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REVIEW

Understanding the Role of Plasma Technology in Food Industry

Shabir Ahmad Mir[1,2] · **Manzoor Ahmad Shah**[2] · **Mohammad Maqbool Mir**[3]

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Abstract The need for enhancing microbial food safety and quality, without compromising the nutritional, functional, and sensory characteristics of foods, has created an increasing interest in innovative technologies in food industry. Plasma is an emerging, green processing technology offering many potential applications and fulfills the need of the industry. The present review presents the latest developments and applications of plasma technology in food industry. Recent research investigations showed that plasma processing have caught the interest of various areas of industry including cereal, meat, poultry, dairy, fruits, vegetables, packaging, etc. Plasma processing helps to modify the food material for the desirable trait, and maintains the nutritional and textural properties in addition to microbial decontamination.

Keywords Plasma processing · Non-thermal plasma · Food safety · Microbial decontamination

✉ Manzoor Ahmad Shah
mashahft@gmail.com

[1] Department of Food Technology, Islamic University of Science and Technology, Awantipora, Jammu and Kashmir 192122, India

[2] Department of Food Science and Technology, Pondicherry University, Puducherry 605014, India

[3] Division of Fruit Science, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, Jammu and Kashmir 190025, India

Introduction

In recent years, promotion of healthier lifestyles and consumer demands for greater food variety and availability has led to increased consumption of fresh produce (Thirumdas et al. 2014). This trend has also been associated with an increase in the number of recorded outbreaks of food-borne illness associated with fresh and minimal processed products. This is due to the fact that these products are consumed raw, without further processing or cooking which would usually remove microbial contamination (Guo et al. 2015). Ensuring safe and quality food has become a more complex task, is the focusing trend nowadays, and is the need of hour. The food industry has reached new levels of innovation in the effort to ensure product safety, driven by consumer demands and government regulations to produce microbial-free foods. Consumers are seeking more nutritious, less processed foods, while simultaneously expecting *microbial-free* products of high quality and long shelf life (Fernandez et al. 2013).

A number of non-thermal technologies have been tested in food industries to improve the quality of the food, while also ensuring the microbial safety of the product. The use of non-thermal surface decontamination processes is desirable for a variety of processing applications, in particular for those in which it is important to maintain the quality and nutritional attributes of food products, often impaired by excessive heating. Plasma is one of the latest technologies used nowadays worldwide for various applications (Garofulić et al. 2015; Misra et al. 2015). Plasma, a quasi-neutral gas, is referred to as the fourth state of matter. It contains a wide variety of active particles, such as electrons, ions, radicals, metastable excited species, and vacuum ultraviolet radiation that have sufficient energy to break covalent bonds and initiate some reactions and form volatile compounds (Şen et al. 2012). Practically, active species disappear immediately once the

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plasma power is turned off; therefore plasma processing is environmentally safe and can be fulfilling all ecological standards (Misra et al. 2011).

Plasma technology is one the novel green technologies used nowadays for various industries especially food industry. This technology has shown the promising applications for retaining the nutritional, functional, and sensory properties thus ensuring the fresh appearance. The technology helps in desirable structural modification of food and packaging material in addition to controlling the microbial load.

Plasma Process and its Generation

The term plasma was first introduced in 1928 by an American physicist, Irving Langmuir. Plasma is believed to be an ionized gas that consists of a large number of different species such as electrons, positive and negative ions, free radicals, and gas atoms, molecules in the ground or excited state and quanta of electromagnetic radiation (photons) (Şen et al. 2012). The number of positive charge carriers is equal to the number of negative ones and that is why the plasma possesses a net neutral charge (Scholtz et al. 2015). Plasma is often referred to as the fourth state of matter because of its unique features. It is a state of matter similar to gas in which a certain portion of the particles are ionized and has widely shown promising applications in various industries.

Plasma is electrically energized matter in a gaseous state that can be generated by electrical discharge. It is produced by subjecting a gas to an electric field (between two electrodes), either of constant (direct current field) or alternating amplitude (usually high frequency field). Plasma state can be attained by the application of energy in several forms including: thermal, electric or magnetic fields, and radio or microwave frequencies, which increase the kinetic energy of the electrons resulting in increased number of collisions in the gas forming plasma products like electrons, ions, radicals, and radiation of varying wavelengths including that in the UV ranges. Electrical discharges at low temperature make this process practical, inexpensive, and suitable for heat-sensitive materials (Thirumdas et al. 2014; Surowsky et al. 2013).

Plasma are distinguished into two groups, high-temperature plasma and low-temperature plasma, depending on the type of energy supply and amount of energy transferred to the plasma (Niemira 2014; Scholtz et al. 2015). This classification of plasma is based on the relative energetic levels of electrons and heavy species of the plasma. Low-temperature plasma is produced through the specific electric field and silent discharge. In this process, a series of physical and chemical reactions happen and gas is activated, many active groups are produced, and hence, high-energy electron collides with gas molecules (Misra et al. 2011). Non-thermal plasma are generated by means of radio frequency power sources such as atmospheric pressure plasma, radio frequency discharge-atmospheric pressure glow plasma, and one atmosphere uniform glow discharges plasma (Kim et al. 2011). Non-thermal plasma at low pressure can be generated by an electric discharge in a gas or using microwaves. Typical illustrations for plasma generation at atmospheric pressure include the corona discharge, dielectric barrier discharges, radio-frequency plasmas, and the gliding arc discharge (Guo et al. 2015). However, thermal plasmas are generated at higher pressures, require high power, and an almost thermal equilibrium exists between the electrons and the heavy species. In generation of cold plasma, most of the coupled electrical energy is channeled to electron component instead of heating entire gas stream so the temperature of heavy particle remains near the room temperature; these characteristics make it suitable for use in processes where high temperature is not desirable (Nehra et al. 2008).

Plasma process is operated by using various types of gases which affects their efficiency. A simple gas such as air or nitrogen may be used, or the system may rely on a mixture of noble gases, such as helium, argon, or neon. The driving energy is typically electricity, but may also be microwaves or lasers. Ionized gases generated from plasma processing create unique conditions that have no thermal equivalent (Pankaj et al. 2014).

The mixture of gases also used for plasma operation such as N_2/N_2O, N_2/O_2, Ar/O_2, He/O_2, He/N_2, and $He/O_2/H_2O$ (Guo et al. 2015). The efficiency of operating gas is mostly enhanced when oxygen is added to them (Scholtz et al. 2015). Deng et al. (2006) evaluated the experimental results using various operating gas (He and $He + O_2$ oxygen mixture) and concluded that primary factor for microbial inactivation is reactive oxygen species such as O, O_3, OH, NO, NO_2 species.

The great variety of reactive species is produced due to collisions between electrons, atoms, and molecules. Therefore, free charge carriers are accelerated by the application of an electric or electromagnetic field, leading to elastic and inelastic collisions. Reactions involving ions and neutrals also lead to charge exchanges or oligomerization as a result, compounds such as reactive species, e.g., O, O_3, OH, NO, NO_2, OH are generated. Due to their high reactivity, they can react with almost all cell components. The ionization of neutral, ground-state atoms, molecules, or radicals by electron impact is the most prominent ionization mechanism (Surowsky et al. 2013). The reactive species generated during the plasma processing can be significant contributors for the food quality and microbial inactivation process.

Application in Food Industry

The application of plasma technology has become increasingly important in recent years. The most attractive features of plasma are their low temperature property, and high efficiency

of microbial inactivation, which make them ideal for use in the application of food industry. Plasma treatment offers various opportunities in food processing, e.g., surface decontamination, modification of surface properties and enhancement of mass transfer with respect for foods and food-related materials (Table 1). Non-thermal plasma has a myriad of potential applications for the food industry including the dry disinfection of food surfaces (like meat, poultry, dairy and freshly harvested horticultural produce), granular and particulate foods (grains, herbs and spices) and sprouted seeds. This technology has also been successfully applied for the surface sterilization of packaging material and also their functional modification for imparting desired properties (Misra et al. 2015; Pankaj et al. 2015; Scholtz et al. 2015).

Cereal Industry

Cereals cover a wide range of crops and supplies, more than 50 % for consumption (Poutanen et al. 2014). Plasma technology is one of the promising non-thermal techniques used in cereal industry for various types of crops. This technology offers various benefits in cereal industry in addition to the decontamination.

Brown rice is less desirable due to its poor cooking and eating qualities. However, brown rice is preferred because of its higher nutritional value (Mir et al. 2015). Plasma processing is used to modify the properties of brown rice. Sarangapani et al. (2015) studied the effect of low-pressure cold plasma on cooking and textural properties of parboiled rice under various treatment time and power. The low-pressure cold plasma increased the water uptake ratio of parboiled rice and also reduced the cooking time up to 8 min. Textural properties were improved after treatment as hardness and stickiness decreased with increase in power and time.

Chen et al. (2012) used the low-pressure plasma to modify the microstructure, cooking, and textural properties of brown rice (Fig. 1). The plasma treatment results in an etching of brown rice surface, which allows water to be easily absorbed by the rice kernel during soaking. After plasma treatment, cooking time of brown rice is reduced, and the cooked brown rice has a soft texture and is easier to chew. The increment of the iodine-stained area indicates that the kernel structure of brown rice is substantially affected by plasma treatment. The plasma technique also used to enhance the nutritional value of brown rice. Chen et al. (2015) investigated the effect of low-pressure plasma on germinated brown rice from 1 to 3 kV for 10 min. Treatment of brown rice by low-pressure plasma increases the germination percentage, seedling length, and water uptake in laboratory germination tests. The possible mechanism could be that the plasma treatment results in an etching of brown rice surface, which allows water to be easily absorbed by the rice kernel and increases germination. The 3 kV plasma exposure for 10 min yielded the best results out of all treatments. In germinating brown rice, α-amylase activity was significantly higher in treated groups than in controls.

Table 1 Recent studies on the influence of plasma technology on food material

Source	Process gas	Type of material	Modification	Reference
Radio frequency air plasma	Argon + Oxygen	Bioxially oriented polypropylene	Decrease in contact angle, increase roughness and aging effect	Mirabedini et al. (2007)
Glow discharge	Air	Polyethylene terephthalate films	Decrease in contact angle, increase in roughness, crystallinity and degradation yield	Pandiyaraj et al. (2008)
Radio frequency argon plasma	Argon	Low density polyethylene	Decrease in contact angle and aging effect, increase in crystallinity	Ataeefard et al. (2009)
Diode plasma discharge	Argon	Polypropylene film	Decrease in contact angle, increase in surface energy	Slepicka et al. (2010)
Air corona	Air	Polypropylene	Decrease in contact angle, increase in adhesion	Dixon and Meenan (2012)
Cold plasma	Argon	Enzyme	Reduced the activity of polyphenoloxidase and peroxidase enzyme	Surowsky et al. (2013)
Dielectric barrier discharge	Air	Apple slices	Reduction of polyphenol oxidase activity	Tappi et al. (2014)
Surface discharge reactor plasma	Air	Wheat seeds	Increased germination rate	Dobrin et al. (2015)
Atmospheric cold plasma	Humid air	Wheat flour	Improvement in the dough strength and optimum mixing time, increased viscous and elastic moduli	Misra et al. (2015)
Cold plasma	Oxygen	Wheat protein isolate	Modified the protein structure, foaming and emulsifying capacity decreased	Segat et al. (2015)
Cold atmospheric pressure gas	Argon	Sour cherry	Enhanced anthocyanin content due to dissociation	Garofulić et al. (2015)
Microwave processed plasma air	Humid air	Fresh-cut kiwi fruit	Improved color retention, reduced darkening area during storage	Ramazzina et al. (2015)

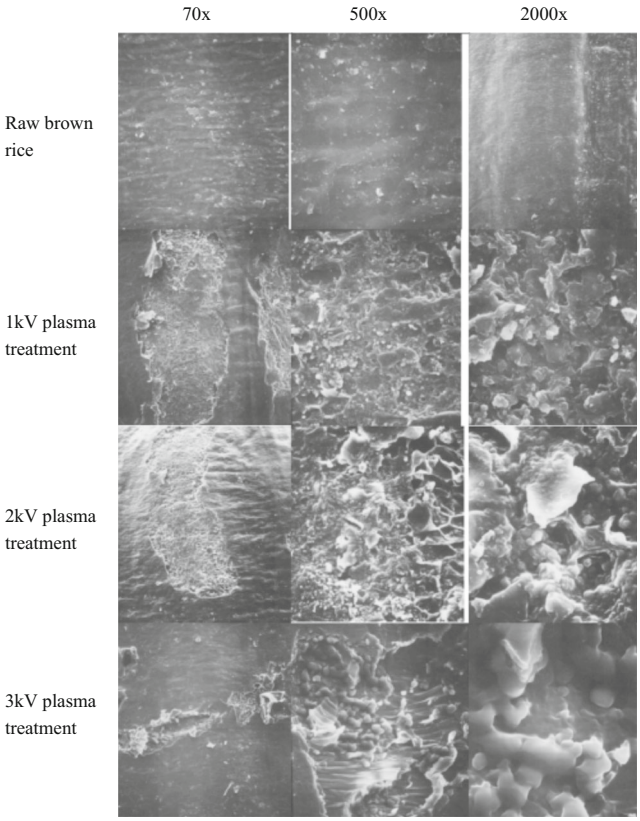

Fig. 1 Scanning electronic micrographs of brown rice treated with and without plasma treatment; Source: Chen et al. (2012)

The higher enzyme activity in plasma-treated brown rice likely triggers the rapid germination and earlier vigor of the seedlings. Low-pressure plasma also increased gamma-aminobutyric acid levels from 19 to 28 mg/100 g. In addition, a marked increase in the antioxidant activity of brown rice was observed with plasma treatments compared to controls.

Suhem et al. (2013) studied the effect of cold atmospheric plasma treatment to inhibit the growth of *Aspergillus flavus* on brown rice cereal bars. Plasma treatment was applied on surface of brown rice cereal bars of power of 40 W and exposure time of 20 min were required to reduce mold growth of approximately 4 log cfu/g and this treatment prevented the growth of *Mycelium* on the surface of bars for at least 20 days. The information obtained from this study are useful for rice producers, who are interested in identifying additional inexpensive and/or alternative practical methods to enhance the microbiological safety of rice-based cereal products.

Plasma treatment has shown the positive effect on growth of wheat seeds. Dobrin et al. (2015) investigated the behavior of plasma treatment on wheat seeds using a surface discharge reactor at atmospheric pressure and room temperature. It was found that plasma had little effect on the germination rate, but influenced growth parameters. The roots and sprouts of plasma-treated samples were longer and heavier than those of the untreated seeds for the investigated treatments. This improvement might be due to increased wettability observed for the treated seeds.

The atmospheric cold plasma was exploited to modulate the functionality of wheat flour. Misra et al. (2015) investigated the effect of atmospheric cold plasma treatment on hard and soft wheat flour. The rheological properties of flours revealed an improvement in the dough strength and optimum mixing time for both strong and weak wheat flours. The elastic and viscous moduli of strong wheat flour progressively increased with applied voltage and treatment time. Changes in the secondary structure of proteins were evaluated using Fourier transform infrared spectroscopy and revealed a decrease in β-sheets and increase in α-helix and β-turns, for both strong and weak wheat flour.

Plasma processing is used as a new physical method to alter the structure and rheological properties of starch, especially for the *green* production of starch products with a low viscosity at a relative high concentration. Dielectric barrier discharge (DBD) plasma significantly affects the granule morphology, crystalline structure, molecular structure and rheological properties of corn starch. Due to the presence of pinhole structures in the starch granule, DBD plasma not only changed the surface of the starch granules but also entered their interior, resulting in larger channels, a decrease in the degree of crystallinity, oxidation of partial hydroxyl groups to carboxyl groups, and molecular degradation. The rheological properties of starch paste changed from a pseudo-plastic (non-Newtonian) fluid to a Newtonian fluid, and the viscosity decreased, although the concentration of starch increased, mainly caused by the degradation of starch molecules (Bie et al. 2015).

Selcuk et al. (2008) successfully decontaminated the seeds of wheat, bean, chickpea, soybean, barley, oat, rye, lentil, and corn, contaminated with *Aspergillus parasiticus* and *Penicillium* sp. to less than 1 % of initial count depending on treatment times. The treatment times varied from 30 s to 30 min. The results suggested that after plasma treatment food qualities of wheat and beans were not affected or only marginally affected. The seeds were found to be viable post plasma processing.

Butscher et al. (2016) studied the effect of atmospheric pressure DBD on the bacterial endospores inactivation of wheat grains. The results showed that surface topography like uneven surfaces, loose pieces of bran, and the ventral furrow of wheat grains shield from plasma generated reactive species. However, the treatment efficiency is improved by increasing treatment time, pulse frequency, and pulse voltage. The defects are created by the impact of ions and attacked by oxygen species, which is responsible for endospore inactivation.

Plasma is also a novel promising method for insect control in stored cereal crops. El-Aziz et al. (2014) studied the effect of atmospheric pressure plasma jet on moth *Plodia interpunctella*. Two treatment variables were used: (1)

distance from nozzle of plasma jet (11, 13, or 15 cm) and (2) number of plasma jet pulses (1, 5, 10, 15, or 20 pulses). Significant increases in larval and pupal mortality and a decrease in adult emergence were observed with increase of plasma jet pulses and decrease of distance from the nozzle. Larvae were more sensitive than pupae to the treatment, but the treated pupae induced a higher percentage of malformed adults than treated larvae. The results suggested that non-thermal plasma causes oxidative damage in *P. interpunctella* larvae, possibly by generating reactive oxygen stress in their bodies. A significant increase in the level of lipid peroxide and reductions in the level of glutathione and protein content occurred in treated larvae in comparison with the control.

Dairy Industry

Raw milk is a natural, highly nutritious product and a quick and easy supplement for human dietary requirements. Use of contaminated milk is still a major health concern because of infectious diseases caused by the ingestion of pathogenic bacteria (Tiozzo et al. 2011; Todd and Notermans 2011). It is therefore standard procedure to properly treat raw milk, to inactivate these pathogens before consumption, either by pasteurization or ultra high temperature. However, the current thermal decontamination methods are known to induce changes to the chemical and physiological composition of milk and milk products. Due to its complex structure, milk has so far shown to be highly sensitive to many current novel technologies (Segat et al. 2015). Plasma technology is one of the novel technologies having potential application in dairy industry. The ability of plasma to work at low temperatures without increasing the operating temperature has opened up the possibility of using plasma technology for treatment of heat-sensitive materials (Korachi et al. 2015). Using the advantages of cold plasma, this system was tested for its ability to decontaminate milk and milk products.

Song et al. (2009) investigated the influence of atmospheric pressure plasma, which is capable of operating at atmospheric pressure in sliced cheese inoculated by three-strain cocktail of *Listeria monocytogenes*. The process parameters considered were input power (75, 100, 125, and 150 W) and plasma exposure time (60, 90, and 120 s). Microbial log reduction increased with increases of input power and plasma exposure time. After 120 s atmospheric pressure plasma treatments at 75, 100, and 125 W, the viable cells were reduced by 1.70, 2.78, and 5.82 log cfu/g in sliced cheese, respectively. More than 8 log reductions can be achieved in 120 s at 150 W. Calculated *D* values, the exposure time required to inactivate 90 % of a population, from the survival curves of 75, 100, 125, and 150 W of atmospheric pressure plasma treatments were 71.43, 62.50, 19.65, and 17.27 s, respectively. These results indicate that the inactivation effects of atmospheric pressure plasma on *L. monocytogenes* are strongly dependent on the type of food.

Pathogen inactivation induced by encapsulated atmospheric pressure DBD plasma (250 W, 15 kHz, air discharge) produced in a rectangular plastic container and the effect of post-treatment storage time on inactivation were evaluated on cheese slices by Yong et al. (2015). The cheese slices were treated with plasma, populations of *Escherichia coli*, *Salmonella typhimurium*, and *L. monocytogenes* showed 2.67, 3.10, and 1.65 decimal reductions at 60 s, 45 s, and 7 min, respectively. The post-treatment storage duration following plasma treatment potently affected further reduction in pathogen populations. Therefore, encapsulated atmospheric pressure DBD plasma system for use in a container are applied to improve the safety of sliced cheese, and increasing post-treatment storage time greatly enhanced the system's pathogen-inactivation efficiency.

Segat et al. (2015) reported that atmospheric pressure cold plasma can be successfully applied to selectively modify the protein structure and therefore, improve whey protein isolate functionality. The interaction between plasma and whey protein isolate model solutions was investigated as a function of treatment time (from 1 to 60 min). Results showed an increase in yellow color and a minor reduction in pH value, which was attributed to the reactions of reactive oxygen and nitrogen species of plasma. Plasma generated overall changes within 15 min of treatment as a result of a *mild* oxidation of the proteins. This was evident from an increase in carbonyl groups and the surface hydrophobicity, besides the reduction of free SH groups. The protein structure modifications revealed a certain degree of unfolding, due to a rate of aggregation for all samples compared to the control, which influence the foaming and emulsifying capacity. Upon extended treatment for 30 and 60 min, the changes were quite pronounced. Overall, the foaming and emulsifying capacity dramatically decreased; however, the foam stability is increased.

Gurol et al. (2012) evaluated the capability of low temperature plasma for killing of *E. coli* in milk at different fat contents. The time-dependent effect of atmospheric corona discharge generated with 9 kV of AC power supply on *E. coli* dispersed in whole, semi skimmed, and skimmed milk was examined. Plasma was applied at time intervals of 0, 3, 6, 9, 12, 15, and 20 min. A significant 54 % reduction in the population of *E. coli* cells after only 3 min was observed regardless of the fat content of the milk. The initial pre-plasma bacterial count of 7.78 log cfu/g in whole milk was decreased to 3.63 log cfu/g after 20 min of plasma application. Plasma treatment did not cause any significant change to the pH and color values of raw milk samples. No viable cells were detected after 1 week examination in whole milk samples and remained so over the 6 week storage period. The findings of this study showed that plasma system is able to significantly reduce *E. coli* in milk by more than a three-fold log reduction without significantly affecting pH or color properties of milk.

Korachi et al. (2015) investigated the biochemical changes of whole raw milk samples by application of cold plasma. Raw milk was treated with a cold plasma system at intervals of 0, 3, 6, 9, 12, 15, and 20 min. Significant changes were observed for 1 octanol, 2 heptanone, 2 hexenal, 2 octenal, nonanal, and benzaldehyde. Plasma treatment showed non-significant changes to the lipid composition of raw milk. However, exposure to cold plasma significantly increased the total aldehyde content following 20 min treatment. No significant difference was observed in the total ketone or alcohol levels.

Meat and Poultry Industry

Meat and poultry industry has been a leader in the development and implementation of new processing. The various food safety intervention technologies used in the meat industry include slaughtering, meat product fabrication (e.g., cutting, blending, and extruding), processing (e.g., cooking, curing, drying, and freezing), packaging and also utilize intervention technologies to ensure a sanitary manufacturing environment. All these needs of the said industry are well fulfilled by plasma technology (Rod et al. 2012). Plasma processing offers a wide selection of gas compositions, generation methods, and methods of product exposure, which all influence the concentration of the generated reactant products (e.g., ozone, peroxides, and monoxides) and their resultant impact on the meat or poultry industry (Kim et al. 2011).

Plasma treatment is able to prolong the shelf life of porcine *musculus longissimus dorsi* with regard to microbiological contamination and shows potential to decontaminate the fresh pork. Frohling et al. (2012) evaluated the impact of indirect plasma treatment on quality and safety of porcine. A microwave plasma setup (2.45 GHz, 1.2 kW; process gas air) was used for indirect plasma treatment of fresh porcine with exposure times of 2 × 2.5 or 5 × 2 min. After plasma treatment the aerobic viable count of *musculus longissimus dorsi* remained between 2 and 3 log cfu/g during the storage period of 20 days at 5 °C. Color measurements showed increased a^* values and decreased b^* values of pork meat after plasma treatment in comparison to untreated meat samples.

Atmospheric pressure plasma treatment on ready-to-eat meat was performed using a DBD plasma device inoculated with *Listeria innocua* (Rod et al. 2012). The inoculated meat samples in bags containing 30 % oxygen and 70 % argon were placed between two electrodes of the DBD device and treated at 15.5, 31 and 62 W for 2 to 60 s. Highest inactivation rates on ready-to-eat meat with 1.5 to 1.6 log cfu/g were observed after multiple plasma treatments for 20 s within a time interval of 10 min at operating powers of 15.5 and 62 W, respectively. Treatments resulted in a reduction of *L. innocua* ranging from 0.8 ± 0.4 to 1.6 ± 0.5 log cfu/g with no significant effects of time and intensity while multiple treatments at 15.5 and 62 W of 20 s with a 10 min interval increased reduction of *L. innocua* with increasing number of treatments. Concentrations of thiobarbituric acid reactive substances increased with power, treatments, and storage time and were significantly higher than those of control samples after 1 and 14 days of storage at 5 °C. However, the levels were low (from 0.1 to 0.4 mg/kg) and beneath the sensory threshold level. Surface color changes included loss of redness of 40 and 70 % after 1 and 14 days of storage, respectively, regardless of plasma treatment.

Moon et al. (2009) found no thermal damage of pork after plasma treatment with atmospheric pressure radio frequency glow discharge at 150 W for 1 min and a helium gas temperature below 370 K. A three-strain cocktail of *L. monocytogenes* (initial contamination approximately 6 log cfu/g) was inoculated on sliced ham and treated with low temperature discharge helium plasma. According to the used operating powers of 75, 100, 125, and 150 W and plasma exposure times of 60, 90, and 120 s, the determined D values were 479.19, 87.72, 70.92, and 63.69 s, respectively (Song et al. 2009). The same plasma source was used by Kim et al. (2011) to decontaminate bacon. They used helium or helium mixed with oxygen as process gas and inoculated *E. coli*, *S. typhimurium*, and *L. monocytogenes* on the bacon. The colony count of *E. coli*, *S. typhimurium*, and *L. monocytogenes* was reduced from approximately 8 log cfu/g to 4.8, 5.79, and 6.46 log cfu/g, respectively, during plasma treatment at 125 W for 90 s using a gas mixture. In contrast, only 1.6, 2.0, and 1.5 log cfu/g, respectively, were reduced after the same plasma treatment time and an operating power of 125 W with helium only as process gas. An atmospheric pressure plasma jet with helium or nitrogen as process gas with or without addition of oxygen was used to inactivate *L. monocytogenes* inoculated on chicken breast and ham by Lee et al. (2011).

Kim et al. (2013) evaluated the use of a DBD plasma system to improve the safety of pork loins. When pork loin was exposed to DBD plasma with the input gases He and He + O_2, the population of *E. coli* was reduced by 0.26 and 0.50 log cycles following a 5 min treatment and by 0.34 and 0.55 log units following a 10 min treatment, respectively. *L. monocytogenes* was also reduced from 0.17 to 0.35 and 0.43 to 0.59 log cycles when the samples were exposed to DBD for 5 and 10 min using He and He + O_2, respectively. The pH and L^* values (lightness) of the samples decreased significantly with DBD plasma treatment, but a^* (redness) and b^* values (yellowness) exhibited no obvious changes. Lipid oxidation was greater in samples with He + O_2 than in other samples. Significant reductions in sensory quality parameters including appearance, color, odor, acceptability, etc. were observed in DBD-treated samples. These results indicate that the DBD plasma system has potential for use in sanitizing pork loins by inactivation of foodborne pathogens.

The effects of a flexible thin-layer DBD plasma system using a sealed package on microbial inactivation and quality attributes of fresh pork and beef were investigated by Jayasena et al. (2015). Following a 10-min treatment, the microbial-load reductions of *L. monocytogenes*, *E. coli* O157:H7, and *S. typhimurium* were 2.04, 2.54, and 2.68 log cfu/g in pork-butt samples and 1.90, 2.57, and 2.58 log cfu/g in beef-loin samples, respectively. Colorimetric analysis showed that DBD plasma treatment did not significantly affect *L** values (lightness) of pork and beef samples, but lowered *a** values (redness) significantly after 5 and 7.5 min exposures. Plasma treatment significantly influenced lipid oxidation only after a 10-min exposure. The texture of both types of meat was unaffected by plasma treatment. All sensory parameters of treated and non-treated samples were comparable except for taste, which was negatively influenced by the plasma treatment.

Radio-frequency atmospheric pressure plasma discharge was tested to reduce *Staphylococcus aureus* on the surface of polystyrene and beef jerky (Kim et al. 2014). *S. aureus* was reduced by 3 to 4 log colony forming unit on the polystyrene after 2 min treatment, but on beef jerky sample after 10 min treatment. The results suggested that the surface feature can significantly affect the inactivation of *S. aureus* by plasma. The scanning electron microscopy analysis showed that the *S. aureus* cells were disintegrated into pieces and many holes were created. The analysis of optical emission spectrum suggests that reactive oxygen species, especially the singlet state of oxygen are mainly responsible for the inactivation and cellular deformation of *S. aureus*. Non-significant change was observed in the fatty acid composition, color, and shear force of the beef jerky samples.

The most commonly enteric pathogens that contaminate poultry carcasses are *Salmonella*, *Campylobacter* and *L. monocytogenes* (Murphy et al. 2004). The possibility of cross-contamination of poultry carcasses post slaughter is high and hence decontamination of poultry carcasses is desirable. Gas plasmas generated at atmospheric pressure and ambient temperatures offer a possible decontamination method for poultry products.

The efficacy of cold atmospheric gas plasmas was evaluated for decontamination of chicken skin and muscle inoculated with *L. innocua*. The higher values of AC voltage, excitation frequency, and the presence of oxygen in the carrier gas resulted in the greatest inactivation efficiency. The presence of oxygen in the carrier gas played a desirable role on muscle than skin for reduction of *L. innocua*. The treatment of 8 min gave 1 log cfu/g reduction on skin and a 4 min treatment gave 3 log cfu/g reductions on muscle. The results showed that the efficacy of gas plasma treatment is greatly affected by surface topography of sample (Noriega et al. 2011).

Salmonella spp. has been largely reported as a potential hazard for egg consumers, and a need for alternative methods of decontaminations (Davies and Breslin 2003). Ragni et al. (2010) investigated the efficacy of resistive barrier discharge plasma for the decontamination of egg shell surfaces. Their work revealed a maximum reduction of 2.2 to 2.5 log cfu/egg shell in *Salmonella enteritidis* levels following a 60 to 90 min of treatment at 35 % RH. Further, the effectiveness of the treatments enhanced at a higher RH level of 65 %, where maximum declines of 3.8 and 4.5 log cfu/egg shell were achieved after 90 min of exposure.

Food products enriched with healthier unsaturated fatty acids are more sensitive to lipid oxidation, leading to quality deterioration and the development of unwanted aroma profiles. Vandamme et al. (2015) used the plasma processing for oxidative stability and is capable to generate a wide range of highly reactive oxidative species (e.g., atomic oxygen, hydroxyl radicals, singlet oxygen) while maintaining ambient temperatures. DBD plasma jet (Ar/0.6 % O_2) is used on fish oil samples as a faster and more realistic accelerated lipid oxidation method. Experiments were done using both virgin and alpha-tocopherol-enriched fish oil samples. Both accelerated oxidation techniques induced the formation of typical lipid oxidation markers (e.g. 2-propenal, (*E*)-2-pentenal, heptanal). However, in both cases, significant differences were observed compared to the naturally aged fish oil. On the other side, non-thermal plasma correctly predicted an antioxidative effect when 1000 μg/g alpha-tocopherol was added to the fish oil, while thermally based tests resulted in the induction of prooxidative chemistry.

Fruit and Vegetable Industry

Plasma is the promising technology used in fruit and vegetable processing industry. This technique has been used from last decade mostly for this industry to improve the quality of produce (Zhang et al. 2013). Plasma processing is capable of reducing microbial populations on produce surfaces. Critzer et al. (2007) investigated the effect of atmosphere uniform glow discharge plasma on inactivation of *E. coli* O157:H7, *Salmonella*, and *L. monocytogenes* on apples, cantaloupe, and lettuce, respectively. Samples were exposed inside a chamber attached to the plasma blower unit operated at a power of 9 kV and frequency of 6 Hz. Cantaloupe and lettuce samples were exposed for 1, 3, and 5 min, while apple samples were exposed for 30 s, 1 min and 2 min. An approximate 3 log cfu/g reduction was observed with *E. coli* O157:H7 on apples after exposure to plasma for 2 min, and similar levels of reduction were achieved with *Salmonella* and *L. monocytogenes* on cantaloupe and lettuce, respectively, after 3 min of exposure to plasma. *L. monocytogenes* proved to be the slightly more sensitive to plasma treatment than *E. coli* O157:H7 and *Salmonella*. Populations of *L. monocytogenes* were reduced to undetectable levels and barely detected when lettuce was exposed to plasma for 5 min. *E. coli* O157:H7 and *Salmonella* populations were never reduced to below 1 log

cfu/g. Perni et al. (2008) evaluated the decontamination effect of plasma on pericarp of melon and mangoes inoculated by *Saccharomyces cerevisiae*, *Pantoea agglomerans*, *Gluconobacter liquefaciens*, and *E. coli*. It was observed that *S. cerevisiae* was the most resistant. *P. agglomerans* and *G. liquefaciens* disappeared below the limit of detection (3 log cfu/g) after only 2.5 s of exposition on both fruits, whereas to reach the same level of inactivation of *E. coli* required 5 s.

Bermudez-Aguirre et al. (2013) exposed lettuce, carrots, and tomatoes contaminated by a pathogenic strain of *E. coli* to non-thermal plasma and assessed the microbiological quality after processing, using Hunter's color parameters. The degree of inactivation was dependent on the intensity of inoculation, i.e., it was easy to inactivate low bacterial counts. The color of the treated product was not affected. The structure of exposed microbial cells displayed extensive electroporation, cell membranes were deformed, disrupted, and partially lost.

Decontamination of fresh food packed in a sealed package is one of non-thermal plasma special applications. Using the DBD with properly ordered electrodes, the plasma can be inductively generated directly inside the container. The DBD ozone generation system was used by Klockow and Keener (2009) to decontaminate fresh spinach inoculated with *E. coli* inside a sealed package. After 5 min of exposure, the reductions of 3 to 5 log 10 cfu/leaf was observed after 24 h of storage.

The effect of microwave processed plasma air on seven different microorganisms spiked on apple (peal and pulp), strawberry, lamb's lettuce, and carrot was studied by Schnabel et al. (2015). The investigation showed promising results, because after only 7 s of direct plasma activity followed by 15 min incubation in microwave processed plasma, the microbial load was reduced more than 6 log cfu/g. The sensory properties, texture, and appearance of tested fruits and vegetable remained unaffected. Misra et al. (2014a) studied the effect of DBD on strawberries. The background microflora of strawberries consisted of mesophilic aerobic bacteria and fungi (molds, yeasts) which were reduced within 5 min by 2 log cfu/g. The color and firmness of strawberries were not significantly affected by the plasma treatment.

Ramazzina et al. (2015) evaluated the effect of cold plasma treatment on the quality of fresh-cut kiwifruit. The results showed that plasma treatments positively influenced the quality maintenance of the product, by improving color retention and reducing the darkened area formation during storage. The plasma treatments caused an immediate slight loss of pigments, but a better retention during storage. Non-significant changes in texture and antioxidants including ascorbic acid and polyphenols were observed among treated samples and control ones.

Matan et al. (2015) studied the combined effect of cold plasma (20 and 40 W) and green tea extract on pathogens of fresh-cut dragon fruit. The plasma at 40 W extended the protection against all pathogen growth on the surface of fresh-cut dragon fruit treated with a 5.0 % of green tea to at least 15 days. The green tea extract treatment without plasma treatment could not inhibit the bacterial growth. In addition, higher values of total phenolic content, crude protein, crude fat, and crude fiber were observed in the fresh-cut dragon fruit with green tea after the plasma treatment. The results indicated that green tea extract and atmospheric plasma in combination could protect against the growth of pathogens on fresh-cut dragon fruit and extend its shelf life without damaging the nutritional and sensory quality.

Lacombe et al. (2015) investigated the effect of atmospheric cold plasma on inactivation of aerobic microorganisms of blueberries and its effects on quality attributes. Berries were treated with plasma for 0, 15, 30, 45, 60, 90, or 120 s at a working distance of 7.5 cm with a mixture of 4 cubic feet/min (cfm) of cold plasma jet and 7 cfm of ambient air. All the treatments reduced microbial growth ranging from 0.8 to 1.6 log cfu/g and 1.5 to 2.0 log cfu/g compared to the control after 1 and 7 days, respectively. Treatments longer than 60 s resulted in significant reductions in firmness may be due to the collisions between the berries and the container contributed to softening. Significant reduction in anthocyanins was observed after 90 s. Surface color measurements were significantly impacted after 120 s for the L^* and a^* values and 45 s for the b^* values.

The non-thermal oxygen plasma treatment shows a potential for the efficient sanitization of fresh produce surfaces. Zhang et al. (2013) investigated the feasibility of low-pressure oxygen plasma on sanitization of spinach, lettuce, tomato, and potato surfaces from *S. typhimurium* LT2. The time of exposure and plasma power density were two critical parameters influencing the bactericidal efficiency. Surface roughness and hydrophobicity of produce did not influence the sanitization of produce. Oxygen plasma was more effective than washing with 3 % H_2O_2 on eliminating *S. typhimurium* LT2 on spinach. The results showed that oxygen plasma treatment (0.34 W/cm^3) only affects the wax cuticle layer under conditions of short- to intermediate-exposure times. However for long exposure times, wax cuticle layer and upper epidermis cells may be damaged. Oxygen plasma changed the wax surface chemistry through oxidation reactions forming aldehyde and carboxylic acid, and by decomposition of carbon chains.

Bermudez-Aguirre et al. (2013) used atmospheric pressure cold plasma for the inactivation of a surrogate microorganism of the pathogenic strain *E. coli* inoculated on lettuce, carrots, and tomatoes at 5 and 7 log cfu/g. Vegetables were exposed to plasma discharges from a needle array from 3.95 to 12.83 kV (60 Hz) in argon, from 30 s to 10 min. Results showed that the inoculation level had an effect on the degree of inactivation and was easier to inactivate the bacteria at lower counts. The highest voltage and longest treatment time were more

effective in microbial inactivation (1.6 log cfu/g). Tomatoes, followed by lettuce, were easier to disinfect than carrots, maybe because of the surface structure. Color parameters did not show significant changes after processing. However, the structure of *E. coli* cells showed a totally damaged surface; a high degree of electroporation, fusion between cells, disruption of cell membrane, and change in shape of cells after treatment.

The effect of DBD atmospheric gas plasma was tested against *L. monocytogenes* and shigatoxin-producing *E. coli* serogroups O157 and O26 (Berardinelli et al. 2016). The tests were carried out on samples of cut celery and radicchio leaves inoculated with a mix of five strains of *L. monocytogenes* or the two strains of *E. coli* immersed in deionized water. For deionized inoculated water alone, a treatment time-dependent strong effect was observed and a pathogens reduction higher than 6 log cfu/g was obtained after 40 min of treatment. The presence of vegetables in the liquid medium reduced the efficacy and related to the treatment time, microorganism, substrate, and storage duration (reduction up to 2.5 and 3.7 log cfu/g for *L. monocytogenes* and *E. coli*, respectively). No significant changes were observed on celery visual attributes, soluble solids content, and textural parameters. However, significant decrease of the chroma color parameter during storage was observed in treated radicchio samples with respect to control ones.

Atmospheric cold plasma appears to be a promising processing technology for the decontamination of leafy vegetables. The effect of atmospheric cold plasma on the safety, antioxidant activity, and quality of radicchio (*Cichorium intybus* L.) was investigated after 30 min of treatment (in afterglow at 70 mm from the discharge, at 22 °C and 60 % of RH) by Pasquali et al. (2016). The 30 min plasma treatment significantly reduced *L. monocytogenes* counts (2.2 log cfu/g) inoculated on radicchio leaves. Immediately after cold plasma treatment, no significant effects emerged in terms of antioxidant activity assessed by the ABTS and ORAC assay and external appearance of the radicchio leaves.

Fernandez et al. (2013) evaluated the efficacy of cold atmospheric plasma treatment for decontaminating of lettuce and strawberry surfaces and potato tissue inoculated with *S. typhimurium*. The results showed that the rate of inactivation of *S. typhimurium* was independent of the growth phase, growth temperature, and chemical treatment regime. Under optimal conditions, a 15-min treatment was necessary to achieve 2.72, 1.76 and 0.94 log cfu/g of *S. typhimurium* viability on lettuce, strawberry, and potato, respectively. The differing efficiency of plasma treatment on the inactivation of *S. typhimurium* on these different types of fresh foods is a consequence of their surface features. Scanning electron microscopy of the surface structures of contaminated samples of lettuce, strawberry, and potato revealed topographical features whereby *S. typhimurium* cells could be protected from the active species generated by plasma.

Garofulić et al. (2015) evaluated the effect of cold atmospheric pressure gas phase plasma treatment on anthocyanins and phenolic acids in sour cherry Marasca juice. Plasma treatment was optimized using a response surface methodology regarding the treatment time, sample volume, and applied gas flow and compared to thermal pasteurization and untreated juice. Short treatment (3 min) of larger volume of the juice (3 mL) resulted in the highest concentration of both anthocyanins and phenolic acids. Compared to pasteurized and untreated juice, plasma-treated sour cherry Marasca juice at optimized conditions had higher amount of anthocyanins and phenolic compounds. Short exposure of plasma treatment dissociates the agglomerates or particles and consequently leads to increases in anthocyanin content of sour cherry.

Kovačević et al. (2015) studied the effect of cold atmospheric gas plasma on anthocyanins and color in pomegranate juice. In comparison to untreated pomegranate juice, plasma treatments showed higher anthocyanin content (21–35 %), which confirms that plasma has a positive effect on anthocyanin stability. The highest anthocyanin stability was found at 3 min treatment time, 5 cm^3 juice volume, and gas flow of 0.75 dm^3/min. Observed increased in anthocyanin content after plasma treatment was attributed to improved extractability and disruption of the cell membrane integrity in cloudy particle of pomegranate juice. The change of juice color did not vary with change of sample volume and treatment time, while it dropped with increased gas flow. Herceg et al. (2016) evaluated the effect of gas phase plasma on phenolic compounds in pomegranate juice and compared with pasteurized juice. Pasteurization and plasma treatment resulted in total phenolic content increasing by 29.55 and 33.3 %, respectively. The results showed that plasma-treated pomegranate juice retain maximum phenolic compounds as compared to pasteurized juice.

Lee et al. (2015a) studied the effect of cold plasma treatment on the microbiological safety of cabbage, lettuce, and dried figs. The plasma treatment at 900 W, for 10 min using nitrogen as a plasma-forming gas, inactivated *S. typhimurium* inoculated on cabbage and lettuce by approximately 1.5 log cfu/g. The cold plasma treatment at 400 to 900 W and 667 Pa, for 1 to 10 min using a helium-oxygen gas mixture, inactivated *L. monocytogenes* on cabbage by 0.3 to 2.1 log cfu/g. The plasma treatment at the optimum conditions of treatment power (400 W) and time (10 min) inactivated *L. monocytogenes* on lettuce by 1.8 log cfu/g. The microbial inactivation by plasma treatment increased synergistically when the pH of the figs was reduced from 6 to 4. The reductions in numbers of *E. coli* O157:H7 and *L. monocytogenes* on figs increased from 0.5 to 1.3 log cfu/g and from 1.0 to 1.6 log cfu/g, respectively.

Ziuzina et al. (2014) investigated the effect of atmospheric cold plasma on inactivation of *E. coli*, *Salmonella enteric serovar typhimurium*, and *L. monocytogenes* inoculated on

fresh produce of cherry tomatoes and strawberries. The bacteria were spot inoculated on the produce surface, air dried, and sealed in polypropylene container. Samples were indirectly exposed (placed outside plasma discharge) to a high-voltage (70 kV_{RMS}) air plasma and subsequently stored at room temperature for 24 h. Atmospheric cold plasma treatment for 10, 60, and 120 s resulted in reduction of *Salmonella*, *E. coli* and *L. monocytogenes* populations on tomato to undetectable levels from initial populations of 3.1, 6.3, and 6.7 log cfu/g, respectively. However, treatment times of up to 300 s were required to attain substantial reductions on strawberry surfaces. Similarly, yeasts/molds and mesophiles on tomato surface were not detected after 120–300 s, respectively. Thus, atmospheric cold plasma treatment with 24 h post-treatment storage can eliminate microorganisms on fresh produce surfaces inside a sealed package.

Cold plasma was employed as a means for decontamination of cherry tomatoes while retaining product quality. Misra et al. (2014b) evaluated the effect of in-package atmospheric pressure cold plasma treatment on cherry tomatoes. Respiration rates and weight loss were monitored continuously, while other parameters are reported at the end of storage period. The plasma treatment of cherry tomatoes does not adversely affect critical quality parameters of color, firmness, pH, and weight loss. The respiration rate of cherry tomatoes does not exhibit a rise following cold plasma treatments.

Decontamination effect of plasma generated by an AC voltage (variable 12–16 kV) on pericarp of melon and mangoes inoculated by *S. cerevisae*, *P. agglomerans*, *Gluconacetobacter liquefacien*, and *E. coli* was reported by Perni et al. (2008). The most resistant *P. agglomerans* and *G. liquefaciens* were reduced below the detection limit (corresponding to 3 log cfu/g) after only 2.5 s on both fruits, whereas *E. coli* required 5 s to reach the same level of inactivation.

Deng et al. (2006) studied the inactivation of *Bacillus subtilis* by cold atmospheric plasma. The leakage of cytoplasm content and a complete rapture of the spore membrane were observed after plasma treatment. The investigation done by optical emission spectroscopy showed that spore inactivation was most probably induced by the reactive oxygen species. For improving production of reactive oxygen species and hence more inactivation, it was observed that it is more effective to use an atmospheric helium plasma plume rather than a comparable atmospheric helium-oxygen plasma plume, because the former supported a greater level of gas ionization oxygen dissociation.

Tappi et al. (2014) investigated the effect of gas plasma on fresh-cut apples using DBD generator at three different times: 10, 20, and 30 min. The promising results have been obtained regarding enzymatic browning inhibition and the reduction of polyphenol oxidase activity. The enzyme residual activity decreased linearly by increasing the treatment time (up to about 42 %). The results showed that treatments slow down the metabolic activity of the tissue. Niemira and Sites (2008) reported the reduced in viable populations of *Salmonella* and *E. coli* 0157:H7 inoculated on apple surfaces using cold plasma generated in a gliding arc. The direct current corona discharges for reduction of *E. coli O157:H7* in apple juice was employed and the number of cell reduction was more than 5 log cfu/g after 40 s treatment at a frequency of less than 100 Hz with 4000 pulses of 9000 V peak voltage.

Surowsky et al. (2013) evaluated the effect of cold plasma on enzyme activity and the results showed that this technique is a promising non-thermal pasteurization technology, which is capable of reducing the activity of quality determining enzymes, polyphenoloxidase, and peroxidase in a model food system. The activity of polyphenoloxidase was reduced by about 90 % after a treatment time of 180 s. Peroxidase was more stable and reduced by about 85 % after 240 s. Circular dichroism and tryptophan fluorescence measurements indicate that the reason for their loss of activity is based on a plasma-induced modification of their secondary structure. A decrease in the alpha-helix content was accompanied by an increase of the percentage of beta-sheet regions.

Basaran et al. (2008) studied the effect of low pressure cold plasma using air gases and sulfur hexafluoride on anti-fungal efficacy against *A. parasiticus* on various nut samples. Artificially, *A. parasiticus*-contaminated hazelnuts, peanuts and pistachio nuts were treated with air gases plasma and sulfur hexafluoride plasma for up to 20 min duration. The sterilizing effect of plasma on *A. parasiticus* was higher during the early treatment period than the later treatment period. Air gases plasma treatment for 5 min resulted in 1 log cfu/g reduction of *A. parasiticus* and a further 5 min treatment resulted in additional 1 log cfu/g reduction. Sulfur hexafluoride plasma application was more effective resulting in approximately a 5 log cfu/g decrease in fungal population for the same duration. Plasma treatment against aflatoxins showed that 20 min air gases plasma treatment resulted in a 50 % reduction in total aflatoxins (AFB1, AFB2, AFG1, and AFG2), while only a 20 % reduction in total aflatoxin was observed after 20 min sulfur hexafluoride plasma treatment.

Atmospheric pressure fluidized bed plasma system was investigated on the effect of aflatoxigenic fungi (*A. flavus* and *A. parasiticus*) on the surface of hazelnuts (Dasan et al. 2016). Hazelnuts were artificially contaminated with *A. flavus* and *A. parasiticus* and then were treated with dry air plasma for up to 5 min in the fluidized bed plasma system. Significant reductions of 4.50 log cfu/g in *A. flavus* and 4.19 log cfu/g in *A. parasiticus* were achieved after 5-min treatments at 100 % V-25 kHz (655 W) by using dry air as the plasma-forming gas. The decontamination effect of plasma on *A. flavus* and *A. parasiticus* spores inoculated on hazelnuts was increased with the applied reference voltage and the

frequency. No change or slight reductions were observed in *A. flavus* and *A. parasiticus* load during the storage of plasma-treated hazelnuts, whereas on the control samples fungi continued to grow under storage conditions (30 days at 25 °C).

Plasma technology is an innovative and a promising technique to investigate the role of individual reactive species and/or unravel oxidation reaction pathways, with the potential to become more representative accelerated food aging technique. Van Durme et al. (2014) studied both a thermally based reference test and experiments using three types of plasma (argon plasma, oxygen-doped argon plasma, water-doped argon plasma). Treatment of fresh reference vegetable oil with pure argon plasma did not induce lipid oxidation reactions. Contrarily, a short treatment with both 0.3 % O_2/argon and 0.3 % H_2O/argon plasma resulted in the production of several oxidation products that were also identified in naturally oxidized oil. MS-fingerprinting analyses, supported by the degree of difference sensory testing, indicated that current plasma configuration induces changes that are different from these measured in naturally aged vegetable oil. Chemical profiling of the secondary volatile lipid oxidation products showed that atomic oxygen resulted mainly in aldehyde production, while singlet oxygen induced the formation of 2-pentyl furan. Vegetable oils exposed to argon/0.3 % H_2O plasma were characterized by lower amounts of oxidation products.

Spice Industry

Plasma processing also used for decontamination of spices and showing the promising results. Hertwig et al. (2015a) studied the effect of plasma treatment on natural microbial load and quality parameters of selected herbs and spices (pepper seeds, crushed oregano, and paprika powder) with plasma processed air up to 90 min and the inactivation of their native microbial flora was examined. The remote plasma treatment reduced the native microbial flora of the pepper seeds and the paprika powder by more than 3 log cfu/g after 60 min treatment time. However, remote plasma treatment of red paprika powder resulted in a considerable loss of redness after a treatment time of ≥5 min due to the destruction of carotenoids. Lower inactivation of native microbial flora of oregano of 1.6 log cfu/g, was related to the much lower initial microbial load. The treatment had only a minor impact on the pepper seed's and oregano's color.

Hertwig et al. (2015b) studied the antimicrobial effect of two different atmospheric pressure plasma on the decontamination of whole black pepper. The naturally contaminated peppercorns inoculated with *B. subtilis* spores, *Bacillus atrophaeus* spores, and *S. enteric* were treated using a plasma jet or a microwave-driven remote plasma. Results of the direct cold atmospheric pressure plasma treatment showed a much lower inactivation, probably due to different involved inactivation mechanisms and the complex surface structure of peppercorns. The *S. enteric*, *B. subtilis* spores and *B. atrophaeus* spores were reduced to 4.1, 2.4, and 2.8 log cfu/g, respectively after 30 min remote plasma treatment, whereas, direct plasma jet did not result in equivalent inactivation levels. However, the quality parameters like color, piperince, and volatile oil content were not significantly affected.

Packaging Industry

Packaging of foods plays a very important role in the success of the industry as packaging is the main concern for the well being of the product and its marketing. Food packaging materials are aimed at serving the functions of both preserving food and protecting it from deterioration, outside contamination or damage during distribution and storage. When not stored in proper conditions, packaging materials can get contaminated with microorganisms. These contaminants are transferred to food via packages, and their growth on food can result in economic losses because of spoilage (Guillard et al. 2010).

Plasma processing is one of the innovative methods used successfully for packaging industry. Plasma-treated material provides tremendous advantages to a package. Through plasma processing, the packaging industry is becoming capable of three unique abilities: (1) To remove all unwanted *organic contaminants*, (2) Surface treating, or activating a material to gain an increased wettability quality, and (3) the deposition of substrates onto a material, adding desired new qualities. There is not a more effective method than plasma to obtain molecular cleanliness as plasma bombards the surface of a substrate, and the reactive particles within the plasma chip away and remove all organic material (Pankaj et al. 2015). The ability to maintain a lower temperature through sterilization giving companies the opportunity to easily sterilize packaging material sensitive to high heat (Muranyi et al. 2010). The limitless applications of plasma, through low heat and aggressive speed, give the packaging industry the ability to continue to grow immensely and efficiently.

The plasma mechanisms based gas composition, chemical radicals as well as charged particles enable a fast and efficient inactivation of biomolecules like microorganisms or toxins on surfaces. Because of their low temperature, optimized gas plasmas are suitable for the treatment of heat-sensitive polymers like polyethylene or polystyrene. Lei et al. (2014) evaluated the effect of atmospheric pressure plasma on polyethylene terephthalate/polypropylene films. Results showed that the surface hydrophilicity and roughness of films increased after the plasma treatment. In addition, antimicrobial activities of the films against three kinds of microorganisms (*S. aureus*, *B. subtilis*, and *E. coli*) were investigated and the results indicated that the inhibition ratios against *B. subtilis* and *E. coli*

reached almost 100 % while the inhibition ratios against *S. aureus* were lower than 85 %.

Lee et al. (2015b) investigated the effect of low-pressure glow discharge plasma on the surface decontamination of the common food packaging materials including glass, polyethylene, polypropylene, nylon, and paper foil. Plasma was generated over a vacuum pressure range of 0.5 to 5.0 Torr, and at a power density range of 12.4 to 54.1 mW/cm^3. Compared to plasma-unexposed surfaces, no significant changes in optical properties, color characteristics, surface temperatures, tensile strengths, and deformation strains were observed with plasma-exposed surfaces. On plasma exposure of food pathogens loaded packaging materials surfaces, as high as 4 log cfu/g reduction (99.99 %) in viable cell counts of tested food pathogens, especially *E. coli* O157:H7 and *S. aureus*, was observed within 5 min.

Plasma processing also induced changes in the biodegradable packaging polymers. Pankaj et al. (2015) studied the effect of DBD atmospheric air plasma treatment in high amylose corn starch films. Plasma treatment significantly increased the surface roughness of starch films. Thermal degradation profiles of all the starch films were similar, although a decrease in the maximum degradation temperature was observed after plasma treatment. X-ray photoelectron spectroscopy and Fourier transform infrared spectra confirmed the increase in surface oxygen content and appearance of new O═C–O groups on the film surface after plasma treatment at 70 and 80 kV for 5 min. X-ray diffraction showed the A-type crystal pattern which was not affected by plasma treatment. Surface hydrophilicity was also found higher after cold treatment. However, no significant change was observed in the water vapor permeability of starch films.

Cold plasma treatments are used for sterilization of polyethylene terephthalate, polystyrene, as well as multi-layer packaging material (Muranyi et al. 2008). The relative gas humidity was increased and as a key factor to achieve a minimum of 2 log cfu/g inactivation in *Aspergillus niger* and *B. subtilis* for 1-s treatments. Damage to the DNA of *B. atrophaeus* endospores and vegetative cells as a consequence of synergistic combination of UV radiation and direct plasma from cascaded DBD has also been reported (Muranyi et al. 2010). This treatment combination suggests effective sterilization with very short treatment times, whereby changes in packaging materials are restricted and functionality remains uncompromised.

Yun et al. (2010) investigated the effect of atmospheric pressure plasma on *L. monocytogenes* inoculated onto disposable food containers including disposable plastic trays, aluminum foil and paper cups. The parameters considered in plasma processing were input power (75, 100, 125, and 150 W) and exposure time (60, 90, and 120 s). The bacterial reduction in the disposable plastic trays, aluminum foil, and paper cups was associated with increased input power and exposure time of atmospheric pressure plasma. The D_{10} values were calculated as 49.3, 47.7, 36.2, and 17.9 s in disposable plastic trays, 133, 111, 76.9, and 31.6 s in aluminum foil and 526, 65.8, 51.8, and 41.7 s in paper cups at 75, 100, 125, and 150 W of input power, respectively. There were no viable cells detected after 90 and 120 s of plasma treatment at 150 W in disposable plastic trays. However, only three decimal reductions of viable cells were achieved in aluminum foil and paper cups at 150 W for 120 s. These results demonstrate that atmospheric pressure plasma treatment is effective for inactivation of *L. monocytogenes* and applicable for disposable food containers.

Microbial Effect

Considerable research has been performed on the mechanism of microbial inactivation by plasma agents. The plasma agents contribute to the lethal action by interacting with the biological material. Plasma treatment effectively inactivates a wide range of microorganisms including spores (Lee et al. 2006) and viruses (Terrier et al. 2009) (Table 2).

The reactive species in plasma, such as O•, O_2, OH•, NO•, NO_2, etc. have been widely associated to the direct oxidative effects on the outer surface of microbial cells. Reactive oxygen species are assumed to affect significantly the membrane lipids due to their location along the surface of bacterial cell, by allowing them to be bombarded by these strong oxidizing agents (Scholtz et al. 2015). Proteins of cells and spores are equally vulnerable to the action of these species, causing denaturation and cell leakage. Oxidation of amino acids and nucleic acids may also cause changes that result in microbial death or injury (Guo et al. 2015). Microorganisms in plasma are exposed to an intense bombardment by the radicals most likely provoking surface lesions that the living cell cannot repair sufficiently faster. This may partially explain the observations wherein cells are in many cases destroyed very quickly (Hayashi et al. 2013) (Fig. 2). The morphological changes in *E. coli* cells treated with atmospheric plasma at 75 W for 2 min as observed under an electron microscope by Hong et al. (2009). The results revealed that the treated cells had severe cytoplasmic deformations and leakage of bacterial chromosome. These observations demonstrate the loss of viability of bacterial cells after plasma treatment.

Van Bokhorst-van de Veen et al. (2015) studied the biocidal effect by nitrogen cold atmospheric plasma for chemical (hypochlorite and hydrogen peroxide), physical (UV) and heat-resistant spores. The three different spore formers used were *Bacillus cereus*, and *B. atrophaeus*, and *Geobacillus stearothermophilus* that were used as biological indicators for validation of chemical sterilization and thermal processes, respectively. The different spores showed variation in their degree of inactivation by applied heat, hypochlorite, hydrogen peroxide, and UV treatments, whereas similar inactivation

Table 2 Recent studies on the microbial inactivation by plasma technology

Sample	Plasma source	Process gas	Microorganism	Log reduction	Reference
Almond	Dielectric barrier discharge	Air	*E. coli*	5	Deng et al. (2006)
Cantaloupe rind	Dielectric barrier discharge	Air	*Salmonella*	3	Critzer et al. (2007)
Apples	Gliding arc	Oxygen	*E. coli*	3.7	Niemira and Sites (2008)
Mango and melon skin	Atmospheric plasma jet	Helium + oxygen	*G. liquefaciens*, *P. agglomerans*, *S. cerevisiae*, *E. coli*	3	Perni et al. (2008)
Grains	Cold plasma	Oxygen	*A. parasiticus*	3	Selcuk et al. (2008)
Sliced pressed ham	Dielectric barrier discharge	Helium	*L. monocytogenes*	8	Song et al. (2009)
Egg shell	Resistive barrier discharge plasma	Air	*S. enteritidis*	4.5	Ragni et al. (2010)
Chicken meat	Plasma jet	Helium + oxygen	*L. innocua*	3.3	Noriega et al. (2011)
Bacon	Radio frequency glow discharge	Helium + oxygen	*L. monocytogenes*, *E. coli*	2.6	Kim et al. (2011)
Orange juice	Dielectric barrier discharge	Air	*S. aureus*, *E. coli*	5	Shi et al. (2011)
Cooked chicken breast	Plasma jet	Nitrogen + oxygen	*L. monocytogenes*	4.73	Lee et al. (2011)
Chicken breast	Dielectric barrier discharge	Air	*Campylobacter jejuni*	2.45	Dirks et al. (2012)
Ready-to-eat meat product (bresaola)	Dielectric barrier discharge	Air	*L. innocua*	1.6	Rod et al. (2012)
Strawberry	Cold oxygen plasma	Nitrogen	*S. typhimurium*	1.76	Fernandez et al. (2013)
Romaine lettuce	Corona discharge	Argon	*E. coli*	1.6	Bermudez-Aguirre et al. (2013)
Lettuce	Plasma jet	Nitrogen	*S. enteric*	2.72	Fernandez et al. (2013)
Spinach, lettuce, tomato and potato	low-pressure oxygen plasma	Oxygen	*S. enteric*, *S. typhimurium*	3.4	Zhang et al. (2013)
Brown rice cereal bar	Plasma jet	Argon	*A. flavus*	4	Suhem et al. (2013)
Apple juice	Cold plasma	Argon + oxygen	*Citrobacter freundii*	5	Surowsky et al. (2013)
Strawberry	Dielectric barrier discharge	Humid air	*Yeast/molds*	3	Misra et al. (2014b)
Seed grains	Surface microdischarge plasma	Air	*Natural flora*	2	Mitra et al. (2014)
Tomatoes	Dielectric barrier discharge	Air	*S. typhimurium*	3.8	Ziuzina et al. (2014)
Lettuce	Cold oxygen plasma	Oxygen	*S. typhimurium*	5	Jahid et al. (2015)
Corn salad	Plasma jet	Argon + oxygen	*E. coli*	2.75	Baier et al. (2015)
Blueberries	Atmospheric cold plasma	Air	Aerobic microbes	2	Lacombe et al. (2015)
Cabbage, lettuce and dried figs	Cold plasma treatment	Helium + oxygen	*S. typhimurium*, *L. monocytogenes*	2	Lee et al. (2015a)
Apple, strawberry, lettuce, carrot	Microwave processed plasma air	Air	*C. freundii*	6	Schnabel et al. (2015)

results were obtained with the different spores treated with nitrogen plasma. *G. stearothermophilus* spores displayed high resistance to heat, hypochlorite, hydrogen peroxide, while for UV treatment *B. atrophaeus* spores are most tolerant. Scanning electron microscopy analysis revealed distinct morphological changes for plasma-treated *B. cereus* spores including etching effects and the appearance of rough spore surfaces, whereas morphology of spores treated with heat or disinfectants showed no such changes. Furthermore, microscopy analysis revealed plasma-exposed *B. cereus* spores to turn phase gray conceivably because of water influx indicating damage of the spores, a phenomenon that was not observed for non-treated spores.

Maeda et al. (2015) investigated the effect of N_2 gas plasma, generated by applying a short high-voltage pulse using a static induction thyristor power supply (1.5 k pulse per second), exhibited a bactericidal/disinfecting effect against *Salmonella*. Viable cell number of *Salmonella* was efficiently decreased with a decimal reduction time (D value) of 0.178 min (initial slope) and 3.105 min (single-slope approximation). Plasma treatment altered the surface structure of *Salmonella*, as observed by scanning electron microscopy. Polymerase chain reaction analysis suggested that the *Salmonella* genomic DNA was damaged by the plasma treatment. Reactive chemical products (hydrogen peroxide-like chemicals), ultraviolet light and slight temperature elevations were observed during the

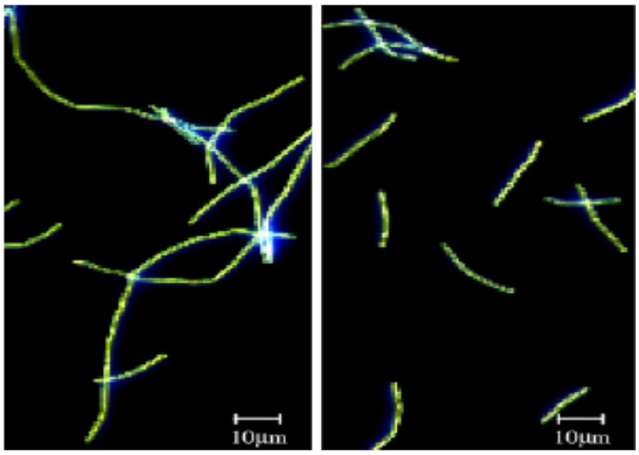

Fig. 2 Microscope images of *Bacillus thuringiensis* before (*left*) and after (*right*) the plasma treatment; Source: Hayashi et al. (2013)

operation of the gas plasma device. The results suggested the N_2 gas plasma generates reactive chemical species that alter components of *Salmonella* such as the cell surface as well as damaging the genomic DNA and the combined effect of these reactive species induce the cell death.

Mok et al. (2015) studied the effect of afterglow corona discharge air plasma for inactivation of common food-borne pathogens namely pathogenic *E. coli*, *S. aureus*, *S. typhimurium*, *B. cereus, L. monocytogenes,* and *Vibrio parahaemolyticus*. Corona discharge plasma was generated at an output voltage of 20 kV DC, and a frequency of 58 kHz. The centrifugal blower that provides an airflow velocity of 2.5 m/s at electrode tip level was used for generating the flowing afterglow of the plasma. Upon plasma exposure, as high as 3.5 log cfu/g (99.97 %) reduction in viable cell counts of tested food pathogens, especially *E. coli* O157:H7, was observed over a 24-h exposure. The main components of air are nitrogen and oxygen, the reactive species could be composed of reactive oxygen species and reactive nitrogen specie, involving nitrogen oxides. Possibly, the reactive chemical species of plasma are predominantly responsible for microbial inactivation.

Plasma treatment has the potential to reduce pathogens such as *E. coli* O104:H4 on the surface of fresh produce. Baier et al. (2015) studied the antibacterial efficiency of cold plasma by an atmospheric pressure plasma jet against the *Shiga* toxin-producing outbreak strain *E. coli* O104:H4. Argon was transformed into non-thermal plasma at a power input of 8 W and a gas flow of 5 L min^{-1}. At 5-mm treatment distance and 5 log cfu/g initial bacterial count, plasma reduced *E. coli* O104:H4 after 60 s by 4.6 ± 0.6 log cfu/g, *E. coli* O157:H7 after 45 s by 4.5 ± 0.6 log cfu/g, and *E. coli* DSM 1116 after 30 s by 4.4 ± 1.1 log cfu/g. On the surface of corn salad leaves, gentle plasma application at 17 mm reduced 4 log cfu/g of *E. coli* O104:H4 by 3.3 ± 1.1 log cfu/g after 2 min, whereas *E. coli* O157:H7 was inactivated by 3.2 ± 1.1 log cfu/g after 60 s.

Reineke et al. (2015) investigated the influence of argon as plasma carrier gas with admixtures of oxygen (0 to 0.34 vol.%) and nitrogen (0 to 0.3 vol.%) towards its emission intensity of UV-C light, excited OH and N_2 species and atomic oxygen. A mixture of argon, 0.135 vol.% oxygen and 0.2 vol.% nitrogen emitted four-fold more UV photons than pure argon. However, sporicidal effects on *B. atrophaeus* (3.1 log cfu/g) and *B. subtilis* spores (2.4 log cfu/g) were found for pure argon plasma, which were similar as compared to the sporicidal effect of the plasma with highest UV emission. To distinguish lethal effects caused by emitted UV-light and reactive species, UV-sensitive mutant spore strains (PS578 and FB122) were exposed to plasmas with different UV emission intensities and a significant impact of UV-light on the first phase of spore inactivation was confirmed. The potential sporicidal effect of this plasma was confirmed by determining inactivation kinetics of *B. atrophaeus* and *B. subtilis* spores at a distance of 15 mm. All assessed inactivation kinetics showed a biphasic inactivation with extended initial inactivation phase with increasing UV emission from the plasma. However, compared to pure argon the process gas with the highest UV emission showed a similar sporicidal effect, presumably due to higher amount of reactive oxygen, nitrogen and metastable species in the pure argon plasma expanding into the surrounding atmosphere.

Limitations

There are some limitations of plasma processing like increase in oxidation of lipids and decreases in firmness of fruits, etc. were reported. The main important problem encountered is increase in peroxide value of nuts at higher power and time of treatment (Thirumdas et al. 2014). This is may be because radicals are capable of oxidizing lipid molecules and resulted in increase in peroxide value. The plasma processing also affects the color properties of fruits. The decrease in L^*, a^*, and b^* was observed for strawberries treated with cold atmospheric plasma (Misra et al. 2014a). In addition, certain food components such as antioxidants and other nutrients might affect the efficiency of a plasma treatment, which focuses on the need for a product-specific process optimization. Another main disadvantage of this technology is that it is not possible to be used for inactivation of endogenous enzymes which are present intact in the whole fruits because plasma effect is a surface phenomenon. The plasma treatment also affected by the produce surface topography as a consequence influence the decontamination efficiency (Fernandez et al. 2013).

Conclusion

The selective adoption of emerging low temperature processing technologies to provide shelf life extension and enhanced

levels of safety for food products is the need of hour. Plasma processing of foods has gained much attention during the last decade. Plasma technology is a unique and effective non-thermal technology that minimizes the thermal effects on nutritional and sensory quality parameters of food. This technology provides high efficacy, preservation, and does not introduce toxicity to the medium. The behavior of the plasma is influenced by the feed gas used, the applied voltages, plasma generation, type of food material, and interaction with the food, etc. Plasma technology showed novel and promising applications in various areas of food industry viz., cereal processing, fruit and vegetable processing, dairy processing, meat and poultry processing, etc. This technology also modifies the food and packaging materials for the desirable treat and fulfills the need of industry.

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