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RESEARCH ARTICLE

Atmospheric cold plasma: A novel technique for microbial inactivation and quality preservation of spices and herbs

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Abstract

The global production of spices and herbs has increased significantly in recent decades due to growing consumer demand. However, this expansion has been accompanied by a rise in foodborne illness outbreaks associated with these products, necessitating advancements in processing methods. Atmospheric cold plasma (ACP) has emerged as a promising food treatment technique for improving product safety and extending shelf life. This paper reviews the application of ACP in spices and herbs processing, focusing on its microbial inactivation capabilities and its effects on nutritional and physico-chemical properties. While research generally supports the effectiveness of ACP, its impact varies significantly based on treatment parameters and the specific spice or herb being processed. Comprehending these variations is critical for optimizing ACP conditions to ensure the safety and quality of the final products. Further research is required to refine ACP applications tailored to different spices and herbs, providing deeper insight into its potential. The findings underscore the importance of customized processing strategies that meet safety standards while preserving the natural qualities of spices and herbs, catering to an increasingly health-conscious market. Additionally, the scalability of ACP technology for industrial applications remains an area of active investigation, as larger-scale processing introduces unique challenges. Addressing these challenges will be critical for the widespread adoption of ACP in the spice and herb industry, ensuring consistent outcomes across diverse production environments.

Keywords

atmospheric; cold plasma; decontamination; herbs; spices

Introduction

Spices are crucial in modern diets, significantly enhancing flavor, aroma, and food preservation. Botanically, spices and herbs originate from plants, with herbs derived from green leafy parts and spices obtained from seeds, bark, or underground stems. Compounds such as capsaicin in chili peppers, thymol in thyme, and curcumin in turmeric contribute to the taste and color of food while providing functional benefits. Additionally, phytochemicals like flavonoids and phenolic acids offer antibacterial and antioxidant properties and contribute to natural pest resistance (1). Each spice possesses a unique set of biological activities, collectively contributing to the body's protection.

Traditionally, spices have been integrated into diets for their intense flavors, requiring minimal quantities and providing negligible caloric value.

However, spices particularly those derived from seeds, can be rich in fats, proteins, and carbohydrates when consumed in larger amounts. Certain spices are also high in essential minerals. For instance, fenugreek is abundant in iron, sesame seeds are a rich source of calcium, and coriander provides significant magnesium. Cumin and turmeric contain iron and other vital micronutrients (2).

Increased consumption of spices and phytochemical -rich foods has been shown to positively influence ageing, mitigate oxidative stress, and reduce the risk of chronic diseases. While chemoprevention is a recognized strategy, public health initiatives should prioritize consuming foods, beverages, herbs, and spices rich in phytonutrients. These phytoprotectants enhance various physiological and metabolic processes, such as improving digestion, boosting immunity, and reducing inflammation, thereby promoting overall health (3).

Traditional methods for spice decontamination include chemical fumigation, superheated steam treatment, and high hydrostatic pressure (HHP). However, these techniques have several limitations. They often exhibit low antibacterial efficacy and are influenced by pH and water activity (aw). Additionally, these methods can cause the oxidation of aromatic components, leading to undesirable changes in sensory qualities such as flavor and color. They may also degrade the quality of fatty acids and vitamins, further impacting the nutritional value of the products (4).

While radiation is a highly effective decontamination method, it faces low consumer acceptance due to safety concerns and negative perceptions (5). The use of chemical fumigants has been increasingly restricted due to their carcinogenic potential. Steam sterilization, a widely used thermal disinfection method, also poses challenges. When steam is applied to heat-sensitive products, especially ground spices and herbs, it can significantly alter their flavor profiles and reduce the volatile compound content, affecting the overall quality (5).

In response to the limitations of conventional decontamination techniques, researchers are exploring non-thermal, chemical-free, and sustainable alternatives that aim to preserve spices' bioactive components and sensory qualities. One study investigated gamma irradiation at doses up to 10 kGy to inactivate microbes in spices (6). However, high levels of gamma radiation have been shown to negatively affect the bioactive compounds and antioxidant capacity of certain spices, including cumin seeds and rosemary, leading to significant reductions in their natural antioxidant levels post-irradiation (7, 8).

Microwave irradiation has also been studied for its effectiveness in reducing microbial loads, but it has been associated with a substantial decrease in moisture content, which negatively affects product quality (9). For instance, microwave treatment at a power level of 500 W for 90 seconds substantially reduced microbial counts in spices such as cinnamon and fennel but also resulted in diminished antioxidant capacity, flavonoid content and polyphenol levels (6). Researchers are also investigating other innovative methods, including ACP, pulsed light, and ultrasound, for their ability to decontaminate spices while preserving their quality and nutritional integrity efficiently.

Atmospheric cold plasma is an innovative technology that produces reactive species capable of interacting with food biomolecules. Produced under atmospheric conditions, these reactive species have demonstrated potential in food preservation and safety by effectively inactivating microorganisms while improving the quality of food products (10). The technique has proven effective in eliminating pathogenic microorganisms, including *Escherichia coli*, *Salmonella spp.*, *Listeria monocytogenes*, and *Aspergillus* species, across diverse food systems while preserving nutritional value and sensory attributes (11).

Applying cold plasma-based treatments to mitigate fungal contamination, such as *Aspergillus flavus* in onion powder (12) and aerobic bacteria in red pepper (13), without affecting product quality highlights the necessity for additional investigation in this field. Furthermore, the positive impact of low-temperature atmospheric plasma on the texture profile, bioactive composition, and other physicochemical properties of food makes it a favorable alternative for enhancing food protection and quality (14).

This review intends to offer a concise summary of ACP technology, outlining its fundamental principles and operational parameters across different applications. Additionally, it also examines the effectiveness of ACP in microbial decontamination and its impact on food quality, with a specific focus on its application in the treatment of spices and herbs.

Fundamental of Non-thermal Plasma

Plasma, sometimes called the plasma state, is an ionized gas composed of reactive species, energetic particles, and stable atoms and molecules, all maintaining an overall neutral charge. It is recognized as the fourth phase of matter. The practical generation of plasma devices emerged nearly 50 years after Crookes' 1879 discovery, with significant advancements made by Tonks and Langmuir in 1929 in plasma-generating technology.

Plasma can be categorized based on several factors, including concentration, levels of ionization, and thermal balance (15). Additionally, plasma is classified by thermal conditions into heat, cold, or localized thermal balance types (16). In thermal plasma, all species—electrons, ions, and neutral particles—exist in thermodynamic balance (15). Conversely, non-thermal equilibrium plasmas exhibit a substantial temperature difference between the electrons (Te) and the dense particles, such as atoms, molecules, and ions (Tg), where Te » Tg (16, 17). In localized equilibrium plasmas, the temperatures of electrons, positively charged, and neutral ions are comparable (16, 18, 19). While the ion temperature in localized equilibrium plasma is significantly higher than in non-thermal plasmas, the electron temperature is notably lower (17, 20). For simplicity, this review refers to non-thermal equilibrium plasmas as cold plasma.

Plasma can additionally be categorized according to pressure conditions as either atmospheric or low-pressure plasmas. Atmospheric plasma is generated under standard air conditions, eliminating the need for costly reaction chambers or vacuum systems (17, 21). This ease of generation and the ability to operate without high temperature or pressure adjustments make atmospheric pressure plasma systems particularly appealing for food industry applications, including equipment design and process optimization.

Various atmospheric pressure plasma production technologies are utilized in food preparation, including glow discharge plasma (GDP) (22), resistive barrier discharge (RBD), microwave plasma (MW) (23), corona discharge (CD) (24), direct barrier discharge (DBD) (25), and atmospheric plasma jet (APJ) (26). Each type operates under particular conditions, including radio frequency, gas discharge, and photoionization, to initiate and maintain electron collisions essential for generating plasma. For instance, radio frequency plasma ensures uniform treatment over larger surfaces, while gas discharge plasma effectively addresses complex shapes and food packaging. On the other hand, photoionization plasma uses light to produce reactive species, making it ideal for sensitive applications that require minimal thermal effects (15).

Among these technologies, atmospheric pressure plasma jet (APPJ) and DBD plasmas have been extensively studied for their effectiveness in decontaminating spices and herbs while preserving product quality (Fig. 1). These systems are user-friendly and can operate under standard atmospheric conditions, making them highly accessible for commercial applications. Direct barrier discharge plasma employs a pair of electrodes, with at least one coated in a dielectric insulating material. This setup generates numerous micro-discharges while preventing arc formation, ensuring consistent and stable decontamination (27, 28). In contrast, APPJ utilizes a pair of concentric electrodes housed within a nozzle, allowing carrier gas to flow. The inner electrode produces a high voltage (100–250 V) at a frequency of 13.56 MHz to ionize carrier gases such as helium, oxygen, or their combinations (29). These gases facilitate the flow of active particles and enhance the plasma jet's reactive section, making APPJ an effective tool for food processing (30).

Atmospheric Cold Plasma In Herb And Spice Processing: Impacts On Safety And Quality

Impact of cold plasma on microbial viability

To effectively implement cold plasma technology in food applications, it is essential to comprehend the mechanisms behind microbial inactivation. Extensive research has demonstrated the efficacy of cold plasma treatments in achieving significant microbial reduction (30). Rather than exploring the various mechanisms of microbial inactivation in detail, this section focuses on the effectiveness of ACP for microbiological decontamination. Table 1 summarizes published studies on ACP applications in spices and herbs and relevant processing parameters.

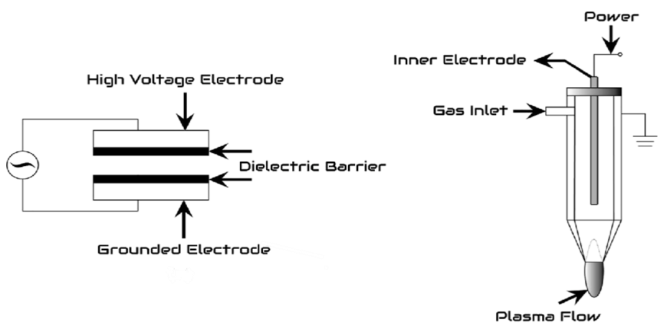

Fig. 1. Schematic representation of (a) dielectric barrier discharge and (b) plasma jet system (71).

Numerous studies have confirmed ACP's ability to neutralize harmful microorganisms in spices and herbs. Critical parameters, including power input, sample size, gas flow rate, and current—determined by frequency and voltage—are instrumental in ensuring effective decontamination. These parameters influence the generation and distribution of reactive oxygen and nitrogen species (RONS), central to microbial inactivation. For instance, power input determines the energy available for RONS production, while gas flow rate regulates their concentration and distribution. Sample size affects plasma exposure and penetration, and the interplay of current, voltage, and frequency ensures stable plasma discharge, optimizing the uniformity and efficacy of treatment (17, 21). Further investigation is needed to enhance understanding of how the specific properties of the food matrix influence microbial inactivation.

Black pepper is widely utilized globally for its distinct flavor-enhancing properties. However, traditional hand-harvesting and natural drying processes make black pepper susceptible to bacterial contamination, leading to various microorganisms in retail products (31). A study demosntrated demonstrated that inoculating black pepper with *Salmonella* and subsequently treating it with atmospheric pressure plasma (APP) for 60–80 seconds resulted in a significant reduction in *Salmonella* levels, approximately 4.5–5.0 log CFU/g (32).

Another study explored the effects of microwave-assisted remote plasma and plasma jet techniques on peppercorns, both with and without prior inoculation. While the plasma jet treatment did not achieve comparable microbial inactivation levels, applying remote plasma effectively reduced microbial counts (33). This included reductions of 4.1 log CFU/g for *Salmonella enterica*, 2.4 log CFU/g for *Bacillus subtilis*, and 2.8 log CFU/g for *Bacillus atrophaeus*.

The interactions between cold plasma and microbial entities are intricate, influenced by gas composition, discharge methods, and the specific microbial species involved, including fungi, Gram-positive, and Gram-negative microbes (34-36). This complexity creates challenges in directly comparing the sterilization efficacy of different plasma technologies. For instance, a study evaluated the effects of a remote plasma system on fungi in black peppercorns, ground oregano, and paprika spice. They reported a reduction of over 3.0 log CFU/g in microbial counts for black peppercorns and paprika, whereas oregano exhibited only a 1.8 log CFU/g decrease in fungal counts (37).

Additionally, it was found that *Bacillus subtilis*,

Table 1. Microbial inactivation by ACP in herbs and spices

Substrate	Microorganism	Processing Conditions	Time	Log reduction	Types of plasma	Reference
Black pepper-corns	*S.enteritidis* *Bacillus tequilensis*	Voltage: 10.3kV Type of gas: Helium Flow rate of gas: 15 L/min	22.1 Min	3.4 log CFU/g 1.7 log spores/g	DBD	(60)
Onion granules	*Salmonella Enteritidis* *E.coli O157:H7* *L.monocytogenes*	Frequency: 15 kHz Gas: Helium ; Frequency: 5 kHz Voltage:9Kv	20 min	3.1 ± 0.1 log CFU/cm² for Salmonella Enteritidis, 1.4 ± 0.1 log CFU/cm² for Escherichia coli O157 , and 1.1 ± 0.3 log CFU/cm² for *Listeria monocytogenes*.	DBD	(43)
Red pepper powder	*Bacillus cereus*	Gas: Nitrogen Voltage: 1.1 Kv	5–15 min	≥6.0 log CFU/g	DBD	(61)
Onion powder	*E.coli O157:H7,* *S.Enteritidis,* *L.monocytogenes*	Voltage: 9 kV, Gas: Helium	20 min	0.3log CFU/cm²	DBD	(12)
Turmeric powder	Aerobic viable cell count	Voltage: 25 kV Gas: Air	3, 5, 7 min	1.5 log CFU g^{-1}	DBD	(44)
Black pepper grains	*Bacillus subtilis* vegetative cells	Voltage: 15, 30 kV Frequency: 20 kHz Gas flow rate: 11 L / min Gas: Air	3, 5 min	2.92 log CFU/Ml	APPJ	(62)
Whole black pepper	*Bacillus subtilis* spores *Bacillus atrophaeus* spores *Salmonella enterica*	Power: 1.2 kW Frequency: 2.45 GHz Gas: Air	30 min	*S. enterica, B. subtilis* spores, and *B. atrophaeus* spores were reduced by 4.1, 2.4, and 2.8 logs respectively.	Radio frequency plasma, Microwave generated plasma	(37)
Black pepper-corn (BP), crushed oregano (OR), paprika powder (PP)	Native microbial flora	Power: 1.2 kW Frequency: 2.45GHz Gas: Dry air	60 min 60 min 90 min	BP 4.0 log10 PP 3.0 log10 OR 1.6 log10	Microwave torch indirect application of exhaust gas	(33)
Seed of Alfalfa, onion, Cress	*E.coli*	Voltage:8 kV Gas: argon	10 min	3.0 log CFU/g for seed alfalfa, 1.4 log CFU/g for seed onion, and 3.4 log CFU/g for seed cress.	DBD	(63)
Whole black peppercorn	*B. subtilis* *E. coli* *S. Enteritidis*	Gas: Ambient air Frequency: 18kHz Voltage: 10 kV	300s	6.45 log10 for *E. coli*, 6.60 log10 for S. *Enteritidis* and *B. subtilis* spore inactivating level of 2.03log10.	Diffuse Coplanar Surface Barrier Discharge (DCSBD	(38)
Thyme and paprika	Total bacterial count	Voltage: 12 Kv, Frequency: 6 kHz	5 min	1.18 log cycle	DBD	(64)
cinnamon, black pepper, fennel	Yeast and mold count	Voltage: 230 V	15 min	1.3 Log CFU/g, 1.1 Log CFU/g, 1.0 Log CFU/g	Pin-to-plate ACP	(52)
Red pepper powder	*A. flavus*	Pressure: 667 Pa; gas: N2, N2–O2 mixture, He, He–O2 mixture; flow rate: 1 L/min; power: 300 –900 W; frequency:2.45GHz	20 min	2.5 log spores/cm2	Microwave-powered cold plasma	(13)
Red pepper flakes	*A. flavus*	Pressure: 667 Pa; gas: He–O2 mixture; power: 900W; frequency: 2.45 GHz	20 min;	1.0 and 1.4 log CFU/g	Microwave-combined cold plasma	(65)
Black pepper powder and Sesame	Bacteria	Rotary valve speed: 40 rpm Pressure: 0.2 MPa	10 min	3.52, 4.62, 2.38, and 4.12 log CFU/g	Pilot-scale atmospheric plasma jet	(66)
Saffron	Total viable count (TVC), coliforms, molds, and yeasts	Power: 110 W	30 min		LPCP	(67)

ng with *E. coli* and *Salmonella Enteritidis*, exhibited resistance to cold plasma treatment on black peppercorns (38). After 300 seconds of treatment, *Bacillus subtilis* counts were reduced by roughly 5.0 log CFU/g.

Furthermore, other researchers have shown that microwave-assisted cold plasma treatment effectively inhibits the growth of *Aspergillus flavus* in red pepper powder. Using nitrogen plasma at 900 W for 20 minutes reduced *A. flavus* levels from 2.5 to 0.3 log CFU/g (13). A couple of more studies highlighted that increasing microwave power significantly enhanced the deactivation efficacy of microwave -assisted cold plasma treatments (12, 39). Vacuum-dried red pepper achieved greater spore reduction than infrared-dried red pepper, likely due to the smoother and more uniform texture of vacuum drying. These findings emphasize the importance of processing parameters, such as drying methods, in optimizing microbial decontamination and food preservation, as evidenced in studies on onion powder and the inactivation of *Bacillus cereus* spores in red pepper flakes (12, 39).

Similarly, another study investigated the use of dielectric barrier discharge technology (DBD-PT) and radiofrequency heat treatment (RF-TT) to inactivate *Staphylococcus aureus* and *E. coli* O157 in red pepper powder (40). Their results demonstrated a proportional reduction in microbial counts with extended treatment durations, with both RF-TT and DBD-PT effectively reducing microbial counts below the detection threshold of 1 log CFU/g.

While mold formation in tea is relatively uncommon, tea can be treated like other dried herbs. The treatment duration and the initial microbial load influenced the effectiveness of plasma jet technology for sanitizing mold and yeast in black and green tea. Complete inactivation of mold and yeast was achieved after 7 minutes of treatment when the initial populations were 3.30 and 3.0 log CFU/g, respectively (41). Furthermore, it was demonstrated in a study that 15 seconds of plasma irradiation partially inactivated *Aspergillus niger* across different raw materials. However, it was less effective against the Gram-positive bacterium *Bacillus subtilis* (42).

The efficacy of DBD plasma in inactivating *Salmonella Enteritidis*, *E. coli* O157, and *L. monocytogenes* in onion flakes was also explored. Using helium as the carrier gas at a frequency of 5 kHz and a voltage of 9 kV, a 20-minute treatment resulted in reductions of 3.1 ± 0.1 log CFU/cm^2 for *S. Enteritidis*, 2.0 log CFU/cm^2 for *E. coli* O157, and 1.3 ± 0.1 log CFU/cm^2 for *L. monocytogenes* (43). Similarly, another investigation studied the effect of helium DBD plasma at 9 kV on onions, reporting a 3.0 log CFU/g reduction for both *E. coli* O157 and *L. monocytogenes* after 20 minutes of exposure (12).

A separate study on turmeric powder demonstrated a 3.5 log CFU/g reduction in aerobic visible cell counts using helium DBD plasma at a voltage of 25 kV after just 3.5 minutes of treatment. These findings highlight the potential of plasma -based technologies for effective microbial decontamination across various food matrices (44).

Impact of ACP concerning the quality characteristics of spices and herbs

Food quality is crucial in determining sensory characteristics, such as mouthfeel and color, directly influencing consumer acceptance. However, the impact of ACP processing on the quality of spices and herbs has not been thoroughly studied. Table 2 comprehensively summarizes published studies, including experimental setups, methodologies, and findings.

The quality of red pepper products is primarily determined by their redness, with capsaicin being the key carotenoid responsible for this color (45). Research has shown that plasma jet and microwave-activated remote plasma treatments did not cause significant changes to the surface hue of black pepper seeds (37). In the case of oregano, a slight reduction in the b* value during plasma treatment may indicate the degradation of chlorophyll pigments. Additionally, the a* value of red pepper powder decreased following plasma treatment, suggesting a loss of red hue, while increases in L* and b* values indicated lightening and yellowing (37).

While plasma treatments did not significantly alter the L*, a*, or b* values of red pepper powder, it is important to emphasize the significance of color preservation in the spice industry. Color is a key indicator of quality and freshness, particularly in red pepper powder, where bright, vibrant hues are associated with premium quality. Both consumers and manufacturers rely on color stability as a measure of product quality, directly affecting marketability. Changes in color, such as fading or dulling, can negatively impact consumer perception, reducing demand and product value. Therefore, maintaining color stability through treatments like cold plasma is essential for preserving red pepper powder's visual appeal and market viability.

Similarly, the color and quercetin concentration of onion powder remained largely unaffected by microwave-integrated low-temperature plasma treatment compared to the control group, suggesting that different plasma technologies and gas compositions may influence surface color in various ways(12, 39).

Cold plasma (CP) treatment improved the DPPH-free radical scavenging activity of onion powder compared to untreated samples without compromising its physicochemical or flavor properties (12, 39). A positive correlation was also observed between the CP treatment duration and red pepper powder's antioxidant capacity. This increase in antioxidant activity is likely due to structural breakdown, which enhances the release of antioxidants like vitamin C and polyphenols (46, 47). Similarly, RF low-pressure cold plasma (LPCP) treatment improved the anti-oxidative activity and total phenolic content in *Mentha piperita*, although it also caused slight darkening of the samples (48). The effect of LPCP on phenolic compounds requires further investigation, but some plant species may exhibit resistance to UV radiation generated during CP processing, potentially leading to increased phenolic production (49). The discoloration of saffron after CP treatment may be attributed to cell wall damage or reduced polyphenol oxidase activity (50).

Plasma treatment also effectively reduced water activity, enhancing the microbial stability of spices. Well-

Table 2. Impact of ACP on the quality characteristics of herbs and spices

Product	Processing Conditions	Results	Types of plasma	Reference
Black pepper grains	Voltage: 15, 30 kV Frequency: 20 kHz Gas flow rate: 11 L / min Gas: Air Time: 3, 5 min	The overall change in phenolic content stayed negligible.	APPJ	(62)
Chili pepper	Gas flow rate: 3 116 L/min Frequency: 20 kHz, Power: 750 W Gas: air Time: 30 s	No notable changes in the color profile throughout the treatment. The antioxidant activity also increased as the exposure time to cold plasma lengthened. Pigment extraction was enhanced.	ACP	(46)
Onion powder	Frequency: 2.45 GHz, Power: 400–900 W, Time: 10–40 min, Pressure: 0.7 kPa, Gas: Helium, Gas flow: 1 L/min,	No change in quercetin concentration, antioxidant activity, or colour.	Microwave plasma	(39)
Whole black pepper	Power: 1.2 kW Frequency: 2.45 GHz Gas: Air	The surface color did not significantly change.	Plasma jet and Microwave-driven remote plasma	(37)
Black pepper seeds, Allspice berries and Juniper berries	Gas: Argon Frequency: 2.45 GHz Time: 15–60 s Gas flow: 20 L/min Power: 920 W	Decreased water activity. Improve phenolics' capacity to be extracted. Enhance antioxidant activity with subtle but noticeable color shifts.	Atmospheric Pressure Microwave Plasma	(42)
Cinnamon, Black pepper, Fennel	Voltage:230 V Time: 15 min	Significantly less water activity was present to ensure stability. Every sample's overall phenolic content rose. Spices' essential oil profile remained unchanged.	Pin-to-plate ACP	(52)
Allspice	Gas: Air Power: 400W Frequency 14–15 kHz Voltage: 20 kV Time:60, 120, 180, 240 and 300 s	Reduced water activity. No alterations to the sample's typical chemical connections within or outside. Minimal impact on the spice's fragrance profile after treatment and storage.	Diffuse Coplanar Surface Barrier Discharge (DCSBD)	(68)
Basil	Voltage: 10 and 15 kV Time: 10 and 20 min	Enhanced the levels of total flavonoid contents, carotenoid, and chlorophyll. Enhanced the antioxidant activity of the samples. The biological characteristics remained mostly unaffected.	DBD	(51)
Fenugreek	Gas: Argon Time: 16 hours Voltage: 16 kV Frequency: 24 kHz	Due to the elevated levels of O-radicals and the seed surfaces' etching, the seed germination rates improved.	Cold atmospheric-pressure plasma jet (CAPPJ)	(55)
Cumin	Gas: Ar and Ar-O2 Time: 20 -40 min Voltage: 15 kV Frequency: 17 kHz	Without adversely affecting the quality of the seeds.	DBD	(56)
Cumin seed	Time: 3 min Voltage: 2 Kv Power: 118 W Gas: Air	The dry matter content and rate of photosynthetic activity were enhanced. Exposure to plasma lengthened the roots, shoots, and seedlings. No discernible impact on any of the growth metrics.	DBD	(57)
Dried red pepper	Power:1.5 kW Time:15 min Gas: Air Exposure distance: 10 mm Stored 12 weeks at 25°C	There is no impact on the dried red pepper's hardness, American Spice Trade Association (ASTA) value, or capsaicin concentration.	DBD	(69)

optimized plasma conditions may also improve the

Saffron	Voltage: 8 and 12 kV Frequency: 12-KHz Time: 4 min Gas :Argon	Decrease in saffranal and crocin esters in saffron. Increases saffron's isophorone and 4-ketoisophorone levels.	Atmospheric plasma jet	(54)
Thyme	Time (30, 60, 120 & 300 s) Voltage (17, 19, 21 & 23 kV)	Garden thyme leaves' hydrophilicity was enhanced. Trichomes broke when the treatment's duration and voltage increased. Enhanced the effectiveness of leaf essential oil extraction. Not considerably alter the components of the essential oil.	Modulated voltage-dielectric barrier discharge (MV-DBD)	(70)

extractability of phenolics or piperine from black pepper seeds (42).

Basil did not show significant increases in total phenol, proline, or protein content; however, antioxidant activity notably increased after 10 minutes of treatment at 10 and 15 kV. Several studies have also explored the effects of CP treatment on various characteristics of spices and plants (51). For example, SEM and FTIR analysis revealed that cold plasma treatment did not significantly alter black pepper's internal chemical linkages or surface morphology (38). Increases in microwave-driven cold plasma treatment duration at 650 and 826 watts led to reduced water activity (aw) values in red pepper powder, improving its microbiological stability (13). Similarly, pulsed radiofrequency cold plasma treatment significantly reduced moisture content and water activity in red pepper powder compared to the untreated control group (40).

A 30-second cold plasma (CP) treatment optimized red pepper's properties and hot air-drying kinetics in a separate study. Microstructural measurements revealed the formation of micropores, which improved drying rates (46). Another study on the effect of ACP on pin-to-plate samples showed reduced water activity, enhancing microbial stability across various species, without significant changes in color or texture characteristics ($p > 0.05$) (52). After plasma treatment at 230 V for 15 minutes, the total phenolic content increased in fennel (0.33%), black pepper (0.11%), and cinnamon (2.26%), while the essential oil content remained similar to untreated samples.

Saffron is known for its distinct color and aroma, primarily attributed to volatile essential oils. Monoterpene aldehydes, such as safranal and isophorone derivatives, significantly contribute to its fragrance (53). The effect of cold plasma on crocin esters and essential oils in saffron crocus was explored in a study (54). A reduction in crocin esters and safranal levels was observed after treatment. However, they noted an increase in isophorone and 4-ketoisophorone levels under various working gas conditions, including pure argon, argon with 5% oxygen, and argon with 10% oxygen.

The influence of ACP jet treatment on fenugreek seed germination and early seedling growth was investigated (55). The increase in O-radical emission lines (777.4 nm), caused by the presence of a silver (Ag) electrode, strengthened the axial electric field, forming additional streamers. This phenomenon likely contributed to the enhanced seed germination and seedling growth observed. Scanning electron microscope (SEM) images revealed that the Ag electrode facilitated the etching of the seed surface layers. Additionally, atmospheric pressure DBD plasma using argon (Ar) or argon-oxygen (Ar-O2) gas effectively decontaminated cumin seeds without compromising their suitability for food (56).

Similarly, a study explored the effects of plasma exposure duration on cumin seed growth and germination rates, reporting increases of 15.5%, 41.79%, and 34.5% in total chlorophyll content, shoot length, and root length, respectively, compared to controls (57). After just 3 minutes of cold plasma exposure (2 kV), seed germination improved by 43.24% and increased vigor index and dry weight. Optical emission spectroscopy (OES) confirmed that specific reactive species, such as reactive oxygen species (ROS) and reactive nitrogen species (RNS), play a vital role in activating cellular processes in cumin seeds. Reactive oxygen species enhance metabolic activities and mobilize stored nutrients, improving energy availability for seedling growth. Reactive nitrogen species influences gene expression related to growth and stress responses. The study found that ACP-treated cumin seeds exhibited significantly higher germination rates and seedling growth, suggesting that ACP is a promising strategy for enhancing the vitality of aromatic and medicinal seeds.

Limitations

A significant limitation of cold atmospheric-pressure plasma treatment in achieving antibacterial effects is the non-uniformity of surface structures. These irregularities include rough textures, pores, cracks, and varying surface topographies on food products. Such features can create shadowed regions or microenvironments where plasma and reactive species cannot penetrate effectively, leading to uneven decontamination. These surface variations prevent the plasma from interacting uniformly across the entire surface, making it difficult to achieve consistent microbial inactivation(58, 59). It has been noted that well-defined surfaces, such as corrugated textures, can hinder microbial inactivation. Their research highlighted a significant decrease in the effectiveness of Cold Atmospheric Pressure Plasma (CAPP) on complex surfaces like black peppercorns. In their study, they compared the elimination of *Bacillus subtilis* spores, introduced at a concentration of 4 × 10^6 spores per cm^2, across three surface types: black peppercorns (an actual food matrix), spherical glass beads, and a flat glass surface. The intricate surface of black peppercorns, which feature pits, grooves, and cracks, can create shadowing effects for various plasma components. This shadowing reduces the interaction between reactive species, such as radicals and UV radiation, and the microorganisms, ultimately diminishing the efficacy of the CAPP treatment in inactivation. Additionally, the microbial load on the treated surface plays a crucial role in influencing plasma-based inactivation. Furthermore, the surface-area-to-volume ratio of a product may also impact the neutralization efficacy. It was also noted that powdered substances with a higher surface-area-to-volume ratio are more likely to facilitate plasma interactions with the food surface rather than with the bacteria on it (33).

Conclusions

This research explores ACP's unique non-thermal processing method for decontaminating spices and herbs. ACP is a highly effective non-thermal technique that preserves spices and herbs' sensory qualities and nutritional value while effectively decontaminating them. Unlike traditional methods, ACP leaves no harmful residues, maintains product freshness, and offers faster, energy-efficient processing. It is a sustainable solution to meet the growing consumer demand for high-quality, safe, and residue-free products. The use of ACP in the spice and herb industry has the potential to meet customer needs for safer and more sustainable products. While ACP is already being applied in various fields, research indicates that more studies are needed in herb and juice processing. ACP shows promise in juice processing by offering non-thermal decontamination without compromising sensory or nutritional quality. However, treatment variability, process optimization, and long-term effects on juice stability require further investigation to harness its potential fully.

Additionally, the lack of consistency in processing conditions for spices and herbs hinders cross-study comparisons. Therefore, detailed reporting of operational conditions is essential to avoid confusion in the literature. Further studies must include comprehensive details on processing conditions to adapt ACP technology for large-scale applications.

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Authors' contributions

PDT created the conceptual design based on literature searches and was involved in the writing-reviewing-editing process. GS participated in the conceptual design, writing, and supervision. BM performed editing and supervision. PV performed a comparison study and editing. SU participated in design and coordination. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors, PT, GS, BM, PV, and SU, used Grammarly to improve the grammar in the manuscript; Crossref and EndNote to include DOI and check references. After using this tool, the PT, GS, BM, PV, and SU reviewed and edited the content as needed and took full responsibility for the publication's content.

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