospheric plasma as a transformative technology capable of meeting current industry demands for food safety, quality retention, and sustainability.

Applications of Cold Atmospheric Plasma (CAP) in the Food Industry

Cold atmospheric plasma (CAP) has gained significant attention as a non-thermal, chemical-free, and sustainable technology for improving food safety, quality, and functionality. Its applications in the food industry broadly fall into microbial safety, contaminant removal, and food quality enhancement, achieved through both direct and indirect plasma delivery systems

1. Microbial Inactivation and Food Safety

One of the most established applications of CAP is the inactivation of foodborne microorganisms, including bacteria, fungi, spores, and viruses. CAP effectively disrupts microbial cell membranes, proteins, and DNA through reactive oxygen and nitrogen species (RONS), without raising product temperature. It has been successfully applied to fresh fruits and vegetables, meat and poultry, seafood, grains, spices, and liquid foods, achieving significant microbial reduction while preserving sensory and nutritional quality

2. Decontamination of Chemical Hazards

CAP is highly effective in the degradation of chemical contaminants such as pesticide residues, mycotoxins, food allergens, and industrial pollutants. Plasma-generated reactive species break complex chemical bonds, converting hazardous compounds into less toxic or non-toxic forms. Importantly, this process does not require added chemicals or high temperatures, making it suitable for clean-label food processing

3. Food Functionalization and Quality Enhancement

Beyond safety, CAP is increasingly used for **food functionalization**, where surface and structural modifications improve product quality. Applications include:

- Reduction in cooking time and improvement in the texture of grains such as brown rice
- Modification of starch and protein functionality, enhancing solubility, emulsification, and gelation properties
- Surface etching and wettability enhancement, which improves hydration and processing efficiency

These effects arise from plasma-induced microstructural changes and controlled oxidation, offering new possibilities in food formulation and product development

4. Plasma-Activated Media for Indirect Applications

To overcome the limitations of direct plasma exposure, CAP is also applied indirectly through:

- Plasma-activated gases (PAG) for storage and packaging decontamination
- Plasma-activated liquids (PAL) such as plasma-activated water for washing, spraying, and sanitizing foods
- Plasma-activated hydrogels (PAH) for prolonged antimicrobial activity

These approaches enhance treatment uniformity, scalability, and practicality for industrial use

5. Applications in Packaging and Shelf-Life Extension

CAP is increasingly explored for in-package treatment and packaging material sterilization, reducing post-processing contamination and extending shelf life. Its compatibility with packaged foods makes it particularly attractive for fresh-cut and minimally processed products

Toxicology and Chemical Safety

Whenever a new food processing technology is introduced, consumer safety is the foremost concern, and cold atmospheric plasma (CAP) is no exception. Since CAP works by generating reactive oxygen and nitrogen species (RONS), questions naturally arise about whether these reactive compounds could leave harmful residues or cause undesirable chemical changes in food. Extensive scientific studies, however, indicate that the reactive species produced during plasma treatment are short-lived. They rapidly react with microbial cells and then revert to stable, naturally occurring compounds such as oxygen, nitrogen, and water.

Importantly, research has shown that CAP treatment does not introduce toxic residues or synthetic chemicals into foods when applied under controlled conditions. Most of the chemical changes induced by plasma are confined to the food surface and are comparable to naturally occurring oxidative processes that already happen during storage and handling. Toxicological evaluations conducted so far suggest that plasma-treated foods remain safe for consumption, with no evidence of mutagenic or carcinogenic effects. This growing body of evidence is helping to build confidence among scientists, regulators, and consumers alike.

Global Regulatory Status

From a regulatory perspective, cold atmospheric plasma is still an emerging technology, but it is steadily moving toward wider acceptance. In the United States, plasma-based treatments are being evaluated under existing food safety frameworks, particularly when the process does not introduce additives and leaves no residues. The U.S. Food and Drug Administration (FDA) consider CAP on a case-by-case basis, focusing on its intended use, treatment conditions, and impact on food composition.

In Europe, the European Food Safety Authority (EFSA) is closely examining cold plasma within the context of novel food processing technologies. While CAP is not yet universally approved for all food categories, ongoing risk assessments and research projects are contributing to the development of regulatory guidelines. Other countries, including those in Asia and Australia, are also actively investigating CAP for applications such as surface decontamination of fresh produce, grains, and packaging materials.

The Road Ahead: Challenges and Future Prospects

While cold atmospheric plasma (CAP) has demonstrated remarkable potential at the laboratory and pilot scales, one of the major challenges lies in scaling up the technology for industrial applications. Laboratory systems typically treat small, uniform samples under controlled conditions, whereas industrial food processing involves large volumes, diverse product shapes, and continuous operation. Ensuring uniform plasma exposure across complex food surfaces and maintaining consistent treatment efficacy at high throughput remain key technical hurdles. Addressing these challenges will require advances in reactor design, process control, and integration of CAP systems into existing food processing lines.

The cost factor is another important consideration influencing the adoption of cold plasma technology. Although CAP is energy efficient during operation, the initial capital investment for plasma generators, power supplies, and control systems can be relatively high, particularly for small and medium-scale food processors. Additionally, the lack of standardized commercial equipment and processing guidelines can increase uncertainty for producers. However, as the technology matures and demand increases, equipment costs are expected to decline. Long-term savings associated with reduced energy use, lower water consumption, and elimination of chemical disinfectants may ultimately outweigh the initial investment.

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