**Cold Plasma Technology in Food Processing**

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**ABSTRACT**

*Increased agricultural food production and the subsequent preservation of yielded food are matters of grave importance to all humanity. Cold plasma (CP) technology has proven very effective as an alternative tool for food decontamination and shelf-life extension. The impact of CP on food quality is very crucial for its acceptance as an alternative food processing technology. Due to the non-thermal nature, CP treatments have shown no or minimal impacts on the physical, chemical, nutritional and sensory attributes of various products. Microorganisms and pathogens that cause spoilage are a major problem concerning the food processing industries as they have an unfavorable impact on the health and economy of the public. To eliminate various microorganisms, pathogens and spores, thermal inactivation techniques are practiced such as pasteurization, autoclaving, ohmic heating, canning and steam sterilization. All these methods are effective and efficient; however, they possess numerous side effects viz. nutritional loss, effect sensory properties and degrade functional properties of the food. Thermal processing of food has been in use for more than two centuries and is still the major food processing technique used in the food industries. The use of severe heat leads to undesirable effects such as change in color, texture, loss of nutrients etc. CP’s inactivation of pathogenic and spoilage microorganisms could result in minimally processed, safe food products with extended shelf-life. However, most of the published research has been focused on microbial decontamination, with limited studies on the impact of CP processing on quality attributes.*

Food has long been associated with numerous food borne diseases. Food safety is one of the major concerns prevailing for the food industries, regulatory bodies and customers. Pathogenic microorganisms are a major hassle concerning the food processing industries as they have an unfavorable impact on the health and economy of the public (**Afshan and Hosseini, 2012**). Techniques including pasteurization, autoclaving, canning and steam sterilization are used to eliminate pathogenic microbes. However, they possess several side effects viz. nutritional loss, effect sensory properties and degrade functional properties of the food. To overcome these side effects various cold processing techniques have been introduced (**Yun *et al.,* 2010**).

Food processing technologies have come a long way with developments evolving from application/deprivation of heat, utilization of microorganisms, natural and chemical preservatives, and application of electromagnetic fields for preservation. Of the several food preservation processes that humankind has developed over the centuries, canning holds a distinct place. This technology has stood the test of times, supported humanity during times of peace as well as wars, and remains widely used in the food industry. With the revolution brought by introduction of polymers in the twentieth century, canning branched into retort pouch technology and gained even more popularity (**Misra *et al.,* 2017**). Plasma is an ensemble of several excited atomic, molecular, ionic, and radical species, co-existing with numerous others, including electrons, positive and negative ions, free radicals, gas atoms, molecules in the ground or excited state, quanta of electromagnetic radiation (UV photons and visible light) (**Misra *et al.,* 2018**).

**Plasma**

Plasma is the ionized gas, a collection of ions, electrons and high energy species, capable to initiates chemical reactions. This was first discovered by a physicist **Irving Langmuir**, in year **1928**. On the basis of the ionization degree of the gas ranging from 100 % (fully ionized) to very low values (partially ionized), the term plasma is classified as thermal and nonthermal plasma. In thermal plasma, all the species present in the gas, e.g. the electrons and ions, have the same temperature ranging from 4000 K to 20000 K. On the other hand, the non-thermal (cold plasma) is produced using less power and the electron temperature is much higher than that of the bulk molecules present inside the gas (**Bogaerts *et al.,* 2002; Jiang *et al.,* 2014)**. The presence of these high energy species, capable of generating the chemical reaction is one way to introduce the advanced oxidation process (AOP), inside the process. Especially, the cold plasma is of much interest in food industry due to its lower temperature **(Jovicic *et al.,* 2017)**.

Non-equilibrium plasmas are indispensable in many industrial applications including material processing, electronics **(Takayoshi *et al.,* 2016)**, and polymer processing. Within recent years, the field of cold plasma applications has rapidly expanded into treatment of biomedical devices and biological materials **(Miyamoto *et al.,* 2016)**, including foods **(Ishikawa and Hori, 2014)**. Cold plasma technology, which has recently drawn considerable attention of food scientists and researchers, shows potential for inactivation of a range of micro-organisms and enzymes **(Ishikawa *et al.,* 2012)**. Besides decontamination, cold plasma obtained at atmospheric pressure has also shown promising potential for a number of innovative applications including surface hydrophobicity enhancement in biscuits **(Misra, Sullivan, *et al.,* 2014)**, modification of dough rheology and mixing properties **(Misra, Kaur, *et al.*, 2015)**, modulation of whey protein functionality **(Segat, Misra, Cullen, and Innocente, 2016)**, technological performance of rice flour **(Pal, *et al.,* 2016)**, enhancement of food grain (seed) germination **(Chen, *et al.,* 2016)**, and enhancement of mass transfer **(Kodama, Thawatchaipracha, and Sekiguchi, 2014)**.

Plasma is an ensemble of several excited atomic, molecular, ionic, and radical species, co-existing with numerous others, including electrons, positive and negative ions, free radicals, gas atoms, molecules in the ground or excited state, quanta of electromagnetic radiation (UV photons and visible light) **(Misra *et al.,* 2018)**. The ionization of a given gas can be established via application of thermal energy (heating) or electromagnetic fields (electric field or high energy light). For technological applications of plasmas at room-temperature and under atmospheric pressure conditions, application of electric field is the most popular method. We will confine this review to a discussion of cold plasmas operating at atmospheric pressure. In the context of cold plasma technology, the term “cold” is often debatable. Herein, cold does not refer to sub-zero temperatures; nor is there any convention with regards to the temperature range. However, it is informally known that plasma sources operating at near ambient to under 60˚C can be considered as cold plasmas. From the perspective of physicists, the term cold implies a lower temperature of the heavy species (ions, radicals, neutrals) as compared to electrons in the ionized gas. This thermodynamic non-equilibrium between electrons and heavy species is a direct consequence of the asymmetric momentum transfer during collisions under the influence of an electrical potential difference **(Misra *et al.,* 2018)**.

**Cold Plasma Technology**

Cold plasma technology is a modern non-conventional technique that uses energetic, reactive gases to inactivate contaminating microbes on meats, poultry, fruits, and vegetables. It is an eco-friendly process which is used in the preservation of food and other potential applications as an alternative to common techniques. This technology is the prime consideration in food processing industries viz. post-harvest, meat, packaging etc. Cold plasma plays an important role in decontamination of food and packaging materials from microorganisms, manufacturing of packaging materials, active packaging and retards browning reactions (**Salim *et al.,* 2018).**

Cold plasma kills bacteria better than antibiotics (**Laroussi, 2009; Fridman *et al.,* 2008)**. When treating wounds with cold plasma, a wide range of nutrients (NO, O3, OH-, O2-, H2O2, UV-radiation), that destroy pathogenic microorganisms and toxic substances that are products of their life, are created. It has now been clinically proven that cold plasma is an effective means of inactivating microorganisms, so it is used to disinfect wounds and sterilize medical instruments.

A very large overview of the medical applications of cold plasma is given in (**Han, 2013)**, and the bibliography (which mainly refers to medical articles about the results of cold plasma therapy) has more than 300 titles. Clinics of Western Europe (first of all Germany, Italy and France) and the USA are the main consumers of therapeutic devices using cold plasma. The variety of areas of cold plasma use in medicine determines the need for various constructive solutions for cold plasma generators. The «universal» plasma generator cannot be, but there is and will always be necessary for highly specialized plasma equipment (**Isbary, *et al.,* 2013)**.

The foods may be contaminated by different microorganisms or can undergo deterioration from natural food enzymes. The pathogenic and spoilage microorganisms are problematic in the food industry due to their significant public health risks and economic impact **(Stoica *et al.,* 2011; Afshari and Hosseini, 2014)**. Therefore, in the food industry, the control of undesirable microorganisms is essential and decisive **(Stoica *et al.,* 2011)**. There are a lot of methods to destroy these microorganisms, such as: thermal echnologies, *e.g.* sterilization, pasteurization, ohmic heating, *etc.* **(Afshari and Hosseini, 2014)** and non-thermal technologies, *e.g.* high hydrostatic pressure, pulsed electric fields, high voltage arc discharge **(Stoica *et al.,* 2011; Stoica *et al.,* 2013; Afshari and Hosseini, 2014)**.

**Generation of Cold Plasma (CP)**

 Plasma is a term which refers to the fully ionized gas composed of various substances such as photons and free electrons, along with atoms in excited state having a neutral charge. Plasma has a net charge of zero due to its equal number of positive and negative ions **(Kudra and Majumdar, 2009)**. Plasma consists of two types of species, light (photons) and heavy (all the other constituents). For retaining such particular property, it is regarded as plasma is regarded as the fourth state of matter which starts from solid to liquid state, liquid to gas and finally to plasma **(Misra *et al.,* 2011)**.

 Cold plasma discharges can be generated with stationary and pulsed (DC) and alternating (AC) electrical fields. Various electrical power supplies can be used to generate the cold plasma discharges such as pulsed (DC), Inductively Coupled Plasma (ICP) and Capacitive Coupled Plasma (CCP). Besides, nowadays, many researchers are attempting to develop the configuration of atmospheric pressure plasma discharges such as Arc Discharge, Corona Discharge, Dielectric Barrier Discharge (DBD), Uniform DBD, and Atmospheric Pressure Plasma Jet (APPJ) (**Zainal *et al.,* 2015**).

Cold plasmas, including low pressure DC and RF discharges (silent discharges), discharges from fluorescent (e.g., neon) illuminating tubes, DBDs may be found both at low pressure or atmospheric pressure (**Kylian *et al.,* 2009**). The dielectric barrier discharges (DBDs) are historically refered to as „silent discharges‟. They also operate at approximately atmospheric pressure (typically 0.1–1 atm). An A.C. voltage with amplitude of 1–100 kV and a frequency of a few Hz to MHz is applied to the discharge, and a dielectric layer (made of glass, quartz, ceramic material or polymers) is again placed between the electrodes. When a potential difference is applied between cathode and anode, a continuous current will flow through the discharge; giving rise to direct current (D.C) glow discharge. Capacitively coupled (CC) radio-frequency (RF) discharges are produced whilst alternating voltage is applied between the two electrodes, in order that each electrode will act alternately as the cathode and anode. The frequencies usually used for those alternating voltages are typically in the radiofrequency (RF) range (1 kHz– 103 MHz; with a most common value of 13.56 MHz). Non thermal gas discharges at atmospheric pressure are of interest for the food industries as they don‟t subject the food system to extreme conditions (**Salim *et al.,* 2018**). The characteristics of various cold plasma generators (**Zainal *et al.,* 2015**) given in Table 2**.**

**Fig. 1: Generation of Plasma (Mishra *et al.,* 2016)**

**Table 2: The characteristics of various cold plasma generators** (**Zainal *et al.,* 2015**)

|  |  |
| --- | --- |
| **Generator** | **Characteristics** |
| Pulsed (DC) | Plasma generated within fluorescent light tubes. It is used in material processing and manufacturing to modify ion energies, in sputter sources like magnetrons, and for physical mechanism of surface modification. It is simple in geometry, easy to generate, complex in structure and also has a voltage-current characteristics.  |
| Capacitively Coupled Plasma (CCP)  | Similar to glow discharge plasmas, but instead of a DC or low frequency electric fields, it is generated with high frequency RF electric fields, typically 13.56 MHz. It is widely used in micro fabrication and integrated circuit (IC) manufacturing industries.  |
| Inductively Coupled Plasma (ICP)  | Similar to CCP and has similar applications, but the electrodes consist of a coil wrapped around the discharge volume, which inductively excites the plasma. ICP has slightly more advantages compared to CCP, as CCP is less intense (low ion density and low ion energy).  |
| Arc Discharge  | High power thermal discharges, having very high gas temperature of approximately 10 000 K. The discharge is sustained by thermionic emissions, which can be generated by various power supplies. Commonly used in metallurgical application.  |
| Corona Discharge  | Non-thermal discharge generated by the application of high voltage to sharp electrode tips. The sharp tip creates an electric field sufficient for breakdown only in the vicinity of the tip, the remaining region of discharge gap remain dark. Coronas are very weak discharges, having very low electron and ion densities and are commonly used in ozone generators and particle precipitators.  |
| Dielectric Barrier Discharge (DBD)  | Dielectric barrier discharge is non-thermal in nature and is generated by the application of high voltages across small gaps wherein a non-conducting coating prevents the transition of the plasma discharge into a self-sustained glow or arc. Breakdown occurs in the form of streamers and charges build up on the electrodes during the discharge. A low frequency AC field <100 kHz is used to cycle the discharge and maintain it. They are widely used in the treatment of fabrics in roll to roll configuration. |
| Atmospheric Pressure Plasma Jet (APPJ)  | The atmospheric pressure plasma jet (APPJ) is a type of RF CCP plasma discharge operated at atmospheric pressure. In the APPJ the systems are stabilized by operation in helium or argon gases. The atomic noble gas operation makes it significantly easier to maintain the non-equilibrium system. Such systems can be stably operated in ‘*normal*’ and ‘*abnormal*’ modes in pure helium. However, only a very minor faction of precursor gases can be added.  |

**Principle and Mechanisms of Plasma Technology**

Basically, plasma is generated through applying energy to a gas mixture using mechanical, thermal, chemical and radiant energy, causing the ionization of the gas (low or atmospheric) and generation of active species viz., electrons, free radicals, ions, etc. (**Pignata *et al.* 2014**). Various types of apparatus are used for the generation of cold plasma such as dielectric barrier discharges, corona glow discharges, gliding arc discharges, radio frequencies, atmospheric glow discharges, inductively coupled plasmas and microwave-induced plasmas (**Conrads and Schmidt 2000; Guo *et al.,* 2015**).

**Types of Cold Plasma**

Cold plasma is being generated through a wide array of technologies that could operate at atmospheric pressure or under partial vacuum conditions. The source of energy source could be electricity, lasers, or microwave radiations while the ionizing gas could be normal air/nitrogen or it could be any synthesized noble gas mixture. This kind of flexibility in choosing the power sources and ionizing gas media permits steady design of novel kinds of cold plasma systems. The classification of the cold plasma was done on the basis of distance between the plasma generation field and the product exposure area, that is, the product is located far away from the plasma generation field, closer to the plasma generation field, or within the cold plasma generation field. These categories are actually made on the basis of plasma chemistry, reactivity of the charged active species, and their half-life within the plasma. However, the cold plasma systems intended for food disinfection and processing falls under one of the three types of cold plasma **(Niemira and Gutsol, 2011)**.

**Remote Cold Plasma System:** In this method, the cold plasma is generated at a point and moved to the surface to be treated. The generated cold plasma is carried from the point of generation to the place of action, most commonly with the flow of feed gas and at times by using the magnetic fields. This kind of cold plasma has the specific advantage of placing the products to be treated at a remote point away from the point of generation thus simplifying the fabrication cum operation and improving the flexibility of shapes cum sizes of the objects to be treated **(Chirokov *et al.,* 2005)**. Major limitation with this kind of cold plasma is that the free electrons generated at the source point would react with other charged atomic species during the time of flight resulting in the formation of secondary chemical species with poor reactivity and longer half-life periods (Gadri *et al.,* 2000). The concentration of the reactive ions decrease by the time quench plasma moves to the target place. The ions present in this afterglow plasma are known to produce UV radiation for the activation of chemical species upon reaction with the target but their concentration was much less compared to the active plasma assisted by the electric field **(Fridman and Kennedy, 2004)**.

**Direct Cold Plasma System:** In the direct system, the point of cold plasma generation and the object to be treated stay relatively closer compared to the remote cold plasma system. This system provides greater concentrations of active ions for target treatment as they are used relatively fast before they get recombined and/or lost **(Laroussi and Lu, 2005)**. These kinds of plasma systems operate in pulsed mode and generate pulse frequencies in the range of hundreds and thousands of times per second. Since, the relative distance between the source of plasma generation and the target objects is less, the intensity of UV radiation produced through recombination is relatively more on the target object. The commodities with greater internal moisture/water activity could conduct high-voltage electricity resulting in localized heating and thus causing subtle changes in the sensory properties of the food products. Hence, these cold plasma systems should be designed with precise specifications in order to avoid flow of concentrated high voltages through the product, thereby saving them from heat damage. Thus these direct systems are relatively challenging for fabrication as well as operation compared to the remote cold plasma systems. However, these kinds of plasma systems are flexible for target shape and size based on the kind of emitter but it may have potential limits for the types of products being suitable for such treatment.

**Electrode Contact System:** In this cold plasma system, the target object to be sterilized is placed physically between the electrodes, that is, within the area of cold plasma generation. Under this system, the objects are exposed to the broadest combination of active plasma components, that is, at highest possible intensity of charged ions, free radicals, electrons, and UV radiation **(Fridman *et al.,* 2006)**. Sufficient care must be taken during fabrication of these plasma systems to match the shape and composition of electrodes with the target commodity to be sterilized for avoidance of point discharges and localized heating issues **(Niemira and Gutsol, 2011)**. Though the space between the electrodes act as the physical constraint in this system, the flexibility in changing the feeder gas composition and design of one/both the electrodes allows certain kinds of target objects that could physically fit into the space between these electrodes **(Gadri *et al.,* 2000)**. These kinds of cold plasma systems are best suited for smaller or flatter objects, viz., seeds, berries, nuts, etc.

**Applications of cold plasma**

Cold plasma can be successfully used for microbial destruction on fresh products to increase shelf life. **Feichtinger *et al.,* (2003)** reported cold plasma technology as alternative source for surface sterilization and disinfection process which can act on both vegetative cells and spores with shorter periods of time. The chemical composition of plasma contains free radicals, highly reactive species and radiations are often generated in varying range from UV to visible. It is believed that the role of different constituent depends on the gas and operating pressure. The destruction of microbial DNA by UV irradiation, volatilization of compounds from spore, so-called “etching” of the spore surface by adsorption is because of reactive species like free radicals **(Philip *et al.,* 2002)**. Potential application in food NTP has been applied in the food industry including decontamination of raw agricultural products (Golden Delicious apple, lettuce, almond, mangoes, and melon), egg surface and real food system (cooked meat, cheese). **Pasquali *et al.,* (2016)** reported the effect of cold plasma on red chicory (*Cichorium intybus*) treated with atmospheric cold plasma kept at a difference of 70 mm from discharge. The conditions were kept stable with a temperature of 22°C and 60% RH, only treatment time varied for 15 and 30 min. The load of E. coli and L. monocytogenes at the initial stage was 108cfu/ml and 1.2 x 108 to 1.6 x 108cfu/ml respectively, treated for 15 min and 30 min, respectively. In 15 min of atmospheric cold plasma treatment E. coli reduced to 1.35 log MPN/cm2 whereas, L. monocytogenes took 30 min to have a final load of 2 log cfu/ml.



**Fig. 1: Applications of cold plasma for increasing food safety and quality.**

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**Fig. 2: Applications of plasma for increasing food preservation.**

**Table 1: Applications of Cold Plasma** (**Zainal *et al.,* 2015**)

|  |  |  |
| --- | --- | --- |
| **Sectors**  | **Impact of plasma** | **Reference** |
| Enhance Mechanical properties  | 1. Improve mechanical properties of ceramic fibres tensile system.
2. Improve tensile strength, stress of jute fibre/Poly (lactic acid) biodegradable composites.
 | (Xiem *et al.,* 2009)(Nam Gibeop *et al.,* 2013; Jung, 2013) |
| Improve adhesion  | 1. Improve adhesion of Polymer-Polyethylene, Polypropylene, Polystyrene and Poly (ethylene terephthalate).
2. Packaging surface treatment on wetting and adhesion.
3. Improve adhesion of polymers for good packaging.
 | (Dixon and Meenan, 2012; Borcia *et al.,* 2011)(Wolf and Sparavigna, 2010)(Pankaj *et al.,* 2014) |
| Treatment | 1. Decontamination of strawberries.
2. Treatment on recycle paper-hydrophobic to hydrophilic.
3. Improve fertilization and irrigation of germination.
4. Increase viscoelasticity, Strength of the dough.
5. Softening cotton and reduce felting of wool.
6. Create water repellent on wood.
7. Water, air, food, and drink treatment.
 | (Misra *et al.,* 2014)(Gaiolas *et al.,* 2012)(Jiang *et al.,* 2014)(Misra, Kaur *et al.,* 2014)(Sparavigna, 2008)(Podgorski *et al.,* 2002)(Niemira, 2011; Redzuan, 2010; Yarahmadi *et al.,* 2011) |
| Biology and Medicine | 1. Can Ablate some cancer cells (Lung, Melanoma, head and neck, brain and bladder)
2. Clean and sterilize infected tissue in a dental cavity or on root channel.
3. Treatment of Infectious skin diseases and wound healing.
4. Deactivation of Biofilims –S- Mutans Bacteria- E. Coli.
5. Tooth Bleaching.
6. Instrument sterilization – Dental Instruments.
7. Activation of p23 protein.
8. Activation of p21 CDK inhibitor.
9. Treatment of chronic Venous Leg Ulcers.
10. Reducing bacterial and Fungal Species
 | (Keidar *et al.,* 2013)(Geyter and Morent, 2012)(Heinlin *et al.,* 2011)(Hoffmann *et al.,* 2013) (Emmert *et al*., 2012)(Daeschlein *et al.,* 2012) |

**Cold Plasma Technology in Food Sectors**

Cold plasma technology shows promising dimensions for various sectors of food processing.

**Grain science and processing sector**

Food grains and legumes were investigated for *Aspergillus spp.* and *Penicillum spp.* before and after treatment with plasma products showed significant log reduction after exposure for 15min **(Selcuk *et al*, 2008)**. Depending upon the method of generation, treatment time and type of starch present in the food grains, cold plasma species are able to alter the starch properties. Cold plasma reactive species acts on food grains and causes surface modification, molecular degradation/granular etching or corrosion. Application of cold plasma was effectively studied on various food grain starches such as banana starch, Rice starch, zein, pea protein isolates, Brown rice and Basmati rice to improve its functional properties by surface and molecular modification of starch (**Ezeh *et al*., 2018**). CP helps in improving the swelling capacity, decreasing the cooking temperature, pasting viscosity, water solubility and water holding capability of food grains. When oxygen containing cold plasma are used for food rich in fats it may induce lipid oxidation and reduce the acceptability **(Gavahian *et al*, 2018)**. Plasma when treated on banana starch at different voltages (30kV, 40kV, 50kV) for 3min time interval, it does not show any changes in the level of resistant starch and amylose content but increased the relative crystallinity and gelatinization temperature. Hence it was concluded that plasma could be a righteous tool to modify the characteristics of banana starch and other types of starches **(Wu *et al*., 2018)**. Bacterial counts of *Bacillus cereus*, *Bacillus subtilis* and *E. Coli* were tested on brown rice using plasma. High antioxidant activity were observed on brown rice when treated with plasma and that could probably increase the nutritional value of the consumer **(Chen *et al*., 2016)**.

**Food packaging**

Currently, CP treatments are utilised for the food packaging and biofilms treatments to enhance its antimicrobial and mechanical properties. It is proved that when plasma products acts on food packages it causes the surface functional group activation/addition or surface energies production to make positive impact on the various packaging properties include glazing, sealability, moisture/gas barrier property etc. It is considered to be reliable and cost effective technology **(Rajvanshi, 2008)**. Whether labeling jam jars, printing on glass containers, or sealing liquid packaging, a key factor in the packaging industry is the ability to process materials reliably and at low cost. Pretreatment with atmospheric-pressure plasma makes it possible to process different materials and coatings that are sometimes very thin, for example, in the production of composite packaging. In labeling glass bottles, atmospheric-pressure plasma is employed for pretreating glass. This allows the use of a universal and low-cost water-based adhesive **(Mishra *et al.,* 2016).** Originally cold plasma technology was employed for improving the surface modification and printability for packaging materials. The in-package plasma technology for foods relies on the use of polymeric package itself as a dielectric layer and has been studied using several packaging materials such as LDPE (low density polyethylene), HDPE (high density polyethylene), polystyrene (PS), Tygon etc**. (Keener, *et al.,* 2012)**. Herein, the packaging material is an integral part of the treatment step, being exposed to the plasma discharge. The exposure of the surface of packaging material to the reactive plasma species ensures that the internal package surface is decontaminated. In fact, cold

plasma has been used as a tool to reduce the microbial load of package material, such as PET foils, polystyrene, LDPE, and other polymeric materials **(Mastanaiah, Banerjee, Johnson, & Roy, 2013)**.

**Animal Meat sector**

Pathogens such as L. monocytogenes, E. coli O157:H7, Campylobacter jejuni and Salmonella sp. can easily thrive on meat causing severe foodborne illness in consumers. To meet the growing demands for high quality and safe meat products, it is necessary to develop and implement advanced technologies in the meat industry. In one of well-known studies, **Jayasena, *et al.*, (2015)**. reported the inactivation of L. monocytogenes, E. coli O157:H7 and S. Typhimurium inoculated on pork-butt by 2.04 log10, 2.54 log10, and 2.68 log10 CFU/g, respectively using the SDBD insidepackage plasma configuration in air. In beef loin the counts of L. monocytogenes, E. coli and S. respectively. In meat sector, CP application was reported on beef, pork and chicken meat quality, microbial decontamination and shelf-life extension. The result states that the cold plasma species are effective against *E. coli*, salmonella species*, L.monocytogenes*, yeast and mold species on meat surface **(Rød *et al*., 2012; Misra and Jo, 2017; Lee *et al*., 2011)**. CP technology application is found to have positive effects on surface decontamination of egg shell membrane against *S. enteritidis* and *S. typhimurium* microorganism **(Ragni *et al*., 2010)**. **Jayasena, *et al.* (2015)** found minimal changes in the colour, and texture. However, they observed the malonaldehyde levels to rise for treatment times exceeding 10 min. It may be recalled that the malonaldehyde concentration is an indicator of the lipid oxidation.

**Dairy Industry**

The cold plasma has already been tested on various milk products include Whole milk, skim milk, UHT (Ultra High Temperature) milk and sliced cheese. The results of the study forecasted that cold plasma could be an alternative milk processing techniques because it is less likely affected the colour, pH, flavour and nutritional value of the milk products. It also inactivated contaminating microorganisms and alkaline phosphatase enzyme in few seconds **(Song *et al*., 2009; Coutinho *et al*., 2018)**. With the hope that a non-thermal approach to reduce the microbial load, may allow to protect the distinctive nutrients and flavor of milk, in-package cold plasma has been explored as a decontamination intervention. Whole milk inoculated with E. coli, L. monocytogenes, and S. Typhimurium, have been treated with the in-package SDBD cold plasma at 15 kHz for 10 min **(Kim *et al.,* 2015)**. The process was shown to achieve a 2 log10 -3 log10 CFU/g reduction without any significant changes in the color and lipid oxidation. A specific challenge of treating milk with cold plasma is the resulting pH fluctuations; a 10 min treatment was found to reduce the pH from 6.9 to 6.6 **(Kim *et al.,* 2015)**. Milk is rich in nutrients and therefore particularly susceptible to microbial spoilage. Raw milk is conventionally treated with thermal processes to control pathogenic microorganisms. Thermal processing to reduce the microbial load, though effective, changes the organoleptic and nutritional properties in dairy foods **(Myer *et al.,* 2016)**.

**Fruits and vegetable processing sector**

Fresh produce remains the leading cause of foodborne illness outbreaks implicating pathogens such as Shiga Toxin producing Escherichia coli, Salmonella, L. monocytogenes, among others. An effective means of controlling contamination in fresh produce is to apply post-harvest decontamination interventions that can replace or supplement the washing operation **(Murray, Wu, Shi, Jun Xue, and Warriner, 2017)**. Cold plasma treatment is said to be an ingenious technique since its replaces chlorine and water for decontamination of several fruits and vegetables. Cold plasma treatments on fruits and vegetable products includes berries, cherries, Apple, melon, Kiwi etc. were studied. Results proclaimed that CP treatments on the surface of F &V (Fruits & Vegetables) alters the pH and acidity of the food produce. This occurs when active species of plasma reacts with moisture on the surface. It is also found that the treated produce shows slight changes in texture (firmness) and colour during their storage period **(https://fstjournal.org/features/28-1/cold-plasma, 2019)**. The results were quite promising with 1.5 log10 -2 log10 reduction after 0.5 hour of treatment and up to 3-5 log10 reduction within 24 h of treatment at 12 kV for 5 min. Later, cold plasma treatment of fresh produce was shown to reduce the total aerobic microbes by up to 5 log10 in products such as tomatoes and strawberries, when using a volumetric DBD powered at 60 kV and 50 Hz frequency **(Misra, Keener, Bourke, Mosnier, & Cullen, 2014; Misra, Patil, *et al.,* 2014)**. The in-package decontamination process is particularly important for fruits, vegetables, and ready-to-eat foods **(Misra, Pankaj, *et* al., 2015; Xu, *et al.,* 2017)**; these food categories demand use of ambient temperature processes for ensuring safety, with minimal impact on product quality. The earliest study of volume DBD based in-package plasma treatment involved the treatment of spinach inoculated with E. coli O157:H7 inside a flexible package **(Klockow and Keener, 2009)**.

**Waste water (Effluent) treatment**

Phsico-chemical effects of plasma gernerates the formation of oxidizing species: radicals (H−, O−, OH−) may diffuse into the liquids and molecules (H2O2, O3, etc.), shockwave, ultraviolet light and electrohydraulic cavitation may degrade the pollutant in waste water or decomposes the pollutant into other compound **(Jiang *et al.,* 2013)**. In liquid and gas plasma can be created either directly in the liquid, or in the gas above the liquid, or, in case of hybrid rectors, both in liquid and in gas. The more efficient way which requires less energy for waste water treatment can be done by diffusing gaseous phase species into liquid (**Jiang, Zheng, Qiu, *et al.,* 2014)**. Waste water disposal is now being a major issue faced by food industry since water coming out of food industry is with high concentration of organic loads. So far various thermal, chemical and filtration techniques are used for waste water treatments. ROS (Reactive Oxygen Species) of cold plasma have been reported to cause prompt changes in the degradation or decomposition of liquid waste. UV photons produced during CP treatment causes the pyrolytic effect by electrohydraulic cavitation in an indirect manner **(Ekezie *et al*., 2017)**. Developing an innovative advanced oxidation process for treatment of waste water is a big challenge. As complete oxidation is required for the treatment of waste water and transfer of contaminants is not complete in methods like photocatalysis, ultrasonication, UV/ozone (**Reddy and Subrahmanyam, 2012)**.

**Limitations**

1. Several ROS species has limited penetration into food products.
2. It may affect the sensory and nutritional attributes of the food to some extent during processing.
3. Treatment of bulky and irregularly shaped food is difficult.
4. Restricted volume and size of the food for treatment.
5. It may accelerate lipid oxidation and causes negative impact **(Coutinho *et al*., 2018; Mandal *et al*., 2018; Niemira, 2012; Pankaj and Keener, 2017)**.

**Conclusion**

Cold plasma has proved to be efficient in sanitizing equipment for inactivating the foodborne pathogens from fresh produce and packaging materials. It also helps in catalyzing certain manufacturing processes, acts as an active packaging and retards browning reaction in fruits and vegetables. Being a cold treatment it is effective in retaining the texture, sensory and functional properties of foods. Cold plasma is a unique technology which is responsible for microbial destruction and surface modification of substrate as conventional preservatives techniques as some detrimental effects on nutritional quality. Plasma sterilization provides high efficacy, preservation and does not introduce toxicity to the medium. The most important is to select (choosing) some particular gases which already possess germicidal properties so that the efficiency of plasma sterilization can be increased. The cold plasma techniques are preservation treatments that are effective at ambient temperatures, thereby minimum thermal effects on nutritional and sensory quality parameters of food with no chemical residues. The cold plasma technology has been evaluated on bacteria (positive and negative), molds, yeasts, spores and viruses. Cold plasma is used in minimal processing or acts as a chlorine replacer during washing for decontaminate fruits, vegetables and leafy vegetables from pathogens. Cold plasma technology is gaining fame for its unique characteristics like treatment in low or ambient temperature for a short period of time which helps in retaining the integrity and quality of food products.

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