ISSN: 2347-467X, Vol. 10, No. (2) 2022, Pg.427-446

Current Research in Nutrition and Food Science

www.foodandnutritionjournal.org

Cold Plasma Treatment Concerning Quality and Safety of Food: A Review

JINKU BORA[1], TOOBA KHAN[1] and NIKHIL KUMAR MAHNOT[2*]

[1]Department of Food Technology, Jamia Hamdard, Hamdard Nagar, New Delhi, India.
[2]Department of Food Technology, Rajiv Gandhi University, Rono-Hills, Doimukh, Arunachal Pradesh, India.

Abstract

In the past years, cold plasma was only used in the sterilization of materials but today it has marked major applications in the food sector as well. Cold plasma is a modern green technology or an eco-friendly process, which is used in microbial decontamination of foods and their products like fruits, vegetables, dairy and meat products. As cold plasma consists of reactive ions species and not any hazardous chemicals, which could adversely affect human health, it has gained much importance and it is widely acceptable to consumers. The technology helps in providing safe and nutritious foods with minimal effect in quality. For information collection on cold plasma treatment, we have majorly considered recent and original research work by the scientific community. Major emphasis was on the implication of cold plasma treatment on the different food groups viz. cereals, dairy, meat, fish, eggs, and poultry products, nuts, seeds, fruits and vegetables and spices and herbs.The intent of this review is to bring forth microbial inactivation mechanism and decontamination efficacies upon cold plasma interaction on various food groups. Further, key insights on the quality impact on plasma treatment is evaluated and there on implicating key consideration for selecting cold plasma technology for any food or food products.

Article History
Received: 31 March 2022
Accepted: 19 July 2022

Keywords
Cold Plasma;
Food Quality;
Food Safety;
Microbial Decontamination;
Non-Thermal Process.

Introduction

In the current era, there have been major changes in the eating habits and diet patterns among consumers. Today's consumers are comparably more aware of health and meeting their nutritional needs. Also, various international health organizations have stressed the proven benefits of a diet rich in fresh foods or with minimal alterations. As a consequence, there is arisein the consumption of fresh and minimally processed foods.[1] Such foods contain higher water and nutritional content and also as they are mostly consumed in raw forms

CONTACT Nikhil Kumar Mahnot nikhil.mahnot@gmail.com Department of Food Technology, Rajiv Gandhi University, Rono-Hills, Doimukh, Arunachal Pradesh, India.

Doi: http://dx.doi.org/10.12944/CRNFSJ.10.2.3

without much processing, they are an active carrier of various food-borne illnesses.[2] Shelf-life extension of the fresh and/or minimally processed foods are conventionally achieved by thermal techniques and the addition of the permitted preservatives but the originality and fresh flavors are lost. So, there is a continuous quest for a technique that provides safe, nutritious food with minimum effect over the sensory and functional properties along with an increase in the storage life of the product.

Conventional thermal techniques like-freezing, drying, cooling, pasteurization, are used to enhance shelf-life of foods but employing non-thermal techniques has gained much importance in recent times.[3,4] Plasma technique is one such non-thermal techniques used for food processing.[5] Plasma technology offers major benefits to heat-sensitive products by having minimum deteriorative effects over quality. It has major applications including retaining nutritional properties, functional value, and sensory properties thus ensuring a fresh appearance or characteristics. It is also used for structural modifications of food and even packaging materials. This review investigates and discusses the published articles on cold plasma processing of foods or their products, and the data on the impact of such a treatment on the quality and safety aspects of different food groups.

How Cold Plasma is Generated?

Firstly, the term 'Plasma' was coined by Irving Langmuir an American physicist in 1928.[1,5] Universally, 'Plasma' is mentioned to as the fourth state of matter. It's quite simple to generate with a basic principle involving energizing a neutral gas system. Adding sufficient energy to a gas system leads to excitation of the gas molecules commonly referred to as 'ionization' which is due to collisions among the gas molecules. As a consequence, a combination of varied reactive species like electrons, ions (+ and -) , free radicals, molecules in the ground and/or excited states, photons are generated and this constitutes the 'plasma'.[5,6,7,8] Thus, such quasi-neutral gases have sufficient energy and are chemically very interactive, and confer varied chemical and biological effects. Distinctively, plasmas are differentiated into 'thermal plasma' and 'low-temperature plasma' based upon thermodynamics. Typically, 'thermal plasma' is generated by subjecting a gas to temperatures greater than 20,000 K, in such a setup, all the generated reactive species, electrons and ions are in a thermodynamic temperature equilibrium; thus, the plasma is at a very high temperature.[5] On the contrary, 'low temperature' plasma is commonly generated using electrical discharges at near room temperature. Here, the cooling of the varied gas species/molecules is more effective than energy transfer from electrons i.e. thermodynamic non-equilibrium thus, the gas temperature remains at low temperature. Thus, such non-equilibrium plasma generation is assigned as 'cold plasma' or non-thermal plasma (NTP).[7,8,9,10] In the current, review we are only concerned with 'cold plasma' applications on various foods.

In the available literature, cold plasmas have been generated using varied configuration systems. Widely reported methods to induce ionization are corona discharges, dielectric barrier discharges, microwave discharges, and plasma jets.[1,5,9] In all systems, the feed gas is energized into plasma. Different types of feed gases can be used in plasma generation such as air or nitrogen (N_2) or noble gases like- Helium (He), Argon (Ar), and Neon (Ne) or their mixture with oxygen (O_2) and moisture.[2,9,11] The antimicrobial nature of plasma is attributed to the generated reactive gas species of oxygen (ROS) and nitrogen (RNS) owing to collisions of molecules on energizing.[1,8,9] Commonly identified and reported ROS and RNS include O, O_3, OH_3, NO, NO_2 and these plays a significant role in microbial decontamination.[2,7,9,12] Overall, it been suggested that the preservation efficacy of plasma effects increases when a feed gas is supplemented with O_2.[7]

Mechanism of Microbial Inactivation by Cold Plasma

The mechanism behind microbial decontamination involves the interaction of generated reactive species viz. radicals and reactive molecules with their cell membranes and cellular functions. The major species of interest conferring decontaminating effect includes ROS [atomic oxygen (O), singlet oxygen ($^1O_2$), excited state of oxygen (O^*_2) and superoxide anion (O_2-)] and RNS [atomic nitrogen (N), nitrogen positive ion (N^+_2) and excited state of nitrogen (N^*_2), nitric oxide free radical (NO•), and nitric oxide (NO)]. And in cases where humidity is involved during plasma generation species like H_2O^+, OH^- anion, OH• radical, and hydrogen peroxide (H_2O_2) are generated.[13] NO, and NO_2 damages cells by causing lipid peroxidation, denaturation of proteins and enzymes, and interaction with genetic material.[7,10,12] Additionally, the generation of UV photons has also been linked to plasma-mediated microbial inactivation.[2] The photons impair DNA replication by forming thymine dimers, nucleotide-base modifications, and nucleotide oxidation.[5] Cell damage, cell bursting, pore formation, cell leakage, cytoplasm shrinkage, etc. have also been observed for cold plasma treated microbes under electron microscopy.[14,15,16,17] The foregoing literature indicates that cold plasma proves to be an effective non-thermal strategy to achieve microbial decontamination. However, much more areas need to befurther explored especially in terms of quality impact post plasma treatment on food products.[8,11]

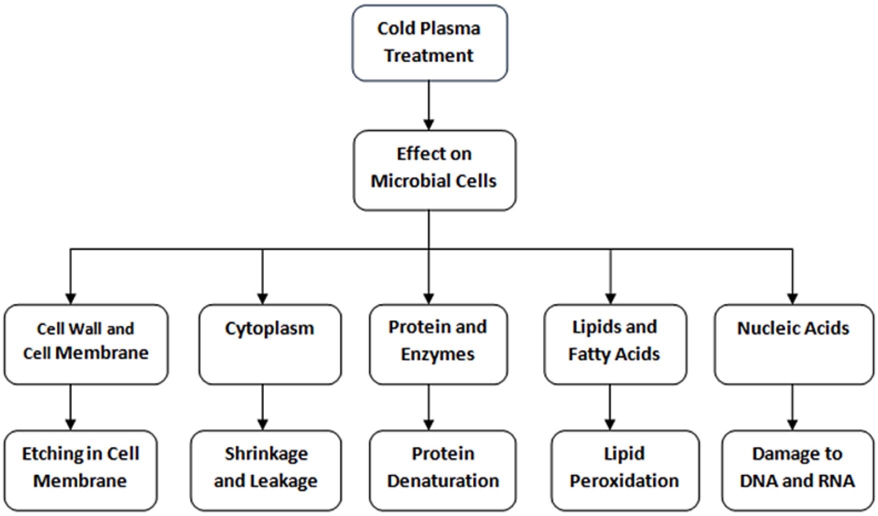

Fig. 1: Flowchart representing the impact on microbes mediated by cold plasma treatment.

Fig. 2: Applications of cold plasma technology in food sector.

Applications of Cold Plasma in Food Processing

Cold Plasma has found effective applications as a non-thermal technology for mild surface decontamination in foods as well as packaging materials. As it employs the use of gases, which could reach every nook and cranny, it is one of the most effective ways of disinfection as compared to cleaning with water or chemicals. When microbes are present on the food surface, cold plasma can be used for inactivating both vegetative cells and spores (Disinfection of foods). The packing material used for food products plays a crucial role in retaining food quality. Cold plasma can also be utilized for surface sterilization of packaging material eliminating microbes and their spores (Disinfection of packaging material). For heat-sensitive materials, it is the best way for controlling disinfection. Cold plasma is a gas so it can easily treat irregularly shaped packages and bottles which is otherwise a difficult task. This technology has found application in not only controlling the microbial contamination of food or food productsbut also able to improve or maintain the quality of raw/processed foods from various food groups.

Cold Plasma Treatment of Cereals

Cereals form a major source of the diet of the people of India. Plasma, a non-thermal technology has proven applications in the cereal industry (Table 1). Brown rice has higher nutritional values[26] but its poor cooking and eating properties limits its desirability. Few experiments with plasma technology suggest improving both cooking and eating properties of rice. A low-pressure cold plasma treatment of parboiled rice resulted in higher water uptake ratio and the cooking time was reduced to 8 min.[27] Textural properties like hardness and stickiness were also improved and a decreasing trend was observed on increasing power and treatment time. A similar low-pressure plasma treatment (1-3kV-10 min) on germinated brown rice led to an increase in the germination rate, seedling length, and water uptake.[28] The 3kV plasma treatment for 10 min gave the best results and α-amylase activity was also higher in the rice as compared to the control rice.

Table 1: Cold plasma treatment impact on cereal grains/products.

Substrate	Plasma	Observations	References
Grains and legumes	Low pressure cold plasma; Air/SF_6; 300W; 5-20 min	• Reduction in amounts of fungi (*Aspergillus* and *Penicillum* spp) attached to seeds to 1% while preserving the germination quality of seeds A • 3 $\log_{10}$ reduction of both the fungi within 15 min for SF_6 treatment	18
Malt extract agar and brown rice cereal bars	Argon plasma jet treatment; 20W/40W; 5-25 min	• Treatment of 40W for 25 min effective for inhibiting A. *flavus* • A 20 min treatment inhibited A. *flavus* growth on storage (25ºC, 100% RH) of brown rice cereal bars	19
Brown rice	Cold plasma; ambient air; 250W; 15kHz; 5-20 min	• Reduction in *B. subtilis*, *B. cereus*, and *E. coli* by 2.30 $\log_{10}$ CFU/g • Increased α-amylase activity, greater water uptake rate, and decreased hardness	20
Wheat flour	Atmospheric pressure cold plasma; air; 15 and 20V; 60/120s	• Lowering of total free fatty acids and phospholipids • Stronger dough for treated flour	21
Wheat germ	DBD atmospheric plasma; 24kV; 25min	• Reduction of lipase and lipoxy-genase activity of wheat germ	22

		to 25.03% and 49.98%, respectively • Increase in shelf-life and stability of wheat germ	
Wheat and barley	High voltage DBD atmospheric cold plasma; 80kV; 20min	• In barley 2.4 and 2.1 log_{10} CFU/g reductions, respectively for bacteria and fungi • In wheat, reduction of 1.5 and 2.5 log_{10} CFU/g for bacteria and fungi, respectively	23
Corn kernels	Cold plasma pretreatment; 500W; 50s	• Reduced drying time and increased drying efficiency of corns	24
Maize grains	Cold plasma treatment; 360 and 240W; 10, 20, and 30min	• Fungal growth inhibited at 360W and 33.33% inactivation • Germination capacity was 33.3% at 240W	25

DBD: Dielectric barrier discharge

Plasma-treatment of brown rice resulted in an increase in the antioxidant activity and the levels of gamma-aminobutyric acid by 32%. Cold atmospheric plasma treatments were employed to inhibit the *Aspergillus flavus* growth on brown rice cereal bars.[19] A plasma treatment (40W-20 min) when applied on rice-based cereal products resulted in decrease of surface mycelium by around 4 log_{10} CFU/g and delayed the mycelium growth for 20 days. Plasma treatment also has a positive impact on wheat seeds.[29] The plasma treatment using a surface discharge reactor on wheat seeds led to an increase in the roots and sprouts of the wheat seeds with little effect on germination rates.

Cold plasm generated by a Dielectric barrier discharge (DBD) method has shown changes in the structure, granule morphology, crystalline properties, and rheological properties of corn starch.[30] Treatment using DBD not only affected the surface morphology of the starch granules, creating pinholes. Also, the plasma treatment caused oxidation of partial hydroxyl groups to carbonyl groups, and molecular degradation occurred resulting in a decrease in the degree of crystallinity. Thus, opening up avenues for development of chemical-free starch modifications. Modified starch finds great applications in food industries as an emulsifier and for the formation of starch-based films. Hence, cold plasma can be an alternative to chemical modifications of starch.

Table 2: Impact of cold plasma treatments on dairy and dairy products.

Substrate	Plasma	Observations	References
Whole; semi-skimmed; skimmed milk	Low Temperature Plasma; corona discharge; 9kV; 0-20 min	• 54% reduction in *E. coli* ATCC 25922 cells after 3min regardless of fat content in milk along with no effects on pH and color of milk • Bacterial count decreased by 4.15log CFU/ml after a 20 min treatment	32
Cheddar cheese	Flexible thin layer DBD plasma; 100W peak power and 2W average	• Reduction in *E. coli* (3.2 logs), *L. monocytogenes* (2.1 logs) and *S. typhimurium* (5.8 logs)	33

	power; 10 min	per gram of cheese. • No difference in color scores and sensory appearance	
Milk	Encapsulated DBD plasma; 250W; 15kHz; ambient air; 5 and 10 min	• Reduction in *E. coli*, *L. monocytogenes* and *S. typhimurium* by around 2.4$\log_{10}$CFU/ml for each. • Slight increase in 2-thiobarbituric acid reactive compounds	34
Cheese slices	Atmospheric pressure DBD plasma; air discharge; 250W; 15kHz; 60s, 45s and 7min	• 2.67, 3.10 and 1.65 decimal reduction in populations of *E. coli*, *S. typhimurium* and *L. monocytogenes*, respectively • Post-treatment storage period more reduction in pathogen populations	35
Milk	DBD cold plasma; 70V and 80V; 120s	• Bacterial DNA destruction • Reduced activity of metabolic enzymes • Broken cell membrane of bacteria	36

DBD: Dielectric barrier discharge

Cold Plasma Treatment in Dairy Products

Milk and milk products are important dietary requirements worldwide. Being highly nutritive dairy and dairy products are very prone to microbial and chemical put refaction. Although thermal treatments like pasteurization or sterilization no doubt ensure microbial safety and extend shelf-life, negatively impact the nutritive and sensory attributes.[31] Thus, the benefits of non-thermal technologies are quite attractive for the dairy sector.

Cold plasma has demonstrated remarkable efficiency in the removal of undesirable microorganisms in the dairy sector while retention under many circumstances, the nutritional, functional, and sensory aspects of the products when compared to conventional approaches (Table 2).

The dielectric barrier discharge (DBD) method has been predominantly tested for milk and milk products. A DBD method (80 V-120s) caused 100% fatality to *Staphylococcus aureus* and *E.coli* and about 98% fatality to *L. monocytogenes* in milk.[36] Also, an increase in voltage and treatment time induced higher lipid peroxidation. However, the increased lipid peroxidation was comparable to that of UHT-treated milk. In another study, with DBD treatment of milk at 2 kV under reduced pressures (0.16 mbar) resulted in approximately 1 log reduction in background microflora without having any detrimental impact on the physicochemical parameters.[37] An interesting study, where in chocolate milk drinks were subjected to cold plasma technology (varying nitrogen plasma flow rate and treatment time) altered the physical and thermal properties.[38] Milder and severe treatment resulted in higher particle size, consistency, and altered melting profile indicative of protein denaturation. However, intermediate processing levels resulted in chocolate drinks having similar characteristics to that of pasteurized ones. Thus, it can suitably be recommended that CP technology can be further tuned for better results in maintaining attributes. Cheese is being a recognized source of food-borne illnesses. Experiments on sliced cheddar cheese, inoculated with *L. monocytogenes*, *E.coli* O157:H7, and *Salmonella thyphimurium* on thin-layer DBD N_2+O_2 plasma (100 W-10 min exposure respectively decreased the counts by, 3.2, 2.1, and 5.8 $\log_{10}$ CFU/g.[33] However, this treatment led to significant reductions in flavor and overall acceptance along with changes in physiochemical parameters. Queso fresco is a cheese that is prone to *Listeria* contamination. Researchers[39] subjected the Queso fresco cheese package to a DBD in package treatment with moisture free air at 60-100 kV for 5 min. A 5 min treatment resulted in respective reductions by 1.4 and 3.5 log_{10} CFU/g reductions for *L. innocua* and *E. coli* K-12. It was also noted that the treatment inflicted slight changes in the pH, color, and lipid oxidation of the cheese but non-significant impact on the texture. Interestingly, subjecting whey protein isolate to plasma treatment lead to mild oxidation and changed surface hydrophobicity of proteins, in turn improving the foaming and emulsifying property and also causing proteins to aggregate.[40] From a technological standpoint, this opens avenues for modulating protein functionality for further research and industrial applications. Overall, CP applications have suggested promising results on microbial inactivation however, fine-tuning of process parameters is critical to safeguard the quality attributes in dairy and dairy products.

Cold Plasma Treatment of Meat and Meat Products

The meat industry is a major player in food manufacturing and processing sector. Historically, as urge in meat consumption occurred world wide between 1960 and 2000, and an increase in the per capita meat consumption from 10 kg to 26 kg annually.[41] Meat being an excellent source of nutrients and is easily contaminated by microbes, such contaminations lead to spoilage and loss of meat and meat products. Overall, losses are also generated due to consumption, processing and packaging (around 21%), distribution, handling and storage.[42] Meat spoilage is dominated by three factors a) microbial proliferation, b) lipid oxidation, and c) enzyme action.[41] Meat spoilage leads to its discoloration, formation of undesirable odors, flavors, and textural losses (softening) which results in rejection by consumers. Pathogens that affect meat include *Salmonella* spp, *Escherichia coli*, *Listeria monocytogenes*, *Staphylococcus aureus*, and *Clostridium botulinum.*[43,44] The most common meat spoiling microorganism being *Pseudomonas spp.* it results indevelopment of put refactive odors and slime when their population levels exceed 10^7 CFU/cm^2 [43] The use of low-pressure plasma technology serves to be advantageous in the meat industry (Table 3) and can treat wide areas uniformly for decontamination.

Table 3: Effect of cold plasma treatment on meat and meat products.

Substrate	Plasma	Results Observed	References
Ready-to-Eat meat	Cold atmospheric pressure plasma; 15.5, 31 and 62W; 2-60s	• Reduction in *L. innocua* to 1.6 log_{10} CFU/g • Thiobarbituric acid reactive substances (TBARS) increased with treatment power.	45
Chicken skin and breast fillet	Cold atmospheric pressure plasma; Argon/Air; 2-3kV; 3-180s; 5, 8 and 12 mm (distance)	• Reduction in *Campylobacter jejuni* by 2 log_{10}CFU/cm^2 using Ar gas after 120s treatment time • Higher surface temperature can cause denaturation that could affect inactivation efficacy	46
Chicken fillets	In-package DBD atmospheric cold plasma; 80kV;70W; 3 min	• Decrease in microbial population with no effect on meat appearance on storage (4ºC-3 days) • Decrease in redness and yellowness of meat	47
Meat batter	Atmospheric pressure cold plasma; 1.5kW; 60 min	• Nitric content of Meat batter increased to 377.68 mg/kg • Treatment did not affect the total aerobic bacterial count • Lipid and protein oxidation increased with treatment time	48

DBD: Dielectric barrier discharge

A DBD type plasma exposure for 10 min on chicken breast decreased the total aerobic counts, *L. monocytogenes*, *E. coli*, and *S. typhimurium* by 3.36, 2.14, 2.73, and 2.71 log_{10}CFU/g.[49] Also in package DBD plasma treatment of inoculated pork butt inactivated *L. monocytogenes*, *E.coli* 0157:H7 and *Salmonella* by 2.04, 2.54, and 2.68 log_{10} CFU/g respectively and inoculated beef loin by 1.90, 2.57, and 2.58 log_{10} CFU/g, respectively for the same microbes.[50] Cold plasma treatment of modified atmosphere gas (high O_2 and CO_2) filled packages increased the shelf-life of chicken meatalong with a reduction in microbial loads compared to air-filled packages.[51] Modified atmosphere (65% O_2, 30% CO_2,5% N_2) gas packages treated with cold plasma resulted in restricting microbial load > 4log_{10} and extended shelf-life of chicken for upto 14 days.

Rosemary (*Rosmarinus officinalis*) extracts have high antioxidant.[52] Rosemary extract addition alongside plasma treatment has shown promising results in reducing lipid oxidation in meats. When chicken breast patties containing 1% rosemary extracts were plasma treated at 70kV for 180s and stored for 0 to 5 days, the addition of rosemary extract prevented lipid oxidation in treated meat and also inhibited the microbial growth.[53] It increased the pH of the treated samples, but altered color reported by a decreased *L** values, and increased *a** and *b** values. Research on natural extracts from plants as additives along with cold plasma treatment can be further pursued to control the microbial quality and lipid oxidation of plasma processed foods. Cold plasma treatment of meat and meat products has shown promising results in decreasing the psychrophilic or mesophilic microbial population without changing the appearance of meat and increasing the nitric content in meat batter (Table 3). Overall, there is promising application of plasma technology in meat processing.

Cold Plasma Treatment of Egg and Poultry Products

There has always been a great demand for egg and egg-based products worldwide. Today consumers have become more aware towards food safety issues and prefer eggs with clean shells and free from contamination. Eggs can be contaminated by many micro-organisms during production, processing, food preparations, and consumption.[54] *Salmonella* spp. contamination presents a major concern for the egg industry. Commercial egg cleaning four steps: wetting eggs to soften the debris on the shell; washing eggs with brushes; rinsing with clean hot water, and drying by air jet.[55] However, chemical washing utilizes chlorine (sodium hypochlorite), and it is capable of destroying a wide spectrum of pathogens but due to its carcinogenic effects its use has become limited.[56,57] Thus, cleaning or treating eggs without chemicals or with reduced water usage is a preceding need, and cold plasma technology presents itself as such a technology.

Table 4: Cold plasma impact on eggs and poultry products.

Substrate	Plasma	Observations	References
Egg shells	After glow corona discharge air plasma; 20kV; 58kHz; 12h	• 96-98% microbial reductions upon treatment • No changes in physicochemical and sensory characteristics	61
Egg surface	Direct or indirect cold atmospheric plasma; He/O2 mixtures (DT) and air (IDT); sinusoidal 25-30kV; 10-12kHz	• Reduction in *S. enterica* population to 100 cells/egg at 10 min DT and 25 min IDT treatment • Humidity important for inactivation owing to hydroxyl radicals formation	62
Chicken egg shells	High voltage atmospheric cold plasma; Dry air (DT) and modified atmospheric gas (IDT); 85kV; 15 min	• 5.53 log_{10} CFU/egg reduction of *S. enteritidis* with no effect on egg quality during DT • No significant difference of DT and IDT on egg quality	60

Poultry egg	Cold nitrogen plasma; 600W; 2 min	• Metabolic activity of *Salmonella typhimurium* decreased by 82.2% without effect on sensory quality of egg • Decrease in extracellular protein, polysaccharides and DNA	63

A high voltage pulsed jet plasma treatment(20kV-5min) exposure sufficiently inactivated all the S. enterica serovar *typhimurium* on eggshells.[58] Also He-gas plasma jet treatments on *L. monocytogenes* at 2kV input voltage for 2 min on steam cooked egg yolk and egg white resulted in a decrease of the microbial population by 5 logs in cooked egg white. Whereas with O_2+ N_2 mixtures reductions in microbial counts by 6.7 logs were reported.[59] Additionally, direct application pattern of plasma was found to be more effective than the indirect plasma application for decontamination of eggshells. An exposure time of 15 min reduced the *Salmonella* counts by about 6.4 and 4.3 log cycles respectively for direct and indirect treatments.[60] Overall, it can be noted that decontamination efficacy is dependent upon the carrier gas compositions employed, treatment duration, and exposure modes. Cold plasma treatment has been successful in controlling the *Salmonella* population without apparent changes in egg and poultry product's quality (Table 4).

Cold Plasma Treatment of Nuts and Seeds

Table 5: Effect of cold plasma treatment on nuts.

Substrate	Plasma	Observations	References
Fresh and dried walnuts	Cold plasma treatment; Argon gas; 15kV; 12kHz; 11 min	• Complete elimination of *A. flavus* • No change in the TPC and antioxidant activity of fresh and dried walnuts	71
Groundnuts	Cold plasma treatment; Atmospheric air; 40W and 60W; 12 and 15 min; 13.56MHz	• *A.parasiticus*: 97.9% reduction & *A. flavus* : 99.3% • Aflatoxin B1 reduction by 70-90%	72
Peanuts	Cold atmospheric plasma; Air; 80kV; 50 Hz; 0-60 min	• 43% reduction in antigenicity for defatted peanut flour and 9.3% for whole peanuts • Secondary structure changes were induced by the reactive species of plasma	73
Pistachio nuts	AP-CCP, DC-DP and ICP; Argon gas; 13.65 MHz and 50Ω (AP-CCP); 2 Torr, 250W and 20 min (ICP); 0.5-2 Torr, 50-300W and 5-20 min (DC-DP)	• 5 log_{10} reduction of fungi *A. flavus* using DC-DP (1 Torr, 300W, 20 min) • 4 log reduction of fungi *A. flavus* using AP-CCP • Maximum 2 log reduction of fungi *A. flavus* using ICP	74

Cashew nuts (*Anacardium occidentale*) are an important source of nutrition and are widely consumed. They are regarded as excellent sources of protein, fats, and vitamins.[64] Their antioxidant activity is attributed to phenolic composition mainly constituted by a mixture of anacardic acids (monoene, diene, and triene). The anacardic acids have bactericide, insecticide, fungicide, cytotoxic and anti-inflammation properties.[65] Cashew nuts also possess allergic reactions in some individuals. Allergy due to cashew nut is a commonly reported tree nut allergy specially in the US.[66]

Influence of atmospheric plasma on the cashew nut composition and allergeni city was investigated using glow discharge plasma at 80W and 50kHz power supply.[67] 30 min treatments resulted in an increase in anacardic acids content from 0.2 to 0.55µg/mg and a decrease in sucrose levels from 33 to 18mg/g. The plasma processing however did not affect the binding of human cashew allergic IgE. In another work, cold plasma application on almonds dipped levels of *E.coli* culture broth,and the most effective treatment was at 30kV, 2000Hz for a duration of 30s which resulted 5 log reduction in bacterial populations.[68] The bactericidal effects on *E.coli* inoculated on almonds increased linearly with the applied plasma treatment voltage and frequency.

Hazelnuts (*Corylus avellana*) are widely consumed nuts, and they can be consumed in-shell and shelled. Commonly such nuts are contaminated by aflatoxins which are also found on other nuts, cereals, spices, etc.[69] The genus *Aspergillus* contaminates hazelnuts and produce aflatoxins (AFs), specifically *A. parasiticus* produces four main aflatoxins viz. AFB1, AFB2, AFG1, and AFG2 whereas *A. flavus* produces AFB1 and AFB2. AFs are as carcinogenic agents to humans and animals. A detailed study on cold atmospheric pressure plasma treatment effect on mycotoxin detoxification was conducted on hazelnuts.[70] Firstly, different gases concentrations were tested (N_2,0.1% O_2 and 1% O_2, 21% O_2) and then power and exposure time were optimized. Power of 1000W for 12 min effectively reduced AFB1 and total aflatoxins concertation by approximately 65 % and 74 % respectively. It was also found that plasma treatments were more effective for degrading AFB1 and AFG1 compared to AFB2 and AFG2. Hence, cold plasma applications seem viable for effectively detoxifying nuts containing aflatoxins, and reduce contaminating microbial populations without affecting the sensory qualities (Table 5).

Cold Plasma Treatment of Fruits and Vegetables (F&Vs)

Recommendation by major governmental agencies has fueled the increased consumption of F&Vs among consumers. Additionally, the consumers are also aware of the primary health-benefiting components in F&Vs.[75,76] Considering,the fact that F&Vs are typically ingested raw, concerns of safety and quality is paramount. CP can be employed as an in-package treatment method for a variety of F&Vs, including surface disinfection and even for fresh-cut produce.[77,78,79]

A CP treatment at 60 kV for 5 min lowered innate aerobic bacterial populations and increased cutting-induced phenolic buildup in newly cut dragon fruit, according to one study.[80] In sliced carrots about 2 log reductions of total mesophiles, yeast and molds were observed on CP treatment (100 kV-5 min) while the process retained textural qualities and the carotenoid content.[79] In pilot-scale studies, interesting results have been observed for CP treatments. In a recent study, aerosolized H_2O_2 ionized using cold plasma under a laboratory setting resulted in ≥ 5 $\log_{10}$ reductions in *L. innocua* and *S. thyphimuriumin* grape tomatoes, apples, cantaloupe, and Romanian lettuce.[81]

The same group further ran a pilot-scale investigation following the same methodology and demonstrated reduction of *S. typhimurium* and *L. innocua* in apples, tomatoes,and cantaloupe below detection limits (<0.7 log CFU/pc).[82] Additionally, the treatment did not significantly affect quality attributes such as appearance, color, texture, pH, ascorbic acid content, soluble solids content and antioxidants in the fruits. Another pilot plant study employing the DBD method involving humid air was efficient inminimizing *E. coli* and *L. monocytogenes* populations in strawberries and spinach by 2-2.2 logs and 1.3-1.7 logs respectively.[78]

Corona discharge air plasma (CDAP) treatment employed for post-harvest storage of onions resulted in lower infections of *Fusarium* spp. and *Alternaria* sp. during cold storage.[83] CP has been widely studied for the treatment of other fruits and vegetables like cabbage, cherry tomatoes, cucumber, baby kale, radicchio leaves, peas to name a few.[5] Interestingly, cold plasm's ability to inactivate norovirus in foods such as blueberries, Tulane virus in Romanian lettuce has opened further possibilities[84,85,86] in attaining viral food safety.

CP treatments impact quality attributes differently in different F&Vs. Existing literature suggesting detrimental impacts of CP treatment on quality attributes both physical and chemical[87] somewhat raises concerns over its potential. However, fine-tuning of CP treatment approaches viz., employing milder treatments, intermittent treatments, and the use of plasma activate water for treating F&Vs have resulted in better preservation of quality attributes.

Several studies (Table 6) have been conducted for cold plasma treatment of fruits and vegetables, and reported that cold plasma treatment can enhance antioxidant activity, phenolic compounds extraction, total sugar and microbial reduction.

Table 6: Impact of cold plasma treatment on fruits and vegetables.

Substrate	Plasma	Observations	References
Strawberries	In-package atmospheric DBD cold plasma; 60kV; 50Hz; 5 min	• Total mesophiles and surface yeasts/ molds was reduced to 2.4 and 3.3 log cycles, respectively • Lowered respiration rate	88
Radish sprouts	Cold plasma treatment; N2 gas; 900W; 667 Pa; 20 min	• Reduction in number of *S. typhimurium* by 2.6$\log_{10}$ CFU/g • Quality attributes of radish sprouts were not affected but moisture content decreased with treatment time	89
White grape juice	High voltage atmospheric cold plasma; 80kV; 4 min	• *Saccharomyces cerevisiae* populations reduced by approx. 7 $\log_{10}$ CFU/ml • Increase in total flavonols post treatment	90
Pitaya fruit	DBD cold plasma; 60kV; 5 min	• Inhibition of the total aerobic bacterial counts • Enhanced antioxidant activity and induced phenolic accumulation in the fresh cut fruit	80
Blueberry	DBD cold plasma 36V; 1.8 A; 0 – 10 min	• Decrease in number of bacteria by 93.0% and fungi by 25.8% after a 10 min treatment. • Decay rates of the berries decreased along with treatment time	91
Tender coconut water	High voltage atmospheric cold plasma; 90kV; 120s	• A 5 $\log_{10}$ CFU/ml reduction of *S. enterica* was achieved with the addition of 400 ppm citric acid • Minimal changes in the physicochemical properties of the substrate	14
Carrot juice	Ultra-sonication and high voltage cold plasma; 70kV; 4 min	• Increase in total carotenoids, lycopene and lutein • Significant decrease in total plate count, yeast and molds	92
Tomato pomace	DBD cold plasma air, Ar, He and N2; 60kV; 15 min	• Enhanced phenolic compounds extraction up to 10% • Increase in antioxidant activity of tomato pomace	93
Fresh cut carrots	DBD atmospheric cold plasma; 100kV; 60 Hz; 5 min	• About 2.1 $\log_{10}$ CFU/g reduction noted in population of total aerobic mesophiles, yeast and molds • Minimal changes in color, texture, pH and total carotenoids	79
Strawberry fruit	Atmospheric cold plasma; 60kV; 15 min	• 2$\log_{10}$ reduction in microbial load • The total phenolic content and antioxidant activity increased	94

DBD: Dielectric barrier discharge

Cold Plasma Treatment of Spices and Herbs

Herbs, spices and their essential oils are quite widely used in varied sectors ranging from food to cosmetics. However, herbs and spices are predominantly used in the dried powdered form. Conventionally processed under open environments e.g. sun/shade drying, resulting in contamination with pathogenic bacteria, bacterial spores and toxigenic fungi raising health concerns.[95,96] However, counteracting those using thermal treatments is not practical, as the key active volatile and aromatic constituents, and color responsible for quality and price are lost. Furthermore, use of chemical fumigants like ethylene oxide is under scanner or has been banned by some countries. Prevailing research is indicative of cold plasma applications as a non-thermal decontaminating technique for herbs and spices without potential toxic residues.

Table 7: Effects of cold plasma treatment on spices and herbs.

Substrate	Plasma	Observations	References
Onion flakes	DBD cold plasma; He; 15 kV; 20 min	• Inactivation of *S.enteritidis*, *E.coli* O157:H7 and *L.monocytogenes* by 3.1, 1.4 and 1.1 log_{10} CFU/cm^2 • Non-significant effect on the surface morphology, ascorbic acid and quercetin contents.	105
Saffron	Cold low-pressure radiofrequency oxygen plasma treatment; 60 W; 15 min	• Complete eradication of *Aspergillus* fungi • No significant reduction in crocin esters, picrocrocin and safranal metabolites	102
Chilli pepper	Cold plasma pretreatment followed by hot air drying; 750 W; 30s	• Enhanced drying kinetics due to formation of micro-holes on the surface and increased antioxidant properties • Retention of red pigments was improved	106
Thyme and paprika	DBD cold plasma 12kV; 6kHz; 5 min	• Total bacterial counts of thyme reduced to 1.18 log cycle • No considerable effect was observed in paprika	107
Red pepper flakes	Microwave-combined cold plasma treatment (LMCPT, 0.17 W m−2 and HMCPT, 0.25 W m−2); 900W; 20 min	• *B. cereus* and *A. flavus* spores reduced by 0.7and 1.4 log_{10} spores/cm^2 after LMCT; and 1.5 and 1.5log_{10} spores/cm^2 after HMCPT, respectively • No effect on color and antioxidant activity after LMCPT and HMCPT	108
Black peppercorns	Simultaneous cold plasma and UV treatment; 10.3kV; 22.1min	• 1.7 log_{10} spores/g reduction of *B. tequilensis* spores; 3.4 log_{10} CFU/g in indigenous bacteria • Black color of peppercorns was unaffected	109
Cumin seeds	Cold plasma treatment; 2kV; 3 min	• 43.24% enhancement of seed germination • Significant increase in the total chlorophyll content, root length and shoot length.	110
Dried peppermint	Low pressure cold plasma; 50W and 60 W; 20min	• Significant reduction in *E.coli* O157:H7 • Increased antioxidant activity and total polyphenols	101

Black pepper grains	Cold plasma; atmospheric air; 15kV and 30kV; 3-20min	• 2.92 log_{10} reduction for all microbes after 24 h post treatment • Total phenolic content change remained insignificant	111

DBD: Dielectric barrier discharge, LMCT: Low microwave cold plasma treatment, HMCT: High microwave cold plasma treatment, UV: Ultra-Violet

A microwave driven plasma setup forming a remote plasma by Hertwig and others[97] applied for decontamination of black pepper seeds, crushed oregano and paprika powder. Result of the treatment suggested effective inactivation of native microflora in each of the samples. Greater reduction was observed in pepper and paprika powder (~3 log CFU/g in 60 min) compared to oregano (1.6 log CFU/g). However, a considerable loss in paprika color was observed within 5 min of treatment while, lesser impact on oregano and pepper seeds were observed. CP treatment when integrated with microwaves or mild heat has been effective in inactivating *Bacillus cereus* and spores in red chilli flakes and powder reaching destruction levels till 2.6 logs for spores and around 4.4. logs for vegetative cells. Importantly, a combined treatment better preserved the color of the samples[98,99] compared to plasma treatment alone. A similar combined treatment involving pulsed light with CP, non-thermally inactivated spores of *A. flavus* (~1.3 log spores/g), *B. pumilus* (~2.3 log spores/g), and *E. coli* O157:H7 (>3.8 log CFU/g) in red pepper flakes while retaining the color and moisture content.[100] A radiofrequency low pressure plasma process (50 W, 20 min, 40 mTorr) with oxygen as working gas proved to be efficient in eradicating *E.coli* O157:H7 in dried pepper mint, maintained its quality, improved its antioxidant activities and total phenolics and darkening of the sample post treatment was observed.[101] Low pressure radio frequency oxygen plasma (60W, 15 min, 8.5 mTorr) also proved to be efficient in eliminating toxigenic fungi viz. *Aspergillus* spp., *Rhizopus* spp., and Penicillum spp. from saffron strands. On comparing plasma-treated saffron to untreated samples, the crocin ester, picrocrocin, and safranal component of treated saffron exhibited no significant decreases. Additionally, the treated sample showed visible etching under SEM which possibly led to accelerated color release.[102] Plasma generated using ambient air using a coplanar surface barrier discharge system led to ~5 log CFU/g reduction in vegetative cells of *B. subtilis* and and ~ 2 log CFU/g for spores on black pepper corns. The treatment also eliminated *E.coli* and *S. enteritidis* below detection levels (1 log CFU/g) and no significant changes in chemical bonds and morphology of the pepper corns were reported.[103] Argon based microwave plasma resulted in complete eradication of A. *niger* molds on black pepper corns, juniper berries, and allspice within 45 s but the treatment was inefficient for inactivating *B. subtilis* spores. Further, experiments suggested antioxidant activities of the three samples increased with plasma treatment but again color loss was notable.[104]

Thereby, available research shows promising aspects of CP in microbial safety of herbs and spices (Table 7). However, color loss is a distinct parameter under a negative impact which needs to be looked into further.

Cold Plasma Treatment of Fish and Fishery Products

Sea foods are a rich source of proteins and lipids (e.g.omega-3-fatty acids).[112] But due to the presence of endogenous enzymes and microbial contamination, sea foods have limited shelf life. As per the United Nations Food and Agricultural Organization (FAO), fish products are demarcated as nutritious food source.[113] Prawns and Shrimps contribute about 16% of export value and are popular worldwide.[114] As the demand for fresh sea foods is increasing, it is quite necessary to develop novel processing and preservation methodology with higher decontamination efficacy.

High voltage cold atmospheric pressure plasma (HVCAP) treatments of Asian Sea Bass slices with argon and oxygen gas mixtures for 5-10 min resulted in a decline in the total viable cell counts by 1.0 log_{10} CFU/g.[115] Also a 5 min treatment extended the shelf-life of the sea Bass slices with refrigeration. However, longer duration of treatments elevated levels of lipid oxidation and caused protein denaturation. In fresh shrimp preservation, plasma activated water (PAW) greatly impacted the inhibition of microbes on a storage time of 4-8 days.[116] PAW treated shrimps did not change shrimp proteins but the pH reduced below 7.7 during storage. Also, there was a delay in change in color and hardness upon treatment, and production of volatile basic nitrogen diminished to below 20mg/100g during PAW ice storage. Microbial and quality parameters were also tested on Mackerel fillets with DBD treatment at 70kV and 80kV for time 1-5 min.[117] The treatment resulted insufficient reduction in the number of spoilage causing bacteria (aerobic, psychotropic, *Pseudomonas* and lactic acid bacteria). On quality parameters no changes in the color and pH were observed, however, lipid oxidation got elevated.

Limitations Associated with Cold Plasma Technology

Plasma technology offers some limitations as its use is still limited over laboratory scale. Due to this it has not been commercialized in the food sector yet. The use of plasma technology to treat nuts has been reported to cause an increase in the peroxide values. With increase in power and treatment time a 20% increase in the peroxide values was observed for plasma treated walnuts, this may be due to fact that the free radicals present in cold plasma induced auto-oxidation of fats and lipids present in the foods.[118] A decrease in the color parameters like L^*,a^* and b^* of plasma treated strawberries was reported.[88] Another disadvantage is that cold plasma technology cannot be used for complete inactivation of endogenous enzymes like polyphenol oxidases and peroxidases that causes enzymatic browning and deterioration of outer surfaces as it is a surface phenomenon. An optimum flow rate and process time of treatment required, otherwise there may be decrease of the bioactive compounds, change is fatty acid composition (more saturated fats, and low MUFA and PUFA), and health indices in case of dairy products.[119] More studies are required on plasma gas compositions, treatment times and mode of treatment (indirect or direct plasma treatment) for efficient use of the cold plasma technology for decontamination and quality maintenance of food products.

Conclusion

Cold plasma technology is one of the most recent and widely explored non-thermal techniques. The ability to generate various reactive gases at room temperature assists in achieving microbial decontamination, inactivation of endogenous enzymes, and preservation with minimal impact on the physical, physicochemical, and functional properties of the treated food. Although remarkable results have been put forwarded for its use in varied food industry, viz, cereals, fruits and vegetables, dairy, meat processing among others, still it needs to overcome certain challenges. Much research is required in the mechanism of action of the reactive ion species with food components. The effect of cold plasma on allergens and anti-nutritional factors is still lesser known and is an area of great interest for further exploration. More scientific work is encouraged for clear and depth knowledge of the cold plasma technology and its future aspects.

Acknowledgement

The authors would like to thank the Departments of Food technology, Jamia Hamdard University and Rajiv Gandhi University for contributing to the work.

Funding

No funds were availed from any funding agencies or sources for preparing this review article.

Conflict Of Interest

The authors declare that there is no conflict of interest

References

1. Thirumdas R., Sarangapani C., Annapure U.S. Cold plasma: a novel non-thermal technology for food processing. *Food Biophys*. 2015;10(1):1-11.
2. 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.

3. Pan Y., Sun D.W., Han Z. Applications of electromagnetic fields for nonthermal inactivation of microorganisms in foods: an overview. *Trends Food Sci. Technol.* 2017;64:13-22.
4. Ramos B., Miller F.A., Brandão T.R., Teixeira P., Silva C.L. Fresh fruits and vegetablesan overview on applied methodologies to improve its quality and safety. *Innov Food Sci Emerg Technol.* 2013;20:1-15.
5. Misra N.N.,Schlüter O., Cullen P.J. *Cold plasma in food and agriculture: fundamentals and applications*. Academic Press;2016.
6. Şen Y., Bağcı U., Güleç H.A., Mutlu M. Modification of food-contacting surfaces by plasma polymerization technique: reducing the biofouling of microorganisms on stainless steel surface. *Food Bioproc* Tech. 2012; 5(1): 166-175.
7. Stoica M., Alexe P., Mihalcea L. Atmospheric cold plasma as new strategy for foods processing-an overview. *Innov. Rom. Food Biotechnol.* 2014;15.
8. Bourke P., Ziuzina, D., Han L., Cullen P.J., Gilmore B.F. Microbiological interactions with cold plasma. *J. Appl. Microbiol.* 2017; 123(2):308-324.
9. Scholtz V., Pazlarova J., Souskova H., Khun J., Julak J. Nonthermal plasmaA tool for decontamination and disinfection. *Biotechnol.* Adv.2015; 33(6):1108-1119.
10. Afshari R., Hosseini H. Non-thermal plasma as a new food preservation method, its present and future prospect. *J Paramed Sci*. 2014; 5:2008-78.
11. Misra N.N., Jo C. Applications of cold plasma technology for microbiological safety in meat industry. *Trends Food Sci. Technol*. 2017; 64:74-86.
12. Mai-Prochnow A., Murphy A.B., McLean K.M., Kong M.G., Ostrikov K.K. Atmospheric pressure plasmas: infection control and bacterial responses. *Int. J. Antimicrob. Agents*. 2014; 43(6):508-517.
13. Deng X., Shi J., Kong M.G. Physical mechanisms of inactivation of *Bacillus subtilis* spores using cold atmospheric plasmas. *IEEE Plasma Sci*. 2006;34(4):1310-1316.
14. Mahnot N.K., Mahanta C.L., Keener K.M., Misra N.N. Strategy to achieve a 5-log *Salmonella* inactivation in tender coconut water using high voltage atmospheric cold plasma (HVACP). *Food Chem.* 2019; 284: 303-311.
15. Mahnot N.K., Mahanta C.L., Farkas B.E., Keener K.M., Misra N.N. Atmospheric cold plasma inactivation of *Escherichia coli* and *Listeria monocytogenes* in tender coconut water: Inoculation and accelerated shelf-life studies. *Food Control.* 2019;106:106678.
16. Han L., Patil S., Boehm D., Milosavljević V., Cullen P.J., Bourke P. Mechanisms of inactivation by high-voltage atmospheric cold plasma differ for *Escherichia coli* and *Staphylococcus aureus*. Appl. *Environ. Microbiol.* 2016; 82(2):450-458.
17. Lunov O., Churpita O., Zablotskii V., Deyneka I.G., Meshkovskii I.K., Jäger A., Dejneka A. Non-thermal plasma mills bacteria: Scanning electron microscopy observations. *Appl. Phys. Lett.* 2015; 106(5):053703.
18. Selcuk M., Oksuz L., Basaran P. *Decontamination* of *grains* and legumes infected with *Aspergillus* spp. and *Penicillum* spp. by cold plasma treatment. *Bioresour.* Technol.2008; 99(11):5104-5109.
19. Suhem K., Matan N., Nisoa M., Matan N. Inhibition of *Aspergillus flavus* on agar media and brown rice cereal bars using cold atmospheric plasma treatment. Int. *J. Food Microbiol.* 2013; 161(2):107-111.
20. Lee K.H., Kim H.J., Woo K.S., Jo C., Kim J.K., Kim S.H., *et al.,* Kim W.H. Evaluation of cold plasma treatments for improved microbial and physicochemical qualities of brown rice. *LWT.* 2016; 73:442-447.
21. Bahrami N., Bayliss D., Chope G., Penson S., Perehinec T., Fisk I.D. Cold plasma: A new technology to modify wheat flour functionality. *Food Chem.* 2016; 202:247-25.
22. Tolouie H., Mohammadifar M.A., Ghomi H., Yaghoubi A.S., Hashemi M. The impact of atmospheric cold plasma treatment on inactivation of lipase and lipoxygenase of wheat germs. *Innov. Food Sci. Emerg*. Technol. 2018; 47:346-352.
23. Los A., Ziuzina D., Akkermans S., Boehm D., Cullen P.J., Van Impe J., Bourke P. Improving microbiological safety and quality characteristics of wheat and barley by high voltage atmospheric cold plasma

closed processing. *Food Res. Int.* 2018; 106:509-521.
24. Li S., Chen S., Han F., Xv Y., Sun H., Ma Z., *et al.,* Wu W. Development and optimization of cold plasma pretreatment for drying on corn kernels. *J. Food Sci*. 2019; 84(8):2181-2189.
25. Silva B., Silva J., Moecke E., Scussel V. Effect of Cold Plasma treatment on fungi inactivation and germination of maize grains (*Zea mays L*.). IOSR-JAVS.2020; 13(7):28-32.
26. Mir S.A., Bosco S.J.D., Shah M.A., Mir M.M., Sunooj K.V. Variety difference in quality characteristics, antioxidant properties and mineral composition of brown rice. *J. Food Meas. Charact.* 2016; 10(1):177-184.
27. Sarangapani C., Devi Y., Thirundas R., Annapure U.S., Deshmukh R.R. Effect of low-pressure plasma on physico-chemical properties of parboiled rice. *LWT.* 2015; 63(1):452-460.
28. Chen H.H., Chen Y.K., Chang H.C. Evaluation of physicochemical properties of plasma treated brown rice. *Food Chem.* 2012; 135(1):74-79.
29. Dobrin D., Magureanu M., Mandache N.B., Ionita M.D. The effect of non-thermal plasma treatment on wheat germination and early growth. *Innov Food Sci Emerg Technol*. 2015; 29:255-260.
30. Bie P., Pu H., Zhang B., Su J., Chen L., Li X. Structural characteristics and rheological properties of plasma-treated starch. *Innov Food Sci Emerg Technol*. 2016; 34:196-204.
31. Nikmaram N., Keener K.M. The effects of cold plasma technology on physical, nutritional, and sensory properties of milk and milk products. *LWT.* 2022; 154:112729.
32. Gurol C., Ekinci F.Y., Aslan N., Korachi M. Low temperature plasma for decontamination of *E. coli* in milk. *Int. J. Food Microbiol.*2012; 157(1):1-5.
33. Yong H.I., Kim H.J., Park S., Kim K., Choe W., Yoo S.J., Jo C. Pathogen inactivation and quality changes in sliced cheddar cheese treated using flexible thin-layer dielectric barrier discharge plasma. *Food Res. Int.* 2015; 69:57-63.
34. Kim H.J., Yong H.I., Park S., Kim K., Choe W., Jo C. Microbial safety and quality attributes of milk following treatment with atmospheric pressure encapsulated dielectric barrier discharge plasma. *Food Control.* 2015; 47:451-456.
35. Yong H.I., Kim H.J., Park S., Alahakoon A.U., Kim K., Choe W., Jo C. Evaluation of pathogen inactivation on sliced cheese induced by encapsulated atmospheric pressure dielectric barrier discharge plasma. *Food Microbiol.* 2015; 46:46-50.
36. Wu X., Luo Y., Zhao F., Mu G. Influence of dielectric barrier discharge cold plasma on physicochemical property of milk for sterilization. *Plasma Process Polym*.2020; e1900219.
37. Manoharan D., Stephen J., Radhakrishnan M. Study on low-pressure plasma system for continuous decontamination of milk and its quality evaluation. *J. Food Process.* Preserv. 2021; 45(2):e15138.
38. Coutinho N.M., Silveira M.R., Pimentel T.C., Freitas M.Q., Moraes J., Fernandes L.M., *et al.,* Cruz A.G. Chocolate milk drink processed by cold plasma technology: Physical characteristics, thermal behavior and microstructure. *LWT.* 2019; 102:324-329.
39. Wan Z., Misra N.N., Li G., Keener K.M. High voltage atmospheric cold plasma treatment of *Listeria innocua* and *Escherichia coli* K-12 on queso fresco (fresh cheese). *LWT.* 2021; 146:111406.
40. Segat A., Misra N.N., Cullen P.J., Innocente N. Atmospheric pressure cold plasma (ACP) treatment of whey protein isolate model solution. Innov. *Food Sci. Emerg. Technol.* 2015; 29:247-254.
41. Dave D., Ghaly A.E. Meat spoilage mechanisms and preservation techniques: a critical review. *Am J Agric Biol Sci*. 2011; 6(4):486-510.
42. Kanerva M. Meat consumption in Europe: Issues, trends and debates. Sustainability Research Center (ARTEC) - University of Bremen, 2013; 1-60.
43. Sofos J.N. Microbial growth and its control in meat, poultry and fish. *In Quality attributes and their measurement in meat, poultry and fish products*. Springer, Boston, MA; 1994:359-403.
44. Borch E., Nesbakken T., Christensen H. Hazard identification in swine slaughter with respect to foodborne bacteria. *Int. J. Food Microbiol.*1996; 30(1-2):9-25.

45. Rød S.K., Hansen F., Leipold F., Knøchel S. Cold atmospheric pressure plasma treatment of ready-to-eat meat: Inactivation of *Listeria innocua* and changes in product quality. *Food Microbiol.* 2012; 30(1):233-238.
46. Rossow M., Ludewig M., Braun P.G. Effect of cold atmospheric pressure plasma treatment on inactivation of *Campylobacter jejuni* on chicken skin and breast fillet. *LWT.* 2018; 91:265-270.
47. Wang J.M., Zhuang H., Lawrence K., Zhang J.H. Disinfection of chicken fillets in packages with atmospheric cold plasma: effects of treatment voltage and time. *J. Appl. Microbiol.* 2018; 124(5):1212-1219.
48. Jo K., Lee J., Lim Y., Hwang J., Jung S. Curing of meat batter by indirect treatment of atmospheric pressure cold plasma. *Korean J. Agric. Sci*. 2018; 45(1):94-104.
49. Lee H., Yong H.I., Kim H.J., Choe W., Yoo S.J., Jang E.J., Jo C. Evaluation of the microbiological safety, quality changes, and genotoxicity of chicken breast treated with flexible thin-layer dielectric barrier discharge plasma. *Food Sci. Biotechnol.* 2016; 25(4):1189-1195.
50. Jayasena D.D., Kim H.J., Yong H.I., Park S., Kim K., Choe W., Jo C. Flexible thin-layer dielectric barrier discharge plasma treatment of pork butt and beef loin: Effects on pathogen inactivation and meat-quality attributes. *Food Microbiol.*2015; 46:51-57.
51. Wang J., Zhuang H., Hinton Jr A., Zhang J. Influence of in-package cold plasma treatment on microbiological shelf life and appearance of fresh chicken breast fillets. *Food Microbiol.* 2016; 60:142-146.
52. Erkan N.,Ayranci G., Ayranci E. Antioxidant activities of rosemary (*Rosmarinus Officinalis* L.) extract, blackseed (*Nigella sativa* L.) essential oil, carnosic acid, rosmarinic acid and sesamol. *Food Chem.*2008;110(1):76-82.
53. Gao Y., Zhuang H., Yeh H.Y., Bowker B., Zhang J. Effect of rosemary extract on microbial growth, pH, color, and lipid oxidation in cold plasma-processed ground chicken patties. *Innov Food Sci Emerg Technol.* 2019; 57:102168.
54. Parisi M.A., Northcutt J.K., Smith D.P., Steinberg E.L., Dawson P.L. Microbiological contamination of shell eggs produced in conventional and free-range housing systems. *Food Control.* 2015; 47:161-165.
55. Hutchison M.L., Gittins J., Walker A., Moore A., Burton C., Sparks, N. Washing table eggs: a review of the scientific and engineering issues. *Worlds Poult Sci J*. 2003; 59(2):233-248.
56. Al-Ajeeli M.N., Taylor T.M., Alvarado C.Z., Coufal C.D. Comparison of eggshell surface sanitization technologies and impacts on consumer acceptability. *Poult. Sci.* 2016; 95(5):1191-1197.
57. Ölmez H., Kretzschmar U. Potential alternative disinfection methods for organic fresh-cut industry for minimizing water consumption and environmental impact. *LWT.* 2009; 42(3):686-693.
58. Apostol L., Georgescu N., Vătuiu I., Gaceu L. Egg surface decontamination by using high voltage pulsed, cold atmospheric plasma jets. *J. Eco Agri Tourism*. 2015; 11(2):45-47.
59. Lee H.J., Song H.P., Jung H.S., Choe W.H., Ham J.S., Lee J.H., Jo C.R. Effect of atmospheric pressure plasma jet on inactivation of *Listeria monocytogenes*, quality, and genotoxicity of cooked egg white and yolk. *Food Sci. Anim. Resour.* 2012; 32(5):561-570.
60. Wan Z., Chen Y., Pankaj S.K., Keener K.M. High voltage atmospheric cold plasma treatment of refrigerated chicken eggs for control of *Salmonella enteritidis* contamination on egg shell. *LWT.* 2017; 76:124-130.
61. Pradeep P., Soee C., Chulkyoon M. Afterglow corona discharge air plasma (ACDAP) for microbial decontamination of shell eggs: Effect on physicochemical properties. Res. *J. Biotechnol.* 2016;11:8.
62. Georgescu N., Apostol L., Gherendi F. Inactivation of *Salmonella enterica* serovar *typhimurium* on egg surface, by direct and indirect treatments with cold atmospheric plasma. *Food Control.* 2017; 76:52-61.
63. Lin L., Liao X., Li C., Abdel-Samie M.A., Cui H. Inhibitory effect of cold nitrogen plasma on *Salmonella typhimurium* biofilm and its application on poultry egg preservation. *LWT.* 2020;109340.
64. Moreira L.S., Chagas B.C., Pacheco C.S.V., Santos H.M., de Menezes L.H.S., Nascimento M.M., *et al.,* da Silva E.G.P. Development of

procedure for sample preparation of cashew nuts using mixture design and evaluation of nutrient profiles by Kohonen neural network. *Food Chem.* 2019; 273:136-143.

65. Hemshekhar M., Sebastin Santhosh M., Kemparaju K., Girish K.S. Emerging roles of anacardic acid and its derivatives: a pharmacological overview. *Basic Clin Pharmacol Toxicol*. 2012; 110(2):122-132.
66. Robotham J.M., Wang F., Seamon V., Teuber S.S., Sathe S.K., Sampson H.A., *et al.,* Roux K.H. Ana o 3, an important cashew nut (*Anacardium occidentale* L.) allergen of the 2S albumin family. *J. Allergy Clin. Immunol*. 2005; 115(6):1284-1290.
67. Alves Filho E.G., Silva L.M.A., Oiram Filho F., Rodrigues S., Fernandes F.A., Gallão M.I., *et al.,* de Brito E.S. Cold plasma processing effect on cashew nuts composition and allergenicity. *Food Res. Int.*2019; 125:108621.
68. Deng S., Ruan R., Mok C.K., Huang G., Lin X., Chen P. Inactivation of *Escherichia coli* on almonds using nonthermal plasma. *J. Food Sci*. 2007; 72(2):M62-M66.
69. Prelle A., Spadaro D., Garibaldi A., Gullino M.L. Co-occurrence of aflatoxins and ochratoxin A in spices commercialized in Italy. *Food Control.* 2014; 39:192-197.
70. Siciliano I., Spadaro D., Prelle A., Vallauri D., Cavallero M.C., Garibaldi A., Gullino M.L. Use of cold atmospheric plasma to detoxify hazelnuts from aflatoxins. *Toxins*. 2016; 8(5):125.
71. Amini M., Ghoranneviss M. Effects of cold plasma treatment on antioxidants activity, phenolic contents and shelf life of fresh and dried walnut (*Juglans regia* L.) cultivars during storage. *LWT.* 2016; 73:178-184.
72. Devi Y., Thirumdas R., Sarangapani C., Deshmukh R.R., Annapure U.S. Influence of cold plasma on fungal growth and aflatoxins production on groundnuts. *Food Control.* 2017; 77:187-191.
73. Venkataratnam H., Sarangapani C., Cahill O., Ryan C.B. Effect of cold plasma treatment on the antigenicity of peanut allergen Ara h 1. *Innov. Food Sci. Emerg. Technol.* 2019; 52:368-375.
74. Ghorashi A.H., Tasouji M.A.R., Kargarian A. Optimum cold plasma generating device for treatment of *Aspergillus flavus* from nuts surface. *J Food Sci Technol.* 2020; 57:3988–3994.
75. Saikia S., Mahnot N.K., Mahanta C.L. Effect of spray drying of four fruit juices on physicochemical, phytochemical and antioxidant properties. *J. Food Process. Preserv.* 2015; 39(6):1656-1664.
76. Saikia S., Mahnot N.K., Mahanta C.L. Phytochemical content and antioxidant activities of thirteen fruits of Assam, India. *Food Biosci*. 2016; 13:15-20.
77. Sharma R.R., Reddy S.V.R., Sethi S. Cold plasma technology for surface disinfection of fruits and vegetables. In *Post harvest disinfection of fruits and vegetables.* Academic Press; 2018:197-209.
78. Ziuzina D., Misra N.N., Han L., Cullen P.J., Moiseev T., Mosnier J.P., *et al.,*Bourke P. Investigation of a large gap cold plasma reactor for continuous in-package decontamination of fresh strawberries and spinach. *Innov. Food Sci. Emerg*. Technol.2020; 59:102229.
79. Mahnot N.K., Siyu L.P., Wan Z., Keener K.M., Misra N.N. In-package cold plasma decontamination of fresh-cut carrots: microbial and quality aspects. *J. Phys. D: Appl. Phys*. 2020; 53(15):154002.
80. Li X., Li M., JiN., Jin P., Zhang J., Zheng, Y., *et al.,* Li F. Cold plasma treatment induces phenolic accumulation and enhances antioxidant activity in fresh-cut pitaya (*Hylocereus undatus*) fruit. *LWT.* 2019; 115:108447.
81. Song Y., Fan X. Cold plasma enhances the efficacy of aerosolized hydrogen peroxide in reducing populations of *Salmonella Typhimurium* and *Listeria innocua* on grape tomatoes, apples, cantaloupe and romaine lettuce. *Food Microbiol.*2020; 87:103391.
82. Song Y., Annous B.A., Fan, X. Cold plasma-activated hydrogen peroxide aerosol on populations of *Salmonella Typhimurium* and *Listeria innocua* and quality changes of apple, tomato and cantaloupe during storage-A pilot scale study. *Food Control.* 2020; 117:107358.
83. Chang E.H., Bae Y.S., Shin I.S., Choi H.J., Lee J.H., Choi J.W. Microbial decontamination of onion by corona discharge air plasma during cold storage. *J. Food Qual*. 2018.
84. Min S.C., Roh S.H., Niemira B.A., Sites J.E., Boyd G., Lacombe A. Dielectric barrier

discharge atmospheric cold plasma inhibits *Escherichia coli* O157: H7, *Salmonella* spp., *Listeria monocytogenes*, and Tulane virus in Romaine lettuce. *Int. J. Food Microbiol.* 2016; 237:114-120.

85. Lacombe A., Niemira B.A., Gurtler J.B., Sites J., Boyd G., Kingsley D.H., *et al.,* Chen H. Nonthermal inactivation of norovirus surrogates on blueberries using atmospheric cold plasma. *Food Microbiol.* 2017; 63:1-5.
86. Filipić A., Gutierrez-Aguirre I., Primc G., Mozetič M., Dobnik D. Cold plasma, a new hope in the field of virus inactivation. *Trends Biotechnol*. 2020; 38(11):1278-1291.
87. Chen Y.Q., Cheng J.H., Sun D.W. Chemical, physical and physiological quality attributes of fruit and vegetables induced by cold plasma treatment: Mechanisms and application advances. *Crit Rev Food Sci Nutr.* 2020; 60(16):2676-2690.
88. Misra N.N., Patil S., Moiseev T., Bourke P., Mosnier J.P., Keener K.M., Cullen, P.J. In-package atmospheric pressure cold plasma treatment of strawberries. *J. Food Eng*. 2014; 125:131-138.
89. Oh Y.J., Song A.Y., Min S.C. Inhibition of *Salmonella typhimurium* on radish sprouts using nitrogen-cold plasma. *Int. J. Food Microbiol.*2017; 249:66-71.
90. Pankaj S.K., Wan Z., Colonna W., Keener K.M. Effect of high voltage atmospheric cold plasma on white grape juice quality. *J. Sci. Food Agric*. 2017; 97(12):4016-4021.
91. Dong X.Y., Yang Y.L. A novel approach to enhance blueberry quality during storage using cold plasma at atmospheric air pressure. *Food Bioproc Tech.* 2019; 12(8):1409-1421.
92. Umair M., Jabbar S., Senan A.M., Sultana T., Nasiru M.M., Shah A.A., *et al.,* Jianhao Z. Influence of Combined Effect of Ultra-Sonication and High-Voltage Cold Plasma Treatment on Quality Parameters of Carrot *Juice. Foods*. 2019; 8(11):593.
93. Bao Y., Reddivari L., Huang J.Y. Development of cold plasma pretreatment for improving phenolics extractability from tomato pomace. *Innov. Food Sci. Emerg. Technol.* 2020;102445.
94. Rana S., Mehta D., Bansal V., Shivhare U.S., Yadav S.K. Atmospheric cold plasma (ACP) treatment improved in-package shelf-life of strawberry fruit. *J. Food Sci*. *Technol*. 2020; 57(1):102-112.
95. Mathot A.G., Postollec F., Leguerinel I. Bacterial spores in spices and dried herbs: The risks for processed food. Compr. Rev. *Food Sci. Food Saf.*2021; 20(1):840-862.
96. Pickova D., Ostry V., Malir J., Toman J., Malir F. A review on mycotoxins and microfungi in spices in the light of the last five years. *Toxins.* 2020; 12(12):789.
97. Hertwig C., Reineke K., Ehlbeck J., Erdoğdu B., Rauh C., Schlüter O. Impact of remote plasma treatment on natural microbial load and quality parameters of selected herbs and spices. *J. Food Eng*. 2015; 167:12-17.
98. Kim J.E., Choi H.S., Lee D.U., Min S.C. Effects of processing parameters on the inactivation of Bacillus cereus spores on red pepper (Capsicum annum L.) flakes by microwave-combined cold plasma treatment. *Int. J. Food Microbiol.* 2017; 263:61-66.
99. Jeon E.B., Choi M.S., Kim J.Y., Park S.Y. Synergistic effects of mild heating and dielectric barrier discharge plasma on the reduction of Bacillus cereus in red pepper powder. Foods. 2020; 9(2):171.
100. Lee S.Y., Park H.H., Min S.C. Pulsed light plasma treatment for the inactivation of *Aspergillus flavus* spores, Bacillus pumilus spores, and *Escherichia coli* O157: H7 in red pepper flakes. *Food Control.* 2020; 118:107401.
101. Kashfi A.S., Ramezan Y., Khani M.R. Simultaneous study of the antioxidant activity, microbial decontamination and color of dried peppermint (*Mentha piperita L.*) using low pressure cold plasma. *LWT.* 2020; 123:109121.
102. Hosseini S.I., Farrokhi N., Shokri K., Khani M.R., Shokri B. Cold low pressure O2 plasma treatment of *Crocus sativus*: An efficient way to eliminate toxicogenic fungi with minor effect on molecular and cellular properties of saffron. *Food Chem.* 2018; 257:310-315.
103. Mošovská S., Medvecká V., Halászová N., Ďurina P., Valík Ľ., Mikulajová A., Zahoranová A. Cold atmospheric pressure ambient air plasma inhibition of pathogenic bacteria on the surface of black pepper. *Food Res. Int.* 2018; 106:862-869.
104. Wiktor A., Hrycak B., Jasiński M., Rybak

K., Kieliszek M., Kraśniewska K., Witrowa-Rajchert D. Impact of atmospheric pressure microwave plasma treatment on quality of selected spices. *Appl. Sci.* 2020; 10(19):6815.

105. Kim J.H., Min S.C. Moisture vaporization-combined helium dielectric barrier discharge-cold plasma treatment for microbial decontamination of onion flakes. *Food Control.* 2018; 84:321-329.

106. Zhang X.L., Zhong C.S., Mujumdar A.S., Yang X.H., Deng L.Z., Wang J.,Xiao H.W. Cold plasma pretreatment enhances drying kinetics and quality attributes of chili pepper (*Capsicum annuum* L.). *J. Food Eng.* 2019; 241:51-57.

107. Rezaee Z. Application of non-thermal plasma for decontamination of thyme and paprika. *Int. J. Food Allied Sci.* 2019; 4(1):28-30.

108. Kim J.E., Oh Y.J., Song A.Y., Min S.C. Preservation of red pepper flakes using microwave-combined cold plasma treatment. *J. Sci. Food Agric.* 2019; 99(4):1577-1585.

109. Bang I.H., Kim Y.E., Lee S.Y., Min S.C. Microbial decontamination of black peppercorns by simultaneous treatment with cold plasma and ultraviolet C. *Innov. Food Sci. Emerg. Technol*. 2020:102392.

110. Shashikanthalu S.P., Ramireddy L., Radhakrishnan M. Stimulation of the germination and seedling growth of *Cuminum cyminum* L. seeds by cold plasma. *J Appl Res Med Aromat Plants.* 2020: 100259.

111. Charoux C.M., Free L., Hinds L.M., Vijayaraghavan R.K., Daniels S., O'Donnell C.P., Tiwari B.K. Effect of non-thermal plasma technology on microbial inactivation and total phenolic content of a model liquid food system and black pepper grains. *LWT.* 2020; 118:108716.

112. Elbashir S., Parveen S., Schwarz J., Rippen T., Jahncke M., DePaola A. Seafood pathogens and information on antimicrobial resistance: A review. *Food Microbiol.* 2018; 70:85-93.

113. Fisheries, F.A.O. Aquaculture Department. *The state of world fisheries and aquaculture. Food and Agriculture* Organization of the United Nations, Rome, 2016.

114. Gillett R. *Global study of shrimp fisheries* (Vol. 475). Rome: Food and Agriculture Organization of the United Nations, 2018.

115. Olatunde O.O., Benjakul S., Vongkamjan K. High voltage cold atmospheric plasma: Antibacterial properties and its effect on quality of Asian sea bass slices. *Innov. Food Sci. Emerg. Technol.* 2019; 52:305-312.

116. Liao X., Su Y., Liu D., Chen S., Hu Y., Ye X., *et al.,* Ding T. Application of atmospheric cold plasma-activated water (PAW) ice for preservation of shrimps (Metapenaeus ensis). *Food Control.* 2018; 94:307-314.

117. Albertos I., Martín-Diana A., Cullen P.J., Tiwari B.K., Ojha S.K., Bourke P., *et al.,* Rico D. Effects of dielectric barrier discharge (DBD) generated plasma on microbial reduction and quality parameters of fresh mackerel (*Scomber scombrus*) fillets. Innov. *Food Sci. Emerg. Technol.* 2017; 44:117-122.

118. Pasquali F., Stratakos A.C., Koidis A., Berardinelli A., Cevoli C., Ragni, L., *et al.,* Trevisani M. Atmospheric cold plasma process for vegetable leaf decontamination: A feasibility study on radicchio (red chicory, *Cichorium intybus* L.). *Food Control.* 2016; 60:552-559.

119. Coutinho N.M., Silveira M.R., Fernandes L.M., Moraes J., Pimentel T.C., Freitas M.Q., *et al.,* Neto R.P. Processing chocolate milk drink by low-pressure cold plasma technology. *Food Chem.* 2019; 278:276-283.