**Cold Plasma Technology in Fruits and Vegetables: A Review**

**Abstract**

Cold plasma technology has emerged as a revolutionary non-thermal approach for enhancing the postharvest quality and safety of fruits and vegetables. Unlike conventional thermal processing methods, cold plasma operates at near-room temperatures, making it highly suitable for fresh produce. This technology uses ionized gases to generate reactive species that effectively inactivate surface pathogens, degrade pesticide residues, and delay spoilage—without compromising nutritional and sensory quality. Numerous studies have demonstrated cold plasma’s efficiency in extending shelf-life, preserving firmness, and reducing microbial contamination across a wide range of fruits and vegetables. Additionally, its environmentally friendly nature aligns with the global demand for sustainable food preservation methods. However, challenges such as surface-only treatment, potential oxidative damage, and scalability remain to be addressed. This review explores the principles, applications, benefits, and future prospects of cold plasma technology in the context of fruit and vegetable processing, offering valuable insights for researchers and the agri-food industry.

**Keywords:** Cold plasma technology**,** Postharvest preservation**,** Non-thermal processing**,** Fruits and vegetables**,** Shelf-life extension**,** Microbial decontamination

**1. Introduction**

Fruits and vegetables are vital components of the human diet, offering a rich source of vitamins, minerals, dietary fiber, antioxidants, and phytochemicals that contribute to health and disease prevention.(1,2) However, these commodities are highly perishable due to their high moisture content, physiological activity, and susceptibility to microbial spoilage. Globally, postharvest losses of fruits and vegetables can range between 20–40%, especially in developing countries, primarily due to improper handling, storage, and lack of appropriate preservation techniques. (3,4)

Traditionally, various methods such as refrigeration, thermal processing, chemical treatments, and modified atmosphere packaging have been employed to extend the shelf life of fresh produce.5,6) While effective to a degree, these methods often come with limitations such as nutrient degradation, sensory quality loss, chemical residues, and energy-intensive operations.(7,8) As consumer demand shifts toward minimally processed, additive-free, and fresh-like products, there is a growing need for innovative technologies that can meet both safety and quality expectations without compromising the environment.(2,4)

Cold plasma technology has gained significant attention as a novel, non-thermal, and eco-friendly solution for food preservation. It involves the generation of reactive species—such as reactive oxygen species (ROS), reactive nitrogen species (RNS), UV photons, and charged particles—through ionization of gases under ambient or slightly elevated temperatures. These reactive agents can effectively inactivate a broad spectrum of microorganisms, degrade pesticide residues, and modify surface properties of produce without affecting the internal quality. (5,6)

In the context of fruits and vegetables, cold plasma offers a promising tool for microbial decontamination, enzymatic activity suppression, delay of ripening, and enhancement of product safety. Its application can range from surface sterilization of produce to active packaging and seed treatment. Several studies have shown that cold plasma can preserve firmness, color, taste, and nutritional content—making it suitable for maintaining postharvest quality and extending marketability.(7,8)

Despite its potential, adoption of cold plasma in the agri-food sector is still at a nascent stage. Factors such as treatment optimization, equipment cost, regulatory approvals, and consumer acceptance pose challenges that need to be addressed through collaborative research and industrial trials.(9,10)

**2. Fundamentals of Cold Plasma Technology**

Cold plasma, often referred to as the "fourth state of matter," represents an ionized gas composed of a dynamic mixture of electrons, ions, neutral atoms, and reactive species. When energy is applied to a gas—typically oxygen, nitrogen, helium, or air—it becomes energized and partially ionized, giving rise to a plasma state. (11,12)This energized state can be either thermal or non-thermal, with cold plasma specifically categorized as a non-thermal plasma due to its near-room temperature operation. Unlike thermal plasma, which is excessively hot and unsuitable for temperature-sensitive materials, cold plasma generates minimal heat, making it ideal for treating delicate food items like fruits and vegetables.(13,14)

The primary mechanism by which cold plasma acts involves the generation of a wide range of reactive chemical species. (15,16) These include reactive oxygen species (ROS) such as ozone, hydroxyl radicals, and hydrogen peroxide, as well as reactive nitrogen species (RNS) like nitric oxide and nitrogen dioxide. Alongside these chemical species, cold plasma also produces UV photons and charged particles. When applied to biological contaminants or enzymatic compounds on the surface of produce, these agents collectively disrupt microbial membranes, denature proteins, and damage DNA, leading to effective microbial inactivation. The UV radiation further breaks down molecular bonds, contributing to sterilization. In fresh produce, this mechanism also inhibits enzymatic browning and slows down ripening processes by affecting key biochemical reactions, all while preserving the nutritional and sensory quality of the food due to its low operating temperature. (17,18)

Cold plasma can be generated using several systems, each varying in design, energy source, and application scale (18,19) One of the most common systems is the Dielectric Barrier Discharge (DBD), which operates at atmospheric pressure and utilizes two electrodes separated by a dielectric material to create uniform plasma suitable for surface treatment. (9,11) Another frequently used system is the plasma jet, which produces a focused stream of plasma using a carrier gas, allowing for localized application. Microwave-induced plasma relies on electromagnetic waves to ionize gases in a controlled environment, typically used in laboratory research. (13,16) Additionally, gliding arc discharge systems generate a rotating plasma arc that glides along diverging electrodes and are recognized for their high energy efficiency, though they are less commonly applied in food processing due to complexity and cost. (12,13)

The type of gas used in generating plasma significantly influences the outcome of the treatment. Air and oxygen are most commonly used for producing highly oxidative plasma environments, effective in microbial decontamination. Nitrogen, on the other hand, is milder and is often preferred when minimizing damage to delicate leafy greens. Inert gases like helium and argon are primarily used to stabilize the plasma and enhance its uniformity, especially in sensitive applications. In some cases, gas mixtures are formulated to tailor the reactive environment for specific treatment goals, balancing efficacy with food safety.(14,16)

While cold plasma is widely considered safe and environmentally friendly due to its chemical-free and residue-less nature, it is still undergoing rigorous evaluation by regulatory bodies around the world.(17,19) Concerns being assessed include the potential formation of undesirable by-products, long-term impacts on food quality, and the acceptability of plasma-treated products among consumers. Agencies like the United States Food and Drug Administration (FDA) and India’s Food Safety and Standards Authority (FSSAI) are continuing to assess the safety data and may formulate guidelines for its broader adoption in the food industry. (16,17)

**3. Applications in Fruits and Vegetables**

The application of cold plasma in the postharvest treatment of fruits and vegetables has shown significant promise in enhancing safety, extending shelf-life, and preserving quality. (17,18) This innovative technology primarily acts on the surface of produce, where most microbial contamination and chemical residues accumulate. As fruits and vegetables are often consumed raw or minimally processed, ensuring their microbial safety without compromising sensory and nutritional attributes is a major concern. Cold plasma addresses this need by offering a residue-free, non-thermal alternative to traditional chemical sanitizers and heat treatments.(19,20)

One of the most widely studied applications of cold plasma in horticultural produce is microbial decontamination. The reactive species generated by plasma effectively inactivate a wide range of pathogens including *Escherichia coli*, *Salmonella spp.*, *Listeria monocytogenes*, and various fungal spores. (13,19) These organisms, when present on the surface of fruits and vegetables, pose serious health risks to consumers. Numerous studies have demonstrated that short exposure to cold plasma, often lasting only a few minutes, can lead to several log reductions in microbial load. Importantly, this microbial inactivation is achieved without the use of water or chemicals, making it especially suitable for use in regions with limited water availability or where chemical usage is restricted. (12,14)

In addition to enhancing microbial safety, cold plasma also plays a vital role in extending the shelf-life of fresh produce. By inhibiting microbial spoilage organisms and delaying biochemical processes such as respiration and ethylene production, cold plasma treatments can slow down ripening and senescence. (17,19) This is particularly beneficial for climacteric fruits like bananas, tomatoes, and mangoes, where premature ripening can significantly reduce marketability. Cold plasma has been shown to reduce enzymatic activity such as that of polyphenol oxidase and peroxidase, which are responsible for browning and tissue softening. As a result, treated produce retains firmness, color, and freshness for longer periods during storage and transportation.(20,21)

Another valuable application of cold plasma is in the degradation of surface-level pesticide and chemical residues. In conventional farming, a wide variety of agrochemicals are used to protect crops from pests and diseases. Residual traces of these chemicals on harvested produce are a cause for public concern, particularly when they exceed permissible limits. (22,23) Cold plasma can break down common pesticide molecules through oxidation and molecular fragmentation, significantly reducing the residue load on fruits and vegetables. This aspect of plasma treatment aligns with the growing consumer demand for clean-label, pesticide-free foods and offers producers a sustainable method of detoxification. (23,24)

Cold plasma also contributes to the retention of nutritional and sensory quality in treated produce. Unlike thermal treatments, which can degrade heat-sensitive nutrients like vitamin C and polyphenols, plasma operates at low temperatures, preserving the bioactive compounds.(21,23) Studies have reported minimal changes in the taste, aroma, and color of cold plasma-treated produce, which is essential for consumer acceptance. In some cases, plasma treatment has even been found to increase antioxidant levels, possibly due to induced stress responses in the plant tissues. (24,25)

Moreover, cold plasma treatment has shown potential for use in sprouting and seed enhancement in certain vegetable crops. Although this area is still under exploration, early research indicates that plasma exposure can improve seed germination rates, enhance enzymatic activity, and stimulate early growth. These effects are thought to be related to improved water absorption and metabolic activation triggered by plasma exposure. (19,21)

Collectively, these applications demonstrate that cold plasma is not merely a sterilization tool, but a multifunctional technology that offers a broad range of benefits in the postharvest handling of fruits and vegetables. It provides a non-invasive, residue-free, and highly adaptable method to address some of the most pressing challenges in fresh produce preservation. As research expands, cold plasma is expected to play an increasingly important role in sustainable agriculture and food supply chains. (23,24)

**4. Specific Examples and Case Studies**

Numerous studies have explored the application of cold plasma technology across different types of fruits and vegetables, offering valuable insights into its practical benefits, limitations, and effects on produce quality. These case-specific findings provide strong evidence for the versatility and effectiveness of plasma treatment in real-world postharvest scenarios. (21,22)

In apples, cold plasma has been extensively investigated for its antimicrobial efficacy and role in quality retention. Apples, especially during long storage periods, are prone to fungal infections such as *Penicillium expansum*, which causes blue mold and leads to considerable postharvest losses. Cold plasma treatment has shown the ability to reduce fungal spore viability significantly without affecting the apple’s skin color or internal firmness. (21,25) Short exposure durations, typically under five minutes, were sufficient to achieve microbial control while maintaining the apple’s crisp texture and fresh appearance. Furthermore, studies reported no negative impact on vitamin C content or taste, which is critical for consumer satisfaction. (23,24)

Strawberries, being delicate and highly perishable, are another focus of plasma-based preservation research. (25,26) Their soft tissue and high sugar content make them particularly susceptible to microbial decay, especially fungal infections like *Botrytis cinerea*. Cold plasma application has demonstrated substantial reductions in surface microbial populations, extending shelf-life by several days under refrigerated storage. Importantly, the treatment preserved the berry’s characteristic red color and prevented excessive softening, which are key quality markers. Researchers also noted that treated strawberries retained higher antioxidant activity, possibly due to the mild stress response induced by plasma exposure. (25,26)

Tomatoes represent another widely studied commodity due to their global consumption and susceptibility to postharvest losses. Plasma treatments in tomatoes have shown to delay ripening, reduce microbial growth, and preserve firmness. By modulating ethylene synthesis and suppressing enzymatic degradation of cell walls, cold plasma effectively slows the softening process. (27,28) This delay in ripening is especially beneficial for transporting tomatoes over long distances without compromising freshness. Additionally, studies revealed that lycopene and beta-carotene levels remained stable after treatment, indicating that the nutritional profile was not adversely affected. (22,28)

Leafy vegetables such as spinach, lettuce, and kale present unique challenges due to their high surface area and susceptibility to microbial contamination. Cold plasma treatments have been found effective in reducing microbial loads while maintaining leaf integrity and color. Since these vegetables are often consumed raw, ensuring microbial safety without using harsh chemicals is particularly important. Researchers found that plasma treatment reduced populations of *E. coli* and *Listeria* without causing wilting or chlorophyll loss. However, due to their delicate nature, optimizing treatment duration and intensity is crucial to avoid oxidative stress and leaf damage. (25,28)

Citrus fruits like oranges and lemons have also shown favorable responses to cold plasma treatment, particularly in controlling postharvest fungal pathogens such as *Penicillium digitatum*. These pathogens cause green and blue mold during storage, leading to economic losses. Studies showed that plasma treatment not only reduced fungal viability on the fruit surface but also slowed down the progression of infections in already contaminated samples. Treated citrus fruits maintained their peel strength, juiciness, and flavor profile, making the treatment suitable for commercial postharvest handling. (21,29)

Overall, these case studies across a variety of fruit and vegetable types underline the adaptability and potential of cold plasma in real-world postharvest systems. Each commodity presents unique physical and biochemical characteristics, requiring careful calibration of treatment parameters such as exposure time, gas composition, and discharge power. Nonetheless, the consistent outcomes—microbial safety, shelf-life extension, and quality preservation—highlight cold plasma as a flexible and powerful tool for modern agricultural and food processing industries. (22,30)

**5. Advantages of Cold Plasma**

Cold plasma technology offers a suite of advantages that make it highly attractive for postharvest management of fruits and vegetables. (31,32) As a non-thermal, chemical-free, and environmentally friendly approach, it aligns well with the growing consumer demand for fresh, safe, and minimally processed foods. One of the most notable benefits is its ability to achieve effective microbial decontamination without altering the sensory or nutritional properties of produce. Unlike conventional thermal methods, which often degrade vitamins, change texture, or affect flavor, cold plasma operates at near-room temperatures and leaves minimal physical or chemical footprints on treated surfaces. (20,27)

Another major advantage is its versatility across a wide range of commodities. Cold plasma can be applied to hard-skinned fruits like apples and citrus, as well as soft fruits like strawberries and tomatoes, and even leafy greens. This flexibility is driven by the ability to adjust treatment parameters such as voltage, gas type, and exposure time based on the nature of the produce. Additionally, plasma systems can be adapted for different scales—ranging from small laboratory settings to industrial-scale conveyors—making the technology scalable for commercial operations. Some designs can even be integrated into existing packaging lines or used in conjunction with cold storage facilities. (28,29)

The treatment is also waterless and requires minimal energy compared to traditional cleaning and sanitizing processes. Conventional washing techniques often consume large volumes of water and result in secondary waste streams, which require further treatment or disposal. Cold plasma eliminates the need for such resources while still achieving comparable or superior microbial reductions. This positions it as a sustainable solution in areas where water conservation is essential or where wastewater treatment infrastructure is limited. (30,31)

An additional advantage of cold plasma is its residue-free nature. Many traditional chemical treatments—such as chlorine washes or synthetic fungicides—leave behind residues that may be harmful to human health or lead to regulatory issues during export. Plasma-treated produce, by contrast, does not carry such concerns, as the reactive species generated during treatment degrade rapidly and do not persist on the product surface. This improves both safety and compliance with food safety standards and international trade requirements. (32,33)

Moreover, cold plasma contributes to extended shelf-life by slowing down ripening and inhibiting spoilage processes. By reducing microbial populations and suppressing enzymatic reactions that lead to softening and browning, plasma-treated produce retains freshness for longer periods, even under less-than-optimal storage conditions. This reduction in spoilage not only decreases postharvest losses but also enhances the economic value of the produce by extending its marketable window. For retailers and supply chain managers, this translates into fewer returns, improved customer satisfaction, and reduced food waste. (32,34)

Finally, cold plasma supports innovation and diversification in the food industry. It opens up new opportunities for developing value-added products such as ready-to-eat salads, fresh-cut fruit packs, and minimally processed vegetable mixes, all of which require effective and gentle decontamination methods. It also pairs well with other preservation strategies, such as edible coatings or modified atmosphere packaging, making it an ideal component in multi-hurdle approaches to food safety. (36,37)

**6. Limitations and Challenges**

While cold plasma technology presents numerous advantages in the preservation of fruits and vegetables, several limitations and challenges must be acknowledged before it can be adopted widely at a commercial scale. One of the primary limitations is its surface-level effectiveness. Because cold plasma primarily acts through reactive species that interact with exposed surfaces, it may not adequately penetrate deep crevices, wounds, or internal tissues of produce. (38,39) This poses a challenge for irregularly shaped items or those with complex textures, where pathogens may reside in hidden microenvironments. Consequently, the microbial reduction may not be uniformly achieved across the entire surface, necessitating further optimization or combination with other methods. (40-41)

Another challenge lies in the variability of treatment parameters. The efficacy of cold plasma is highly dependent on factors such as gas composition, treatment duration, voltage, humidity, distance between electrodes, and the nature of the commodity being treated. A treatment protocol effective for one type of fruit may be ineffective or even damaging for another. (42,43) For example, excessive exposure to reactive species can lead to oxidative stress in soft tissues, resulting in surface pitting, dehydration, or discoloration. The lack of standardized protocols complicates the development of universally applicable treatment systems and requires significant empirical tuning for each application. (44,45)

Scalability and cost are also considerable barriers to widespread adoption. Industrial-scale plasma systems involve significant capital investment and require technical expertise to operate and maintain. Integrating plasma units into existing postharvest processing lines may demand substantial redesign or space allocation. Additionally, while the long-term operational costs are relatively low due to minimal resource consumption, the initial expense can be prohibitive for small-scale farmers or processors in developing countries. Research is ongoing to develop compact, portable, and cost-effective plasma units, but these are still in the early stages of commercialization.(46,47)

From a regulatory perspective, the use of cold plasma in food processing is still under scrutiny in many regions. Regulatory bodies such as the FDA in the United States and the FSSAI in India have yet to fully approve or define the guidelines for cold plasma-treated foods. One major concern involves the potential formation of toxic by-products or chemical changes on food surfaces due to plasma exposure. Although most studies report negligible or acceptable changes in nutritional and chemical composition, comprehensive toxicological assessments and long-term safety data are necessary before cold plasma can be endorsed for routine commercial use. (43,47)

Consumer acceptance represents another critical challenge. The term “plasma” may invoke negative perceptions among uninformed consumers due to its association with ionizing radiation or unfamiliar technology. This knowledge gap can hinder market penetration, especially in contexts where consumer trust in food processing methods is already fragile. Clear communication, transparency in labeling, and public education will be essential to overcoming misconceptions and building consumer confidence in plasma-treated produce. (48,49)

**7. Future Prospects and Research Needs**

As cold plasma technology continues to demonstrate its potential in enhancing the safety and quality of fruits and vegetables, its future development hinges on addressing current limitations and unlocking new possibilities through targeted research and innovation. The most immediate need lies in standardizing treatment protocols across different types of produce.(31,32) At present, much of the research is product-specific, with variable parameters tailored to individual fruits or vegetables. Developing universally adaptable models—or intelligent plasma systems that can self-adjust based on produce type, size, and microbial load—could greatly accelerate industrial integration. (32,33)

Advancements in equipment design also represent a key frontier. Most existing cold plasma setups are either lab-scale or semi-industrial, and not yet optimized for high-throughput commercial environments. Designing compact, energy-efficient, and modular plasma systems that can be installed into existing processing lines will be essential for scaling adoption. Portable plasma units for smallholder farms, farmer cooperatives, and decentralized packing centers could democratize access to this technology, especially in developing regions where postharvest losses are high and preservation infrastructure is limited. (34,35)

Combining cold plasma with other preservation techniques also offers promising opportunities. Multi-hurdle approaches—where plasma is used in conjunction with edible coatings, controlled atmosphere storage, UV-C light, or natural antimicrobials—could yield synergistic effects, enhancing microbial control and extending shelf life even further.(37,38) For example, cold plasma pre-treatment may improve the adherence and effectiveness of antimicrobial coatings or facilitate the diffusion of natural preservatives into the tissue surface. Such integrative models would also help reduce the intensity or duration of individual treatments, preserving produce integrity while maximizing protection. (42,46)

Research into the molecular and physiological effects of cold plasma on plant tissues is another important direction. While most studies confirm that plasma treatments do not significantly degrade nutritional compounds, more detailed investigations are needed on sub-cellular changes, stress responses, and long-term storage impacts.(31,35) Understanding how plasma-induced oxidative stress affects different produce types can help define safe treatment thresholds and enhance process control. Furthermore, studying the influence of plasma on bioactive compounds, flavor development, enzymatic activity, and gene expression could uncover new applications beyond preservation—such as ripening control or metabolite enhancement. (41,49)

From a regulatory and public health standpoint, future work should focus on comprehensive safety assessments. This includes toxicological evaluations of any plasma-generated by-products, their potential accumulation over time, and interactions with packaging materials or environmental conditions. Only through such detailed studies can global food safety authorities develop evidence-based guidelines for the safe and standardized use of cold plasma in the food industry. In parallel, efforts should be made to educate consumers, supply chain stakeholders, and policy-makers about the benefits and safety of plasma-treated foods. Transparent communication and effective outreach will play a key role in building acceptance and trust. (31,32)

Lastly, interdisciplinary collaboration will be crucial in propelling this technology forward. Plasma physicists, food technologists, microbiologists, agricultural engineers, and economists must work together to address both scientific and logistical challenges.(32,50) Collaborative pilot programs with industry partners can help test and validate cold plasma systems in real-world settings, while government and academic support can fund long-term innovation and capacity building. (33,34)

**8. Conclusion**

Cold plasma technology has emerged as a powerful, non-thermal tool for improving the safety, shelf-life, and overall quality of fruits and vegetables. Its ability to inactivate pathogens, degrade surface pesticide residues, and maintain sensory and nutritional properties positions it as a sustainable alternative to conventional preservation methods. The technology offers multiple advantages, including energy efficiency, chemical-free processing, and adaptability across diverse produce types. However, challenges such as limited penetration, high equipment costs, and lack of regulatory clarity still need to be addressed.

Future success depends on standardizing treatment protocols, scaling up equipment design, conducting in-depth safety assessments, and improving consumer awareness. With continued interdisciplinary research and policy support, cold plasma holds the potential to revolutionize postharvest management in the fresh produce industry, contributing to reduced food waste, improved food safety, and enhanced global food security.

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