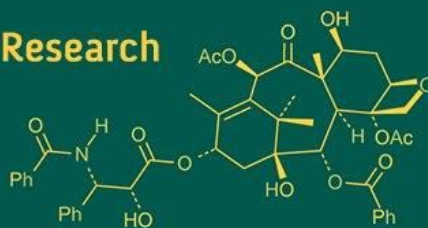


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; SP-10(4): 553-561
www.biochemjournal.com
Received: 15-01-2026
Accepted: 18-02-2026

Pratiksha H Puranik
Ph.D., Scholar, Dr. Annasaheb
Shinde College of Agricultural
Engineering & Technology,
MPKV, Rahuri, Maharashtra,
India

Vikram P Kad
Professor, Department of
Agricultural Process
Engineering, Dr. Annasaheb
Shinde College of Agricultural
Engineering & Technology,
MPKV, Rahuri, Maharashtra,
India

Ritu B Kukde
Scientist, ICAR-Central
Institute of Post-Harvest
Engineering and Technology
(CIPHET), Ludhiana, Punjab,
India

Ganesh N Shelke
Assistant Professor,
Department of Agril Process
Engineering, Dr. Annasaheb
Shinde College of Agricultural
Engineering & Technology,
MPKV, Rahuri, Maharashtra,
India

Corresponding Author:
Pratiksha H Puranik
Ph.D., Scholar, Dr. Annasaheb
Shinde College of Agricultural
Engineering & Technology,
MPKV, Rahuri, Maharashtra,
India

Unlocking the potential of cold plasma technology for safer foods and agricultural commodities: A review

Pratiksha H Puranik, Vikram P Kad, Ritu B Kukde and Ganesh N Shelke

DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i4Sg.8158>

Abstract

Non-thermal Atmospheric Plasma (NTAP) is a breakthrough technology that has recently received substantial attention in the food processing sector over the past decade as a feasible option for food preservation and safety maintenance. It primarily affects the quality attributes of food due to its efficacy in microbial inactivation, including pathogens, spoilage fungi, and bacterial spores. Its benefits include simple layout, ease of use, cost-effective operation, minimal treatment durations, the lack of toxic effects, and a significant reduction in water consumption. The review addresses the design elements of cold plasma technology, its mode of action, and various kinds of cold plasma technologies relevant to food applications. The food sector has demonstrated the relevance of CP for food decontamination, pesticide residue elimination, enzyme inactivation, toxin elimination, and alterations in food packaging. The design versatility, non-thermal features, cost-effectiveness, and sustainable features of CP provide distinct benefits compared to conventional processing technologies. Still, CP processing remains in the infancy phase and requires further research to realize its future potential.

Keywords: Cold plasma, pathogenic bacteria, food quality, food safety, agricultural produce

Introduction

Food preservation stands as a cornerstone of global food security and sustainability, addressing the critical challenge of post-harvest losses that account for approximately 30-40% of fruits and vegetables in developing regions, including India, thereby exacerbating malnutrition and economic burdens (Kitinoja *et al.*, 2015) ^[17]. By inhibiting microbial proliferation, enzymatic browning, and oxidative rancidity, preservation technologies ensure the availability of safe, nutrient-dense foods year-round (Kammari Priyanka *et al.*, 2021) ^[14]. Conventional food preservation methods, encompassing thermal processing (e.g., pasteurization at 72 °C for 15 s, sterilization at 121 °C), dehydration, freezing at -18 °C, and chemical additives like sodium benzoate or potassium sorbate, have underpinned industrial food systems for decades (Rai *et al.*, 2021) ^[29]. These techniques achieve substantial microbial lethality, with canning delivering 12D reductions for *Clostridium botulinum* spores and drying lowering water activity (aw) below 0.6 to preclude spoilage organism growth (Yang and Liu, 2019) ^[50]. Fermentation further enhances organoleptic profiles through lactic acid bacteria metabolism, as seen in sauerkraut or idli, while irradiation (1-10 kGy) penetrates packaging for bulk decontamination (Wilburn and Ryan 2017) ^[48]. The advantages of these conventional approaches are manifold: thermal methods offer high throughput and regulatory validation, with pasteurization inactivating 5-6 log cycles of *Listeria monocytogenes* in dairy; freezing preserves up to 90% of heat-labile vitamins, like ascorbic acid in berries; and preservatives extend shelf life economically for ready-to-eat products. Such scalability has enabled global trade in preserved commodities, from canned tomatoes to frozen peas, while minimizing acute toxicity risks under Codex Alimentarius limits (e.g., 1000 mg/kg for benzoates) (Longdom Publishing, 2023) ^[20].

Nevertheless, conventional technologies harbor significant drawbacks that compromise their efficacy in modern contexts. Thermal processing induces Maillard reactions and protein denaturation, resulting in 40%-70% losses of thermosensitive nutrients such as thiamine, folate, and anthocyanins in fruit juices and vegetable purees (Patras *et al.*, 2010) ^[38]. Sensory degradation manifested as cooked flavors, texture softening via pectin methyl esterase

inactivation, and color shifts from chlorophyll to pheophytin deters consumer preference for "fresh-like" attributes (Rawson *et al.*, 2010) [41]. Chemical preservatives evoke allergenicity concerns (e.g., sulphite-induced asthma in 1% of asthmatics) and microbial resistance, while freezing elevates energy demands (200-300 kWh/ton) and risks cryogenic damage like drip loss in thawed produce (Duygu Agagunduz *et al.*, 2025) [6]. This confluence of nutritional attrition, sensory deficits, and sustainability imperatives has catalyzed the evolution of non-thermal processing technologies, which operate at ambient temperatures (<40 °C) to deliver microbial inactivation sans heat-induced collateral damage (Rawson *et al.*, 2011) [40]. Innovations like high-pressure processing (HPP; 400-600 MPa), pulsed electric fields (PEF; 20-50 kV/cm), ultrasound (20-100 kHz), and ultraviolet light (UVC; 254 nm) preserve 80-95% of bioactives, including polyphenols and carotenoids critical for functional foods derived from dragon fruit peels or watermelon rind (Misra *et al.*, 2021) [32]. These methods slash energy consumption by 50-70% relative to their thermal counterparts, curtail chemical residues, and facilitate hurdle approaches (e.g., HPP + antimicrobials) for synergistic efficacy, thereby fostering circular economy paradigms in food engineering (Ferrari *et al.*, 2010) [9]. Among these, cold plasma (CP) technology emerges as a vanguard non-thermal modality, comprising partially ionized gas at atmospheric pressure laden with reactive oxygen species (ROS: O, OH⁻, O₃), reactive nitrogen species (RNS: NO, NO₂), UV photons (200-300 nm), and charged particles (Jiang *et al.*, 2022) [13]. Generated via dielectric barrier discharge (DBD), radio-frequency plasma, or gliding arc reactors using air, argon, or helium feed gases, CP imparts surface-specific decontamination ideal for heat-sensitive agricultural produce like strawberries, tomatoes, and seeds (Ziuzina *et al.*, 2016) [51]. Unlike volumetric treatments such as HPP, which falter on porous or irregular geometries, CP's dry, non-contact plume penetrates biofilms and inactivates embedded pathogens with 3-6 log CFU/g reductions in treatment times of 1-5 min (Kaur *et al.*, 2024). In general, plasma is characterized as "the fourth state of matter." Thermal plasma, on the other hand, has reactive species generated in environments or gases that have been heated from a few thousand to more than 10,000 K. In thermal plasma, the reactive electrons and heavier species are normally not in a state of equilibrium, and the temperatures of the electrons produced are even greater than those of the heavier charged and neutral ions (Fridman *et al.*, 2005) [10]. The heat generated in the production of

thermal plasma, however, has a detrimental effect on food. The imperative for CP in food preservation stems from escalating threats: foodborne pathogens like *Salmonella* and *E. coli* O157:H7 contaminate 20-30% of fresh produce globally, while mycotoxins (e.g., aflatoxins >4 µg/kg) and pesticide residues (detected on 45% of samples) evade conventional washing (Min *et al.*, 2016) [24]. CP uniquely degrades these via etching (cell wall ablation), genetic mutagenesis (UV-induced thymine dimers), and peroxidation (lipid membrane rupture), extending shelf life by 7-14 days in perishables through polyphenol oxidase inhibition (Jiang *et al.*, 2022) [13]. For common foods like nuts and grains, it slows down fungal growth without stopping them from sprouting, making it a great match for improving products like your mulberry leaf or pseudo-cereal research (Nosheen Amjad *et al.*, 2025) [35]. CP's advantages are compelling: it retains volatile aroma compounds and textural firmness (e.g., <5% firmness loss in apples vs. 20% in blanching), while paradoxically boosting antioxidant capacity by 20-30% through ROS-mediated phenolic activation (Duygu Agagunduz *et al.*, 2025) [6]. Energy efficiency (1-5 kWh/m³ plasma volume) and byproduct-free operation (no wastewater) render it eco-sustainable, with scalability evidenced by pilot plants treating 100 kg/h of poultry (Kaur *et al.*, 2024). Regulatory clearances from FDA (GRAS for meat surfaces) and EFSA (for sprouts) affirm its trajectory toward commercialization (FDA, 2023) [8]. Thus, the need for CP-mediated food treatment is acute, particularly for biofilms recalcitrant to sanitizers (requiring 10-100x higher doses) and spores demanding thermal extremes (Jiang *et al.*, 2022) [13]. In India, where 20-30% horticultural losses burden smallholders, CP's chemical-free, ambient process democratizes safety enhancements, synergizing with ozone or ultrasound for fortified preservation in functional formulations (Nosheen Amjad *et al.*, 2025) [35]. This review elucidates CP's transformative potential, bridging mechanistic insights to industrial deployment for safer foods and commodities.

Fundamentals and Mechanism

Cold plasma generation

The CP technology involves electrical energy supplied via electrodes to carrier gases such as air, oxygen, nitrogen, or helium. A plasma generation system require a carrier gas, a proper power source, and special electrodes (Mishra *et al.*, 2016) [25]. Plasma generation is shown in Fig. 1.

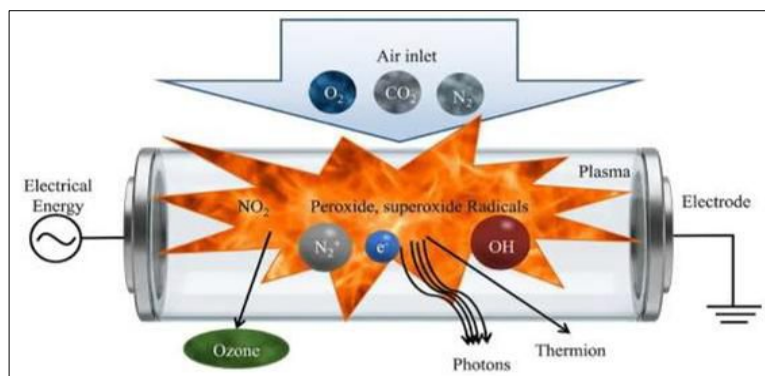


Fig 1: Plasma generation process

Applying an electric current between electrodes (cathode and anode) separated by 1 cm in air, at a voltage of around 30 kV/cm, results in electrical breakdown, ignition of atmospheric air, and the formation of plasma, as per the air breakdown threshold (Mishra *et al.*, 2016) [25]. It often begins as a transient discharge appearing as a spark, which subsequently evolves into a high-current, violent arc at high power levels (Stoica *et al.*, 2014) [44]. The air is maintained at atmospheric pressure or in a vacuum. This procedure necessitates reduced power input at low pressure and increased power at air pressure. In recent years, the majority of system development efforts have concentrated on acquiring atmospheric pressure plasma due to its cost-effectiveness and operational simplicity. Multiple plasma generation sources, such as corona discharge, dielectric barrier discharge, glow discharge, radio-frequency discharge, atmospheric pressure plasma jet, micro-hollow discharge, gliding arc discharge, and plasma needle, have been employed in food processing applications. Utilizing noble gases for plasma generation is advantageous as it mitigates oxidative degradation of food upon exposure to oxygen. Nevertheless, this may elevate the expense of treatment. Nonetheless, the most cost-effective activities in food systems utilize atmospheric air (Misra *et al.*, 2014) [30]. Thermodynamically, as molecules acquire energy, the phase of matter evolves from solid to liquid to gas. Elevating the energy beyond a threshold in the gaseous state results in the ionization of gas molecules, producing a unique plasma state (Mishra *et al.*, 2016) [25]. This energy can be mechanical, thermal, electric current, electromagnetic fields, nuclear, X-rays, radio frequency, etc. (Afshari & Hosseini, 2014; Stoica *et al.*, 2014) [2, 44], leading to the development of many types of systems. These energies disintegrate gas molecules into an array of ions, electrons, free radicals, charged and neutral gas molecules, and other biologically active species that possess the ability to eradicate microorganisms. The reactive species typically generated

include reactive oxygen species (such as ozone O₃, atomic oxygen O, excited oxygen O₂, singlet oxygen O₂^{*}, and superoxide anion O₂⁻) and reactive nitrogen species (including atomic nitrogen N, excited nitrogen N₂, and nitric oxide NO•). Various operational and design parameters produce distinct reactive species, which correspond to varying levels of decontamination (Aboubakr *et al.*, 2015) [1].

Sources of Plasma

Plasma is an ionized gas including many active species with overall neutral charges. It is especially important for application in the food industry, as it may facilitate food processing at low temperatures. It is believed that non-thermal plasma was previously generated at low pressures and power levels. Recent breakthroughs in plasma engineering have led to the development of plasma generators capable of operating at atmospheric pressure. The plasma source mainly includes dielectric barrier discharges (DBD), gliding arc discharge, corona discharge plasma jet, and microwave/radio frequency plasma (Table 1. and Fig. 1). DBD is a non-equilibrium gas discharge characterized by the introduction of an insulating medium into the discharge region. The gliding arc discharge is caused by a high voltage applied by the power supply to the two electrodes causing an electrical breakdown of the gas flowing between the electrodes at the narrowest part of the electrodes. A robust arc of high current is produced, subsequently quenched, and then restarted, with the cycle repeating. A corona discharge is a localized, self-sustaining discharge occurring in a gaseous medium within an inhomogeneous electric field. A plasma jet consists of two coaxial electrodes with gas discharging between them at elevated flow rates. Microwave/RF plasma is a low- temperature plasma generated by ionizing the surrounding air around the electrodes using high frequency and high voltage.

Table 1: Classification of plasma sources

Sources of cold plasma	Generation mechanism and characteristics	References
Dielectric Barrier Discharge (DBD)	Plasma occurs between two electrodes, and then, an AC high voltage is applied on the electrodes. It is an excellent CP source with 1-10 eV and high density.	Xu, (2001) [49]
Gliding Arc Discharge	Two (or more) metallic electrodes connected to an AC or DC high-voltage transformer. A plasma plume is generated when the high voltage is applied. This arc is then pushed away by a gas flow and glides along the electrodes until it collapses.	Tiya-Djowe <i>et al.</i> , (2019) [46]
Plasma Jet	Two coaxial electrodes, between which gas flows at high rates. The free electrons are accelerated by the RF field and collide with molecules of background gas. These inelastic collisions can produce various reactive species (excited atoms and molecules, free radicals) that exit the nozzle at high velocity.	Misra <i>et al.</i> , (2016) [28, 31]; Nishime <i>et al.</i> , (2017) [34]
Corona Discharge Plasma Jet	Containing substantial electric field for expediting the ionization energy of arbitrarily produced electrons to that of milieu gas atoms or molecules.	Scholtz <i>et al.</i> , (2015) [43]
Microwave (MW)/radio frequency (RF) plasma	RF plasma is usually achieved when a gas is placed within an oscillating electromagnetic field, produced by an induction coil or distinct electrodes kept outside the reactor. MW/RF CP is usually generated under reduced pressure.	Ekezie <i>et al.</i> , (2017) [7]; Niemira, (2012) [33]

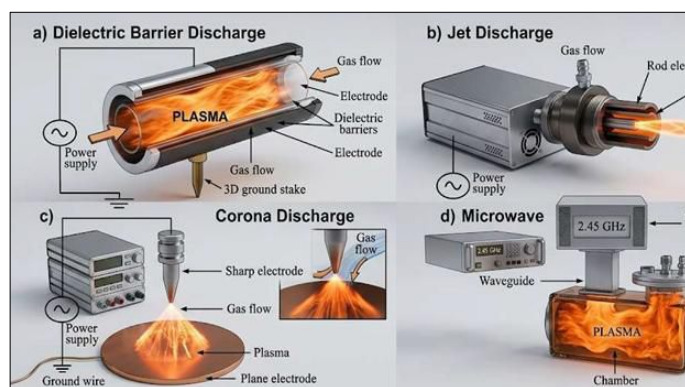


Fig 2: 3D illustration of different plasma sources

Effective mechanism of cold plasma in microbial inactivation in foods

Non-thermal techniques can suppress microbial proliferation, destroy contaminants, and simultaneously improve the nutritional, sensory, and physical attributes of products, which can be utilized for the preservation of unstable bioactive substances and the modulation of enzyme activity. As an emerging non-thermal technique, the mechanics of cold plasma therapies for food sterilization are intricate and not fully comprehended. The majority of existing studies concentrate on the indirect processes of microbial elimination (Mai-Prochnow *et al.*, 2014) [21]. Fortunately, CP has demonstrated effective decontamination of food with low influence on product quality, supported by

a growing number of research on its antimicrobial activity. The summarized mechanisms of microbial decontamination by CP in foods are listed in Table 2.

The electronic actions of impact (excitation, vibration, dissociation, attachment, and ionization), ion-molecule reactions, ion-ion neutralization, Penning ionization, quenching, neutral chemistry, and three-body neutral recombination, alongside photoemission, photo absorption, and photoionization by ultraviolet light and photons, contribute to the generation of active species in a CP (Misra

et al., 2016) [28, 31]. Fig. 2 shows the overview of cold plasma mechanism involved in microbial inactivation. The oxidation of proteins and DNA by reactive oxides and nitrides renders low-temperature plasma highly effective for sterilizing. The gas between the plate electrodes, the design of the plasma source, the power supplied to the gas, vacuum conditions, treatment duration, and humidity levels are some elements that may influence the reactive species and their concentrations in the plasma (Misra and Jo, 2017) [26-27].

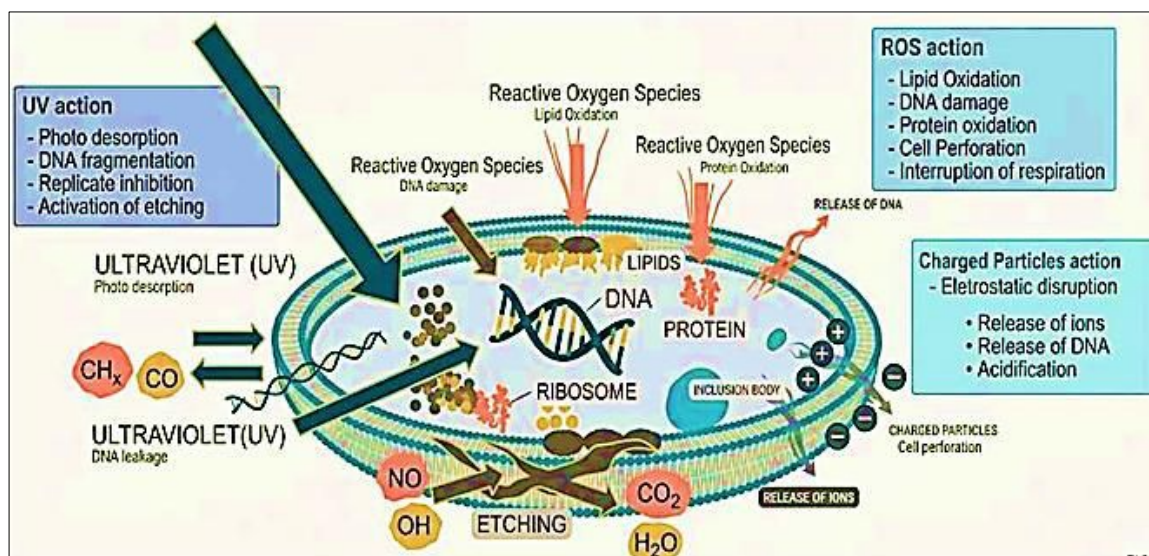


Fig 3: Overview of cold plasma mechanisms involved in microbial inactivation

Impact of Cold Plasma in Food Decontamination

The primary active components acknowledged for the antibacterial efficacy of CP systems are reactive oxygen species (ROS). CP has demonstrated efficacy in the inactivation of pathogens on the surface of fresh food items. Table 3 presents a concise summary of the effectiveness of CP treatment in inactivating several foodborne microorganisms. The study conducted by Albertos *et al.*, (2017) [3] found that the impact of dielectric barrier discharge (DBD) plasma on fresh mackerel (*Scomber scombrus*) fillets indicates that CP may serve as a viable alternative for reducing spoilage germs, including *lactic acid bacteria*, *Pseudomonas*, and *aerobic psychrotrophic bacteria* in fish. The researchers observed that cold plasma (CP) effectively reduced spoilage microorganisms in oily fish, with plasma voltage and duration being critical criteria for microbial inactivation. Nonetheless, they discovered that CP treatment in fish accelerated lipid oxidation and proposed further research to explore the reduction of lipid oxidation by the combination of antioxidants and CP.

Buñler *et al.*, (2015) [4] researched the effects of cold atmospheric plasma pressure on pea physiology and glycoside flavonol (*Pisum sativum Salamanca*). Researchers observed that CP may modify beneficial secondary plant metabolites in agricultural products. Additionally, CP was found to inactivate pathogenic microorganisms in heat-sensitive foods. CP treatment reduced seedling photosynthetic capacity but increased flavonoid glycoside concentration in peas, likely due to excessive UV radiation

and exposure time. In accordance, CP technology could be used to selectively change secondary plant metabolites during post-harvest processing of agricultural products. The research conducted by Grzegorzewski *et al.*, (2011) [11] observed that, treatment of lamb lettuce (*Valerianella locusta*) with a CP affects its phenolic profile. Lamb lettuce CP exposure reduced phenolic acids and flavonoids. CP significantly reduced lamb lettuce phenolic acid. CP breakdown of flavonoids was faster than phenolic acid reduction. They believed that reactive plasma species degraded phenolic acid and flavonoids, not lettuce surface photo- or thermal desorption. In *Valerianella locusta* plasma therapy, diosmetin increased whereas phenolic acid reduced. Researched the impact of dielectric barrier discharge (DBD) atmospheric CP treatment on deactivating Tulane virus and *E. coli* O157: H7 Salmonella, *Listeria*, *monocytogenes*, by Min *et al.*, (2016) [24]. The lettuce was inoculated with *Listeria monocytogenes*, *Salmonella*, *E. coli* O157: H7, and Tulane virus, packaged in MAP, petri dishes, and pouched leaves, then flushed with 5% or 10% nitrogen using O_2 . DBD CP treatment at 34.8 kV for 5 min inhibited *E. coli* O157: H7 by 1.1 log CFU, *L. monocytogenes* by 1.0 log CFU, and Tulane virus by 1.3 log PFU/g in packaged lettuce samples. Data was analyzed at 4 °C immediately or after 24 h of storage. The authors also discovered that MAP was unsuitable for atmospheric CP treatment from dielectric barrier discharge due to the interaction of additional N_2 and O_2 packing.

Table 2: Mechanisms of microbial decontamination by cold plasma (CP) in foods

Reactive species		Mechanisms	References
Charged particles	Electrons, atomic, or molecular ions, etc.		
Reactive oxygen species (ROS)	alkoxyl (RO·), carbonate anion radical (CO ₃ ·-), hydrogen peroxide (H ₂ O ₂), hydroperoxyl (HO ₂ ·), hydroxyl radical (·OH), ozone (O ₃), peroxy (ROO·), superoxide anion (O ₂ ·-), and singlet oxygen (1O ₂). Common examples of RNS in humid air plasma are included.	Membrane lipid of microorganisms peroxidized. Amino acid in proteins of micro-organisms denaturated. Breaking structural bonds in cell wall component peptidoglycan. Permeabilization of the cell membrane or cell wall. Damaging iron-sulphur and mononuclear iron enzymes. Changing the pH that microorganisms rely on.	Mandal <i>et al.</i> , (2018) ^[22] Mai-Prochnow <i>et al.</i> , (2014) ^[21] Deng <i>et al.</i> , (2006) ^[5] Misra <i>et al.</i> , (2017) ^[26-27] Misra <i>et al.</i> , (2016) ^[28, 31] Scholtz <i>et al.</i> , (2015) ^[43]
Reactive nitrogen species (RNS)	alkylperoxynitrite (ROONO), nitric oxide (NO·), nitrogen dioxide radical (·NO ₂), peroxynitrite (ONOO·), and peroxynitrous acid (OONOH).		
Ultraviolet rays	Electromagnetic radiation created by aero-ionization	Directly damaging genetic materials and inhibiting the replication of DNA. Formation of thymine dimer due to photon emissions, modifications of nucleo-bases, and nucleotide oxidation by reactive species.	Guo <i>et al.</i> , (2015) ^[12] ; Misra <i>et al.</i> , (2019) ^[29]
Plasma-activated water treatment	Creating the acidic environment water full of ROS and RNS	Similar to reactive species.	Thirumdas <i>et al.</i> , (2018) ^[45]

Table 3: Summary of the effects of cold plasma (CP) treatment on food commodities

Commodity	Plasma Type	Plasma Parameters	Physicochemical Effects	References
Peas	Dielectric barrier discharge	6-12 kV/20 MHz/5 min/electrode distance was 20 mm	Reduced the photosynthetic efficiency of seedlings and altered the quantity of flavonoid glycosides.	Bußler <i>et al.</i> , (2015) ^[4]
Blueberries	Atmospheric pressure plasma jet	47 kHz/549 W/Air	Firmness substantially diminished after 60 seconds. Significantly lessened in firmness. Affected the surface coloration.	Lacombe <i>et al.</i> , (2015) ^[18]
Blueberries	Dielectric barrier discharge	At 80 kV and 1 A for 5 min./electrode distance was 35 mm	Firmness significantly decreased. The color of blueberries changed but was not statistically significant compared to untreated blueberries. Reduced total polyphenolic content, total flavonoids, ascorbic acid, and anthocyanin with elevated voltage and prolonged exposure duration. Substantially decreased pesticide residues, including Boscalid and Imidacloprid. Removal efficiencies of 75% for Boscalid and 80% for Imidacloprid were recorded	Sarangapani <i>et al.</i> , (2017) ^[42]
Brown rice	Dielectric barrier discharge	15 kHz/250 W/5-20 min./air/electrode distance was 2cm.	Reduction in pH and hardness. Higher L* values and reduced a* and b* values of brown rice	Lee <i>et al.</i> , (2016) ^[19]
Cherry tomatoes	Dielectric barrier discharge	100 kV/150 sec/air/electrode distance was 4.5 cm	Did not substantially impact color, hardness, pH, and total soluble solids.	Ziuzina <i>et al.</i> , (2016) ^[51]
Red chicory (radicchio)	Dielectric barrier discharge	15 KV/12.5 kHz/15-30 min/1.5 m/s/air/electrode distance was 0.15 cm	Did not significantly influence the antioxidant activity and the outside appearance of the food.	Pasquali <i>et al.</i> , (2016) ^[37]
Red chicory	Dielectric barrier discharge	19.15 V/3.15 A/15 min/electrode distance was 2.0 cm	No adverse impacts on color, freshness, or texture. The odor and overall acceptability had a slight decline during storage.	Trevisani <i>et al.</i> , (2017) ^[47]
Beef jerky	Radio-frequency atmospheric pressure plasma	20,000 sccm /200 / argon	Minor variations in nutritional attributes, including fatty acid content and sensory characteristics, were noted.	Kim <i>et al.</i> , (2014) ^[15]
Raw pork loin	Dielectric barrier discharge	3 kV, 30 kHz/10 min./3 mm between DBD actuator and sample/He or He + O ₂	Decreased pH. Modified flesh color. Reduced nutritional quality and shelf life resulting from reactive oxygen species that cause lipid oxidation. Substantially impacted appearance, color, odor, and palatability.	Kim <i>et al.</i> , (2013) ^[16]
Romaine lettuce	Dielectric barrier discharge	42.6 kV/1.5 A/10 min/air/electrode distance was 5.0 cm.	No substantial alterations in surface morphology, shading, respiration rate, or weight loss were detected.	Min <i>et al.</i> , (2017) ^[23]
Romaine lettuce	Dielectric barrier discharge	47.6 kV and 1 A for 5 min./electrode distance was 30 mm	Did not exhibit any indications of burning, wilting, or discoloration.	Min <i>et al.</i> , (2016) ^[24]
Radish sprouts	Microwave plasma	2.45 GHz/900 W/669 Pa/10 min/N ₂	Did not adversely impact appearance, odor, ascorbic acid, or antioxidant activity. Radish sprouts showed wilting following 20 minutes of plasma treatment.	Oh <i>et al.</i> , (2017) ^[36]
Lamb lettuce	Atmospheric pressure plasma jet	27.12 MHz/2 min./argon	Impacted detrimental effects on phenolic acids and flavonoids.	Grzegorzewski <i>et al.</i> , (2011) ^[11]
Fresh mackerel	Dielectric barrier discharge	80 kV/5 min/electrode distance was 35 mm	Lipid oxidation induced. No alterations in color observed	Albertos <i>et al.</i> , (2017) ^[3]

Oh *et al.*, (2017) ^[36] studied the impact of microwave CP treatment on *Salmonella typhimurium* inhibition and radish sprout characteristics. For 1-20 min, the CP microwave generator employed nitrogen gas at 900 W and 667 Pa. optimized 10-minute treatment reduced *Salmonella typhimurium* levels by 1.8 log CFU/g. There was no detrimental impact on appearance or aroma. Treatment with CP at 4-10 °C prevented *Salmonella typhimurium* growth and did not impact water quality, color, antioxidant activity, or ascorbic acid in sprouting radish in plastic containers. The study found that CP can effectively inactivate *Salmonella typhimurium* in radish sprouts without affecting their sensory qualities. They found that preserving radish sprouts in closed plastic packets at cold temperatures following CP treatment was advantageous and applicable to other vegetable sprouts.

An open-air dielectric discharge barrier plasma reactor (SAFE BAG test device, Dublin Institute of Technology, Dublin, Ireland) was tested for its antimicrobial efficacy against *Escherichia coli* and *Listeria innocua*, as well as the indigenous microflora of cherry tomato after packaging as per research conducted by Ziuzina *et al.*, (2016) ^[51]. Extended shelf storage was used to evaluate cherry tomato quality. A continuous cycle of atmospheric CP treatment reduced *E. coli* and *Listeria innocua* by 3-5 log CFU/g. Maximum reductions of 3.5 log CFU/g of indigenous microflora (mesophiles, yeast, and mold) were achieved using static mode. There were no significant differences in mean color (L, a *, and b *), hardness, pH, and total soluble solids. They found that a pilot-scale in-package CP system may increase food package discharges under static and continuous treatment. Researchers concluded that aspects such as bacteria type (Gram-positive and Gram-negative), cell concentration, and treatment mode affect decontamination efficacy, making them crucial for optimizing CP technology in industrial settings.

Trevisani *et al.*, (2017) ^[47] evaluated the inhibitory effects of atmospheric CP, surfactant, and lactic acid on *monocytogenes* and *E. coli* producing verotoxins in red chicory. Red chicory was pre-washed with surfactant, lactic acid, or NaCl, then rinsed with deionized water before CP treatment. CP treatment conditions were maintained at 19.15 V and 3.15 A for 15 minutes. According to authors, pre-washing red chicory with a surfactant before CP treatment reduced VTEC counts by 2.89 log CFU/g, while pre-washing with lactic acid + surfactant resulted in a substantially larger reduction of 4.78 log CFU/g. *L. Monocytogenes* levels decreased by almost 4 log CFU/g after pre-washing red chicory with lactic acid and surfactant. No negative effects on color, flavor, or quality were identified. Overall acceptability and odor dropped slightly after storage. The study found that combining surfactant, lactic acid, and CP treatment enhanced bactericidal activity. Pre-washing with surfactant and lactic acid inhibited free-flowing microorganisms.

To decontaminate radicchio leaves, Pasquali *et al.* (2016) ^[37] used dielectric barrier CP discharge to study its effectiveness against *E. coli* O157: H7 and *L. monocytogenes*. Leaves were evaluated for microbial reduction, antioxidant activity, and sensory qualities. After 15 and 30 minutes, *E. coli* O158:H7 and *Listeria monocytogenes* were reduced by roughly 1.4 and 2.0 log₁₀ CFU/g, respectively. The investigators found that the prolonged treatment for *L. monocytogenes* was

comparable to earlier investigations utilizing an atmospheric CP dielectric barrier discharge system. Additionally, Gram-positive bacteria (*L. monocytogenes*) were less susceptible to atmospheric CP than Gram-negative bacteria (*E. coli* O158:H7). Radicchio leaves showed no significant antioxidant activity loss following CP treatment. The authors recommended improving the equipment configuration of the atmospheric CP system to mitigate negative effects on nutritional quality, such as a considerable decline in color and sensory qualities after storage.

Min *et al.* (2017) ^[23] examined the inactivation efficiency of CP on *Escherichia coli* O157:H7. They examined the impact of dielectric discharge barrier CP on Romaine lettuce surface form, brightness, and dioxide production. Pre-washed cut leaves are dried. Sealing occurred in a commercial clamshell container with stacked leaves in three rows (1, 3, 5, or 7 layers). A study found that atmospheric dielectric barrier discharges suppressed *E. coli* O157: H7 in many stack levels. They found that *Escherichia coli* O157: H7 was reduced in 1, 3, and 5-layer stacked leaves, but not in 7-layer stacks. The authors found that container headspace volume is crucial for treating sealed containers. A sealed container with a headspace volume provided for uniform diffusion of CP reactive species within the sample. No significant changes were seen in leaf particle size, brightness, oxygen saturation, or mass reduction.

An open-air dielectric plasma discharge reactor was found to be effective against *Escherichia coli* O157: H7, *Bacillus cereus*, and *Bacillus subtilis* on brown rice reported by Lee *et al.*, (2016) ^[19]. CP treatments have been discovered to enhance microbiological decontamination of brown rice. Similar to previous research such as Pasquali *et al.* (2016) ^[37], Gram-positive *Bacillus cereus* and *Bacillus subtilis* inactivated more slowly than Gram-negative *Escherichia coli* O157:H7. Plasma treatments enhanced water absorption and α -amylase activity while reducing brown rice pH and hardness. Lee *et al.*, (2016) ^[19] found that CP technology boosted brown rice textural quality and maintained microbiological safety. Lacombe *et al.*, (2015) ^[18] examined that inhibiting aerobic microorganisms on blueberries with CP affects aspects of quality. CP was tested for its ability to reduce total aerobic count, yeast/molds, total anthocyanin, and blueberry firmness. CP treatments substantially decreased microflora on fresh blueberries held at 4 °C for 7 days. CP treatment resulted in significant reductions in compression firmness after 60 seconds and anthocyanin after 90 seconds. In this study, CP treatment did not reduce yeast and mold numbers. Additionally, prolonged treatment affected surface color (L, a*, b* values). The study found that atmospheric CP can inactivate bacteria on blueberries on an experimental scale. They suggested using this method at pilot and commercial scales with existing forced air-cooling processes to optimize decontamination in small fruits like blueberries. Sarangapani *et al.* (2017) ^[42] examined the impact of CP on blueberry agrochemicals. The study also analyzed significant impacts on critical dietary and physical features. Study insecticides were Boscalid and Imidacloprid. In this study, a plasma discharge reactor with a high-voltage dielectric barrier was utilized. CP treatment at 80 kV for 5 minutes reduced pesticide potency by 80% for boscalid and 75% for imidacloprid. They expected that ozone and hydroxyl radicals would degrade pesticides. The significant rise in total flavonoids and phenol content in

blueberries after 1 minute did not significantly impact physicochemical qualities like color and firmness. However, prolonged plasma therapy drastically reduced ascorbic acid levels. The researchers found that CP, despite its nutraceutical benefits, is a potential method for reducing agro-chemicals and deactivating microbes in fresh food.

Kim *et al.*, (2013) ^[16] studied the impact of dielectric barrier discharge plasma on pathogen inhibition, sensory characteristics, and physico-chemistry of raw pork loins. At 101-104 CFU/g, antibiotic-resistant *E. coli* O157:H7 and *L. monocytogenes* strains were injected and applied to pork loin. The dielectric barrier discharge plasma gases utilized were He and He+O₂ for 5-10 minutes. *E. coli* growth was reduced to 0.55 log CFU/g after 10 min of plasma treatment with He and He + O₂. *Listeria monocytogenes* levels decreased to 0.59 log CFU/g after 10 min of exposure. There were no visible color changes; however, a considerable pH reduction was noted. In addition, plasma-treated samples showed significant decreases in sensory quality indices. Research suggests that the plasma device using dielectric barrier discharge could cleanse pork loins by inactivating foodborne germs, but more research is needed to avoid sensory distress.

Kim *et al.* (2014) ^[15] studied the effects of using radiofrequency (RF) atmospheric pressure plasma to inactivate *Staphylococcus aureus* on beef jerky's nutritional and sensory qualities. Argon was used as input gas at 20,000 sccm and 200W. After a 10-minute plasma treatment at 300 °C, *Staphylococcus aureus* levels dropped by 3-4 log CFU/g sample. The beef jerky samples did not significantly change in terms of fatty acid composition, color, or strength. *Staphylococcus aureus* was inhibited by radiofrequency atmospheric pressure plasma in beef jerky, with little changes to nutritional and sensory qualities.

Constraints and Adverse Effects of Cold Plasma

The adverse impacts of CP treatment on the sensory and nutritional attributes of processed foods present an important barrier to the advancement of CP methodologies and equipment designs. The presence of reactive oxygen species (ROS) in chilled products induces lipid oxidation in meat and fish tissues, adversely impacting acceptability and shelf-life due to lipid breakdown and the onset of oxidative rancidity. CP also leads to the breakdown of highly polymerized oligosaccharides in juices following prolonged CP treatment. Ozonolysis initiated glycosidic bond cleavage, resulting in macromolecule depolymerisation and oxidation of functional groups. However, the breakdown of the oligosaccharides following CP treatment was adequate to be categorized as prebiotics. Additional studies must be conducted to enhance the understanding of the degradation mechanism of oligosaccharides by CP application and ozone generation. A comprehensive understanding of the mechanisms of lipid oxidation and oligosaccharide breakdown is essential for the mainstream application of CP in food.

Summary of the Studies and Future Research

Numerous studies included in this review have showed that CP treatment is efficient in microbial inactivation. Although most of the CP systems examined in this research were laboratory-scale configurations, implementing this application in a food production facility is feasible. Nevertheless, adverse effects on the sensory characteristics

and nutritional qualities of certain food items have been noted following treatment with CP. This conclusion arose from certain constraints of CP use, particularly as the technology is product-specific and leads to a highly complex chain of chemical interactions. During the CP treatment of food items, the produced plasma may be excessively close to, or unevenly distributed around, the product, potentially impacting its physical and functional characteristics. CP produces an important electric field, high-energy plasma-reactive species, and high levels of UV radiation; hence, the positioning of products and duration of exposure are significant.

Despite of the specific strategies implemented, it is evident that modifications and enhancements to CP yield superior outcomes. The utilization and chemistry of CP are intricate, necessitating greater understanding of plasma chemistry and dynamics for diverse technical applications. Identifying new plasma sources for process analysis is crucial, as is monitoring and adjusting the various species, including electrons, ions, radicals, and photons, to successfully modify food decontamination properties and food quality.

Conclusion

CP is a significant antibacterial technique effective against pathogens like *Staphylococcus aureus*, *E. coli* O157:H7, *Listeria monocytogenes*, *Salmonella Typhimurium* biofilms, and *Bacillus cereus*. Despite the disadvantages of cold plasma (CP) treatment in food, including accelerated lipid oxidation and negative impacts on sensory attributes, CP has shown significant efficacy as an alternative method for food decontamination and should be approved as a viable technology for the complete elimination of foodborne pathogenic microorganisms in food products.

References

1. Aboubakr HA, Williams P, Gangal U, Youssef MM, El-Sohaimy SAA, Bruggeman PJ. Virucidal effect of cold atmospheric gaseous plasma on feline calicivirus, a surrogate for human norovirus. *Applied and Environmental Microbiology*. 2015;81:3612-3622.
2. Afshari R, Hosseini H. Non-thermal plasma as a new food preservation method: its present and future prospect. *Journal of Paramedical Sciences*. 2014;5:116-120.
3. Albertos I, Martín-Diana AB, Cullen PJ, Tiwari B, Ojha S, Bourke P, et al. Effects of dielectric barrier discharge (DBD) generated plasma on microbial reduction and quality parameters of fresh mackerel (*Scomber scombrus*) fillets. *Innovative Food Science and Emerging Technologies*. 2017;44:117-122.
4. Bußler S, Herppich WB, Neugart S, Schreiner M, Ehlbeck J, Rohn S, et al. Impact of cold atmospheric pressure plasma on physiology and flavonol glycoside profile of peas (*Pisum sativum* 'Salamanca'). *Food Research International*. 2015;76:132-141.
5. Deng X, Shi J, Kong MG. Physical mechanisms of inactivation of *Bacillus subtilis* spores using cold atmospheric plasmas. *IEEE Transactions on Plasma Science*. 2006;34:1310-1316.
6. Agagunduz D, Ayakdaş G, Katircioğlu B, Ozogul F. Advances in non-thermal food processing: a comprehensive approach to nutrient retention, food quality, and safety. *Sustainable Food Technology*. 2025;5(3):1284-1308.

7. Ekezie FC, Sun DW, Han Z, Cheng JH. Microwave-assisted food processing technologies for enhancing product quality and process efficiency: a review of recent developments. *Trends in Food Science and Technology*. 2017;67:58-69.
8. Food and Drug Administration. Application of cold atmospheric plasma in the treatment of viruses and decontamination. 2023.
9. Ferrari G, Maresca P, Ciccarone R. The application of high hydrostatic pressure for the stabilization of functional foods: pomegranate juice. *Journal of Food Engineering*. 2010;100:245-253.
10. Fridman A, Chirokov A, Gutsol A. Non-thermal atmospheric pressure discharges. *Journal of Physics D: Applied Physics*. 2005;38:R1-R24.
11. Grzegorzewski F, Ehlbeck J, Schlüter OK, Kroh LW, Rohn S. Treating lamb's lettuce with cold plasma: influence of atmospheric pressure Ar plasma species on phenolic profile. *LWT - Food Science and Technology*. 2011;44:2285-2289.
12. Guo J, Huang K, Wang J. Bactericidal effect of various non-thermal plasma agents and the influence of experimental conditions in microbial inactivation: a review. *Food Control*. 2015;50:482-490.
13. Jiang J, Zhao Y, Xiong Q, Li Y, Han Z. Food preservation by cold plasma from dielectric barrier discharge. *Foods*. 2022;11(22):3675.
14. Priyanka K, Gandoli M, Goud KSB, Dev H, Venkatesh M, Jeepipalli SPK. Conventional food preservation methods and their biochemical response. *International Journal of Applied Agricultural Research*. 2021;16(1):7-17.
15. Kim JS, Lee EJ, Choi EH, Kim YJ. Inactivation of *Staphylococcus aureus* on beef jerky by radio-frequency plasma treatment at atmospheric pressure. *Innovative Food Science and Emerging Technologies*. 2014;22:124-130.
16. Kim HJ, Yong HI, Park S, Choe W, Jo C. Effects of dielectric barrier discharge plasma on pathogen inactivation and physicochemical characteristics of pork loin. *Current Applied Physics*. 2013;13:1420-1425.
17. Kitinoja L, Kader AA. Measuring postharvest losses of fresh fruits and vegetables in three Indian states. *Postharvest Technology Center, University of California Davis*; 2015.
18. Lacombe A, Niemira BA, Gurtler JB, Fan X, Sites J, Boyd G, et al. Atmospheric cold plasma inactivation of aerobic microorganisms on blueberries and effects on quality attributes. *Food Microbiology*. 2015;46:479-484.
19. Lee KH, Kim HJ, Yun SW, Jo C, Kim JK, Kim SH, et al. Evaluation of cold plasma treatments for improved microbial and physicochemical qualities of brown rice. *LWT - Food Science and Technology*. 2016;73:442-447.
20. Longdom Publishing. The art and science of food preservation: methods, benefits and challenges. *Journal of Food Processing and Technology*. 2023;14(3):100167.
21. Mai-Prochnow A, Murphy AB, McLean M, Kong MG, Ostrikov K. Atmospheric pressure plasmas: infection control and bacterial responses. *International Journal of Antimicrobial Agents*. 2014;43:508-517.
22. Mandal R, Singh A, Singh AP. Recent developments in cold plasma decontamination technology in the food industry. *Trends in Food Science and Technology*. 2018;80:93-103.
23. Min SC, Roh SH, Niemira B, Boyd G, Sites JE, Uknalis J, et al. In-package inhibition of *Escherichia coli* O157:H7 on bulk Romaine lettuce using cold plasma. *Food Microbiology*. 2017;65:1-6.
24. Min SC, Roh SH, Niemira B, Sites JE, Boyd G, Lacombe A. Dielectric barrier discharge atmospheric cold plasma inhibits *Escherichia coli* O157:H7, *Salmonella*, *Listeria monocytogenes* and Tulane virus in Romaine lettuce. *International Journal of Food Microbiology*. 2016;237:114-120.
25. Mishra R, Bhatia S, Pal R, Visen A, Trivedi H. Cold plasma: emerging as the new standard in food safety. *Research Inventy International Journal of Engineering Science*. 2016;6:15-20.
26. Misra NN, Jo C. Applications of cold plasma technology for microbiological safety in meat industry. *Trends in Food Science and Technology*. 2017;64:74-86.
27. Misra NN, Martynenko A, Chemat F, Paniwnyk L, Barba FJ, Jambrak AR, et al. Thermodynamics, transport phenomena, and electrochemistry of external field assisted non-thermal food technologies. *Critical Reviews in Food Science and Nutrition*. 2017;31:1-32.
28. Misra NN, Pankaj SK, Segat A, Ishikawa K. Cold plasma interactions with enzymes in foods and model systems. *Trends in Food Science and Technology*. 2016;55:39-47.
29. Misra NN, Yepez X, Xu L, Keener K. In-package cold plasma technologies. *Journal of Food Engineering*. 2019;244:21-31.
30. Misra NN, Keener KM, Bourke P, Mosnier JP, Cullen PJ. In-package atmospheric pressure cold plasma treatment of cherry tomatoes. *Journal of Bioscience and Bioengineering*. 2014;118:177-182.
31. Misra NN, Schlüter O, Cullen PJ. Cold plasma in food and agriculture: fundamentals and applications. 1st ed. San Diego: Academic Press, Elsevier Ltd; 2016.
32. Misra NN, Yepez X, Xu L, Keener K. In-package decontamination of food by cold plasma. *Trends in Food Science and Technology*. 2021;112:112-123.
33. Niemira BA. Cold plasma decontamination of foods. *Annual Review of Food Science and Technology*. 2012;3:125-142.
34. Nishime TMC, Borges AC, Koga-Ito CY, Machida M, Hein LRO, Kostov KG. Non-thermal atmospheric pressure plasma jet applied to inactivation of different microorganisms. *Surface and Coatings Technology*. 2017;312:19-24.
35. Amjad N, Karabulut G, Wei CR, Naseer MS, Imran A, Chauhan A, et al. A review on cold plasma technology for pesticide-free food safety: mechanisms, efficiency, and future perspectives. *Current Research in Nutrition and Food Science*. 2025;13(2):569-583.
36. Oh YJ, Song AY, Min SC. Inhibition of *Salmonella typhimurium* on radish sprouts using nitrogen-cold plasma. *International Journal of Food Microbiology*. 2017;249:66-71.
37. Pasquali F, Stratakis AC, Koidis A, Berardinelli A, Cevoli C, Ragni L, et al. Atmospheric cold plasma process for vegetable leaf decontamination: a feasibility

- study on radicchio (*Cichorium intybus* L.). Food Control. 2016;60:552-559.
38. Patras A, Brunton N, O'Donnell C, Tiwari BK. Effect of thermal processing on anthocyanin stability in foods: mechanisms and kinetics of degradation. Trends in Food Science and Technology. 2010;21:3-11.
39. Rai AK, Jini R, Swapna HC. Conventional food preservation methods and their limitations. International Journal of Applied Agricultural Research. 2021;16(1):1-12.
40. Rawson A, Patras BKT, Tiwari B, Noci F, Koutchma T, Brunton N. Effect of thermal and nonthermal processing technologies on bioactive content of exotic fruits. Food Research International. 2011;44:1875-1887.
41. Rawson A, Koidis A, Rai DK, Tuohy M, Brunton N. Influence of sous vide and water immersion processing on polyacetylene content of parsnip. Journal of Agricultural and Food Chemistry. 2010;58:7740-7747.
42. Sarangapani C, O'Toole G, Cullen P, Bourke P. Atmospheric cold plasma dissipation efficiency of agrochemicals on blueberries. Innovative Food Science and Emerging Technologies. 2017;44:235-241.
43. Scholtz V, Pazlarova J, Souskova H, Khun J, Julak J. Non-thermal plasma: a tool for decontamination and disinfection. Biotechnology Advances. 2015;33:1108-1119.
44. Stoica M, Alexe P, Mihalcea L. Atmospheric cold plasma as new strategy for foods processing: an overview. Innovative Romanian Food Biotechnology. 2014;15:1-8.
45. Thirumdas R, Kothakota A, Annapure U, Siliveru K, Blundell R, Gatt R. Plasma activated water: chemistry, physico-chemical properties, applications in food and agriculture. Trends in Food Science and Technology. 2018;77:21-31.
46. Tiya-Djowe A, Acayanka E, Mbouopda AP, Boyom-Tatchemo W, Laminsi S, Gaigneaux EM. Producing oxide catalysts using gliding arc atmospheric plasma. Catalysis Today. 2019;334:104-112.
47. Trevisani M, Berardinelli A, Cevoli C, Cecchini M, Ragni L, Pasquali F. Effects of atmospheric cold plasma on *Escherichia coli* and *Listeria monocytogenes* in radicchio. Food Control. 2017;78:138-143.
48. Wilburn JR, Ryan EP. Fermented foods in health promotion and disease prevention: an overview. In: Fermented foods in health and disease prevention. 2017. p. 3-19.
49. Xu X. Dielectric barrier discharge—properties and applications. Thin Solid Films. 2001;390:237-242.
50. Yang B, Liu XJ. Metabolite profile differences among different storage time in beef preserved at low temperature. Journal of Food Science. 2019;84(11):3163-3171.
51. Ziuzina D, Misra NN, Cullen PJ, Keener K, Mosnier JP, Vilaró I, et al. Demonstrating industrial scale in-package atmospheric cold plasma for decontamination of cherry tomatoes. Plasma Medicine. 2016;6:397-412.