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# Post Harvest Applications of Cold Plasma Technology: A Review

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## ABSTRACT

Plasma is the fourth state of matters which have a wide application in food processing and post harvest technology. Plasma when applied over crops has tremendous effects in improvement in the quality and other post harvest attributes. Application of cold plasma technology could effectively induce desirable changes in its overall quality and diverse physiology. The following review would discuss the application of non-thermal plasma technology to disinfect and decontaminate processed food product and fresh horticultural crops. Horticultural crops which are treated with plasma technology do not show any loss in nutrients. The packaging materials can also be sterilized by using plasma technology. Similarly, the food packed inside a package can also be sterilized without harming the package integrity. Beside that it can also be used to reduce the enzymatic activity of fresh fruits and vegetables and help to modify the food properties. Cold plasma technology can penetrate fungal biofilm and destroy resting fungal spores. This technology can also be harnessed to remove residual toxic pesticide from food products and fresh fruits and vegetables. However, the technology might sound a bit expensive but have a long future in terms of utility.


**Key words:** Cold plasma, Disinfecting food, Non-thermal plasma, Sterilization.

Cold plasma technology is also known as non-thermal plasma technology. It is a relatively new technology in terms of its application in post-harvest technology and food processing sector. Treatment of food products with cold plasma technology is very much needed for food products which are not suitable to be sterilized using heat, chemicals or other conventional processing tools. Generally high nutrient food is needed to be plasma disinfected to avoid nutrient loss (Misra *et al*., 2015).

There are some other methods of non-thermal processing techniques which include gamma irradiation, ozonation, beta irradiation, power ultrasound, UV treatment, pulsed light, pulsed electric field (PEF), high hydrostatic pressure *etc.* Most of these techniques are commercially viable and considerably economically feasible. But there are some disadvantages associated with these processes. Some methods like treatments of gamma irradiation, UV treatment and high energy electron beams are limited in practice because of economic feasibility and very high initial investment. Purely physical techniques such as high hydrostatic pressure are chemically safe but require complex equipments (Rastogi *et al.,* 2007) and its ability to work in case of fresh fruits and vegetables (Kruk *et al.,* 2009). Not all these methods are capable to microbiologically sterilize contaminated fruit and vegetables. Other modern techniques of disinfections like power ultrasound, UV treatment, pulsed light, ozonation and electric discharge are known as Advanced Oxidation Processes (Niemira *et al.,* 2008). Pulsed UV light technology have wide application in microbial inactivation and surface disinfection of packaging materials, but it demonstrates limitations due to shadowing effects in food products (Gómez-López *et al.,* 2007). However there are several methods for sterilization of fresh and processed food products but till there is no ideal technology to achieve sterilization of multiple products at ambient temperature other than non-thermal plasma (NTP) or cold plasma (Basaran *et al*., 2008; Selcuk *et al*., 2008). Hence this technology has recently drawn considerable attention of post-harvest technologists and food scientists.

Losses in fresh horticultural produce and processed food products are enormous till today. With increasing population, it is a tedious task to ensure safe and nutritionally stable food to all the population. Non-thermal plasma can significantly reduce loss and wastage of fresh and processed horticultural products, cereals, pulses, meat and dairy products. Gradually there is a shift of food habit and perception of food from just being a satire to stomach to a nutritionally balanced diet. With increasing arena of food technology, new risks are also found including micro-organism safety, changing production technologies and an increase of the global trade of food stuffs (Havelaar *et al*., 2010).

### Plasma and its properties

An American scientist 'Irving Langmuir' in the year 1928 proposed that electrons, neutrals and ions in an ionized gas

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are similar to a corpuscular material entrained in some kind of fluid medium. This entraining medium was termed as 'plasma'. But later it was found that there is actually no specific fluid medium which are entraining the electrons, neutrals and ions in an ionized gas (Bellan, 2006).

Plasma is more similar to gas than solid or liquid. Properties showed by plasma are quite different from solid, liquid and gas. When energy is supplied, matter changes its state from solid to liquid to gas and ultimately to plasma. When gases are heated sufficiently to higher energies thus that the intra-atomic and molecular structures get loosen, it breaks down resulting in the formation of free electrons and ions. Plasma is partially or solely ionized gas composed of free electrons, neutrals and ions. Plasma contains equal number of positive charge carrier and negative charge carrier and hence is neutral charged (Misra *et al*., 2011; Kudra and Mujumdar, 2009). In other words, plasma can be defined as a hot ionized gas into which if sufficient energy is provided, the electrons can be freed from atoms/molecules. In plasma both ions and electrons usually co-exist along with a cloud of active particles. This retains the imparted energy for specific time duration and then discharges it as visible/ ultraviolet (UV) light during the process of recombination. Hence plasma is often specified to as the fourth state of matter. In the universe more than 99% of visible matter is composed of plasma. Unlike gases plasma is in ionized state and hence it is a good conductor of electricity.

On the basis of relative energy levels of electrons and constituent species, plasma is either hot plasma or cold plasma. Hot plasma is also known as thermal plasma and cold plasma is known as non-thermal plasma. Hot plasma has electrons and other heavy particles at thermodynamically equilibrium stage. Hot plasmas are produced in atmospheric arcs, sparks and flames. Cold plasma or non-thermal plasma is less well ionized as compared to thermal plasma. Cold plasma is generated under atmospheric pressure (1 bar) or at vacuum when a temperature of 30-60°C is maintained. Unlike thermal plasma, non-thermal plasma is not thermodynamically equilibrium.

## Production of plasma

At earlier days, the entire plasma treatment was carried out under vacuum or low pressure condition. But now atmospheric pressure plasma system has been developed. This process is very much economical, technically feasible and industrially acceptable (Yun *et al*., 2010). The capability to produce plasma at atmospheric pressure has made the system much more industrially acceptable because of its lowered input cost (Kim *et al*., 2011).

Plasma is known to develop when inert gas comes in contact with electricity. In this entire process the charged particles, neutrons, free radicals and several radiations are generated. The whole formulation is known as plasma. The gas that can be used to generate plasma may include a single gas or a mixture of some gases. Oxygen, nitrogen, helium, argon and neon are the gases which can be used for plasma generation. However the quality depends on the type of gas or its combination used.

In case of non-thermal plasma or cold plasma, the electron temperature is much higher than that of the positive ions and neutral particles. As there is a difference in thermal equilibrium so a NTP cannot be said to be as thermodynamic equilibrium. NTP can be generated by an electric discharge in a gas at lower pressure or using microwaves. The temperature in this case should be within 30-60°C. Some common instance of plasma generation at atmospheric pressure includes the dielectric barrier discharges (DBD), corona discharge, radio-frequency plasmas (RFP) and the gliding arc discharge. In contrary, thermal plasmas are generated at higher pressures which also require high power and an almost thermal equilibrium exists between the electrons, positive ions and neutral particles. In case of post-harvest sector and food industries, non-thermal plasma (cold plasma) is needed. This is produced at atmospheric pressure (1 bar) or lower.

## Types of plasma

In the last 3 decades, there are numerous techniques that were being developed to produce non-thermal plasma. This includes radio frequency (RF), dielectric barrier discharges (DBD), corona discharges (CD), gliding arc discharges (GAD), plasma spray, plasma needle and atmospheric pressure plasma jet (Stepczynska, 2016).

### A. Radio frequency discharges (RF) plasmas

Radio-frequency discharges are obtained when gas is subjected to an oscillating electromagnetic field. The field is generated by an induction coil surrounding the reactor (inductive discharge) or by separate electrodes is arranged on the external surface of the reactor (capacitive discharge).

### B. Corona discharges (CD) plasmas

Corona discharges generated through asymmetric electrode pair, where relatively high voltage occupies the region of one electrode which exceed the breakdown strength of gas and creates weakly ionized plasma in surrounding of electrode.

### C. Dielectric barrier discharges (DBD)

DBD discharge can be produced in different mediums at high frequency and high electric discharge through ionization and produces non-equilibrium plasma at atmospheric pressure.

### D. Gliding arc discharge plasmas

The plasma is produced by injecting the gas between two electrodes and resultant generated arc at the shorter electrode distance, blown to electrodes and broken into plasma.

### E. Microplasma

Microplasma is a miniature version of plasma in which the dimensions of the plasma can range between tens, hundreds, or even thousands of micrometers in size.

Recently the micrometer range plasmas has gain much attention as it enables rapid reactive species generation at atmospheric temperature and relatively low power (1 W) consumption.

#### F. Plasma spray and plasma needle plasmas

The plasma needle is a type of non-thermal atmospheric glow discharge; it has a single electrode configuration and is operated in helium.

## Utilization of cold plasma

Non-thermal plasma technology is having multipurpose utilization potential in post-harvest technology and food technology sector. Initially the application of cold plasma technology was applicable to microbial disinfection, but now it have a wide application including the aspects discussed below:

## Disinfection/Decontamination/microbial inactivation

The efficiency of plasma to serve as a de-contaminant came to notice in the year 1968 (Menashi, 1968). It was the year 1989, when the efficacy of $O_2$ as an anti-bacterial agent was showcased (Nelson and Berger, 1989; Niemira, 2012). Later on it was found that cold plasma technology can also have lethal effect on spores (Lee *et al*., 2006) and viruses as well (Terrier *et al*., 2009).

Oxygen based plasma at pressure lower than atmosphere was found highly effective against pathogenic microbes as it causes lipid oxidation, protein denaturation and DNA alteration of microbial cells. The outer surface of the microbial cells contains unsaturated fatty lipid which gets oxidized as soon as it comes with contact to plasma (Guzel-Seydim *et al*., 2004). The oxidative species which are produced during the plasma discharge process (reactive oxygen and nitrogen species) leads to peroxidation of lipids and oxidation of proteins and DNA (Montie *et al*., 2000). Atomic oxygen is a $10^6$ stronger oxidative agent as compared to oxygen molecular. The oxidative potential of oxygen and nitrogen can be understood by understanding their reactive ionic species like $O^{\bullet}$ (singlet oxygen), $O_2$ (atomic oxygen), $O_3$ (ozone), hydroxyl (OH), hydroxyl radicals ($OH^{\bullet}$), nitric oxide ($NO^{\bullet}$), nitrogen dioxide ($NO_2$), dinitrogen pentoxide ($N_2O_5$) and UV photons (Ziuzina *et al*., 2015; Sakiyama *et al*., 2012). Lysis of cells can also take place due to oxidation of amino acids and nucleic acids (Critzer *et al*., 2007).

Not only oxidation of lipid bi-layer but the bombardment of radicals or the charged particles have significant potential to cause lysis of microbial cells. The bombardment of the radicals causes the cells to rapture (Laroussi *et al*., 2003). The cells would also get raptured due to persisting electrostatic forces on the cell membrane (Mendis *et al*. 2002). UV photons that are released during plasma treatments causes dimerization of thymine base of the DNA of the fungal cells and spores (Boudam *et al*., 2006; Misra *et al*., 2018).

In an experiment it was observed that UV-C radiation that was released during the process is one of the most effective in the inactivation of microorganisms (Roth *et al*. 2010). Another feature of this technology is the capability to have plasma treatment even inside a sealed package. This approach is referred as the “in-package plasma technology” and can be an alternative to canning and high pressure processing.

#### A. Fresh horticulture produces

The application of cold atmospheric pressure plasma (CAPP) is an innovative non-thermal technology for inactivating undesirable microorganisms which are present on food products. As this method does not promote application of heat so it can be effectively used in case of heat-sensitive products. Denaturation of desirable components including thermo labile vitamins and amino-acids are not affected. Some instances of disinfection of fresh horticulture produces are mentioned in Table 1.

#### B. Processed products

Plasma technology is also known to decontaminate processed products of horticultural crops as well. Some instances of disinfection of processed products are mentioned in Table 2.

#### C. Cereals and pulses

Non-thermal cold-plasma technology is also known to decontaminate cereals and pulses as well. Some instances of disinfection of processed products are mentioned in Table 3.

## Sterilization of packaging materials and in-package decontamination

The purpose of packaging is not only containment but also preservation and protection during handling, storage and transportation. In the entire process, packaging material can also get contaminated with pathogens. These pathogens get transferred to the produce in mean time and can spoil the food or cause serious health hazard (Turtoi and Nicolau, 2007). A salient feature of this non-thermal plasma technology is the ability to establish plasma inside a sealed package. This approach is referred to as the “in-package plasma” technology and has a striking parallelism with that of canning and HPP in that the plasma treatment is carried out inside a sealed package. Some cases of in-package decontamination are mentioned in Table 4.

Non thermal plasma technology is very much effective in decontamination of packaging materials as well. Packaging material sterilization is very important as it can ensure the stability of the stored product directly. Some findings about package sterilization of cold plasma technology is mentioned in Table 5.

#### Reducing enzymatic activities

Enzymes are naturally found in fresh fruits and vegetables. Polyphenoloxidase (PPO) and peroxidase (POD) are the two enzymes that are needed to be inhibited or inactivated so as to avoid undesirable browning reactions. The browning reaction also leads to the loss of sensorial or nutritional quality of fruits and vegetables. Some findings about

**Table 1:** Disinfection/Decontamination of fresh horticulture produces.

| Crop | Treatment details | Observations | References |
|---|---|---|---|
| **Vegetables** | | | |
| Lettuce | Nitrogen ($N_2$), Nitrogen-oxygen ($N_2$-$O_2$) and Helium (He) based cold plasma treatment (400 W and 900 W - 10 min) | •Inhibition of both *Escherichia coli* and *Salmonella Typhimurium* were observed.<br>•CPT inhibited both pathogens on lettuce by up to 2.8 log CFU/g.<br>•Non-thermal plasma technology was found improving the overall microbial stability of vegetables without significant loss of physicochemical or sensory properties | Song *et al.* (2015) |
| Cabbage | Long wavelength UV light photoplasma | •*Listeria* spp. population showed a drastic decline by 4 $\log_{10}$ cycle. | Srey *et al.* (2014) |
| Spinach | Air based cold plasma | •*E. coli* population showed a 5 $\log_{10}$ reduction. | Klockow and Keener, (2009) |
| Potato | Oxygen based radio frequency plasma | •3 $\log_{10}$ reduction of the *Salmonella* spp. Population was observed. | Zhang *et al.* (2013) |
| Carrots and cucumbers | Air based plasma micro jet<br>Air based plasma | •*Salmonella* spp. Population was reduced by 4-5 $\log_{10}$ cycle.<br>Showed a significant reduction of *Escherichia coli*, *Salmonella* sp. and *Listeria monocytogenes* | Wang *et al.* (2012)<br>Critzer *et al.* (2007) |
| Cantaloupe | (9 kv power - 6 khz frequency) | | |
| **Fruits** | | | |
| Kiwifruit (*Actinidia* sp.) | Double barrier discharge plasma (10 and 20 min) | •No significant changes in color, hardness, vitamin C and antioxidant activity of the fruits.<br>•The pigment degradation was significantly reduced over the storage. period in plasma treated samples.<br>•The overall dry matter content and organoleptic properties were better in plasma treated samples as compared to control ones. | Ramazzina *et al.* (2015) |
| Mangoes and melons | Cold atmospheric plasma (12-16 kV) | •*Escherichia coli, Saccharomyces cerevisiae, Pantoea agglomerans* and *Gluconacetobacter liquefaciens* present in pericarps of mangoes and melons showed a decline in bacterial population below safety level.<br>•The most pathogenic microbe *S. cerevisiae* was best killed when 16 kV was used. | Perni *et al.* (2008) |
| Mandarin c.v. Satsuma | Direct non-thermal plasma | 84% reduction of disease incidence due to *Penicillium italicum* when the treatment duration was 10 minutes. | Won *et al.* (2017) |
| Lemon | Non-thermal plasma | •100% inactivation of all bacterial spores and absence of colony forming units when the duration time was 20 minutes. | Hayashi *et al.* (2014) |
| Apples cv. Golden delicious | Gliding arc plasma (20-50W) - 10 min, 20 min and 30 min | •Reduction in *Escherichia coli* population were observed.<br>•Maximum decline wasobserved when the flow rate and duration of exposure were increased. | Niemira and Sites, (2008) |
| Strawberry | Nitrogen based plasma jet | •2.7 $\log_{10}$ reduction of *Salmonella* spp. were observed. | Fernandez *et al.* (2013) |
| Dates | Direct plasma | •After 7.5 minutes of plasma exposure, complete inactivation of *A. niger* spores were observed. | Ouf *et al.* (2015) |
| Red chicory (*Cichorium intybus*) | Atmospheric cold plasma | •The counts of verotoxin producing *E. coli* on red chicory decreased by 4.78 Log CFU/cm$^2$ against control after a treatment with Lactic acid and SDS for 5 min and ACP for 15 min. *L. monocytogenes* showed a comparatively higher tolerance to this sanitizing treatment and the level of inactivation was 3.77 Log CFU/cm$^2$ as compared to control. | Trevisani *et al.* (2017) |

**Table 1: Continue....**

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| | | | |
|---|---|---|---|
| **Nuts** | | | |
| Pistachio and hazelnut | Non-thermal plasma | •Significant reduction in number of colony forming units (CFU) of *Aspergillus* sp. was observed for hazelnut (5 min) and pistachio nut (18 min). | Sohbatzadeh *et al.* (2016) |
| Hazelnuts, peanuts and pistachio nuts | Air and sulphur hexafluoride ($SF_6$) based plasma (20 minute) | •$SF_6$ plasma application was more effective with 5-log decrease in fungal population.<br>•Air based plasma gave 50% decline in aflatoxin production as compared to 20% reduction incase of $SF_6$ based plasma. | Basaran *et al.* (2008) |
| Avocado | Cold plasma technology | •Cold plasma is an effective treatment for the *in vitro* control of *C. gloeosporioidies*.<br>•Cold plasma does not appear to have any phytotoxic effects on the host fruit avocado. | Siddique *et al.* (2018) |
| **Spices** | | | |
| Whole black pepper | Argon based radio frequency plasma jet | •There was 4.1 $log_{10}$ reduction in *Salmonella spp.* Population, 2.4 $log_{10}$ reduction in *Bacillus subtilis* and 2.8 $log_{10}$ reduction in *Bacillus atrophaeus* population. | Hertwig *et al.* (2015) |

enzymatic activities reduction potential of cold plasma technology is illustrated in Table 6.

## Bio-film penetration capabilities

Biofilms are specialized structure of tightly grouped masses of microorganisms which are usually clustered together in complex extracellular polymeric substances excreted by the bacterial communities. The sole purpose is protection and to provide a water impermeable cellular protection. As soon as a bacterium gets attached to the food surfaces, it starts extracting nutrients and continues to reproduce and proliferate in the form of "biofilms". Bacterial biofilms which gets developed in food and food processing surfaces germinates later on and leads to bacterial rot and affects the overall food's quality and safety. The free radical liberated during the plasma treatment eventually penetrates the bacterial biofilms and leads to destruction of the hibernating bacteria.

Abramzon *et al.* (2006) applied RF high pressure cold plasma on *Chromobacterium violaceum* in polystyrene microplates and observed that there was 100% cell death on 10 minute plasma treatment of 100 W.

Abbaszadeh *et al.* (2018) evaluated the effect of non-thermal plasma technology (7 KHz for 0, 1 and 5 minutes) on quality preservation of fresh fig fruit both in packed and unpacked condition. Results shows a significant shelf life improvement for the treated figs compared to that of the control samples. Direct application of plasma for 90 s and in-package treatment for 30 s was suggested for further researches.

## Modification of food properties

Cold atmospheric pressure plasma (CAPP) ensures a dynamic approach for systematic modification of food product properties along value-added chains of plant and animal related products. A prominent recent advances within the evolution of non-thermal food processing technologies is the feasibility of cold plasma for the enhancement of food properties (Misra *et al.*, 2016). Some findings about modification of food properties are mentioned in Table 7.

### Insecticide and fungicide dissipation

Insecticides and fungicides are chemical compounds which are extensively used in modern agriculture to control pests. However these chemicals have some residual effects on the crops that are being consumed. Some findings about insecticide and fungicide dissipation utilizing cold plasma technology is mentioned in Table 8.

## Other uses of non-thermal plasma technology

### Fluorescent light bulbs/tubes

Fluorescent light bulbs works with the principle of plasma technology in which electric energy is converted to light energy. In a fluorescent lamp, there is a fluorescent tube that contains inert gas in very low pressure. An electric current in the plasma chamber excites the electrons.

**Table 2:** Disinfection/Decontamination of processed products from fruits and vegetables.

| Products | Treatment details | Observations | References |
|---|---|---|---|
| Mango flour noodles | Atmospheric cold plasma | •No significant change in case of water activity, colour and total phenolic content.<br>•Significant decline in total plate count of the noodles and better antioxidant activity as compared to the control. | Abidin *et al.* (2018) |
| Orange juice | Air based DBD plasma (Voltage: 70 Kv - Time: 15-60 sec) | •No significant changes were observed in phenolic content, antioxidant activity, colour and pH.<br>•There was a decline in oligosaccharide content in the juice which has positive effect on natural sweetening. | Almeida *et al.* (2015) |
| Coconut endosperm | Microwave plasma jet | •Inactivation of *Kluyvera spp., Klebsiella spp., Staphylococcus spp., E. coli, Salmonella enterica* and *Listeriamonocytogenes*in took place significantly. | Gabriel *et al.* (2016) |
| Minimally processed melons | Cold gas plasma (15+15 min and 30+30 min) | •Plasma treated samples were having a high dry matter content, decreased titratable acidity, better colour retention and improved fruit firmness. | Tappi *et al.* (2016) |
| Sour cherry juice | Argon based plasma jet | •Anthocyanin and phenolic content were significantly higher in plasma treated sample. | Elez-Garofuli´c *et al.* (2015) |
| Tomato juice | Non-thermal plasma | •Overall quality of tomato fruit was unaffected by plasma disinfection treatment.<br>•Volatile components like *trans*-2-hexenal and *n*-hexanal were significantly higher. | Ma and Lan, (2015) |
| Sliced cucumber | Micro jet cold plasma | •Slight decline in vitamin C content. | Wang *et al.* (2012) |
| Onion powder | Microwave plasma (2.45 Ghz; 400-900 w; 10-40 min) | •No effect of plasma treatment was observed on color, antioxidant activity and quercetin concentration.<br>•The microbial count for *Bacillus cereus, A. brasiliensis* and *E. coli* were reduced to 2.1, 1.6 and 1.9 $\log_{10}$ CFU respectively. | Kim *et al.* (2017) |
| Red pepper powder | Microwave-powered atmospheric cold plasma | •*Aspergillus flavus* population was reduced by 2.5 $\log_{10}$ cycle.<br>•*B. cereus* population was reduced by 3.4 $\log_{10}$ cycle. | Kim *et al.* (2014) |
| Cashew apple juice | Plasma treatment . | •Decline in vitamin C, glucose and fructose content were observed.<br>•In treatments with long duration treatment, polyphenol and total flavonoid content were found increased. | Rodríguez *et al.* (2017) |
| White grape juice | Air based di-electric barrier discharge (60 Hz; 80 kv; 1-4 min) . | •No significant change in pH, acidity and electrical conductivity of the juice<br>•Increase in non-enzymatic browning with minimal total colour difference<br>•Decrease in total phenolics, total flavonoid and antioxidant capacity<br>•Increase in total flavonols content<br>•7.4 log10 CFU/ml reduction in *Saccharomyces cerevisiae.* | Pankaj *et al.* (2017) |

**Table 3:** Disinfection/decontamination of cereals and pulses.

| Crops | Treatment details | Observations | References |
|---|---|---|---|
| Rice | Direct cold plasma | •*Aspergillus oryzae* spores were visible but did not get germinated and unculturable after 20 minutes of treatment. | Hayashi *et al.* (2014) |
| Lentil and chickpea | Non-thermal plasma | •99% reduction of *A. parasiticus* and *Penicillium* spp. population when exposure time was 20 minutes. | Selcuk *et al.* (2008) |
| Maize | Cold plasma technology (5 min) | •Significant reduction in colony forming units of *Aspergillus flavus* and *Aspergillus parasiticus* in maize. | Dasan *et al.* (2016) |
| Rice seedlings | Direct cold plasma | •There was a decline in *Fusarium fujikuroi* population in rice.<br>•Significant reduction of bakanae disease in rice seedlings as compared to that of the control. | Ochi *et al.* (2017) |
| Wheat | Cold plasma | •Decreasing population of colony forming units of *Alternaria* sp. and *Aspergillus* sp. were observed. | Kordas *et al.* (2015) |
| Groundnut | Cold plasma | •Total aflatoxin and $AFB_1$ decreased to 70%.<br>•It was also observed that the aflatoxin $B_1$ and $G_1$ were also more sensitive to plasma application than $B_2$ and $G_2$. | Siciliano *et al.* (2016) |

**Table 4:** In-package disinfection/decontamination.

| Crops | Package | Treatment details | Observations | References |
|---|---|---|---|---|
| Strawberry | Polythene based modified atmosphere package | Non-thermal plasma [60 kV - 50 Hz] | •Population of microorganisms inside the package drastically fell from 5 $\log_{10}$ CFU/g to 3 $\log_{10}$ CFU/g in exposure duration of 5 minutes.<br>•Both the gas mixture has similar effect except the fact that when the gas has a higher $O_2$ concentration, the fruits were 11% firmer. | Misra *et al.* (2014) |
| Spinach | LDPEpouch | Air based dielectric barrier discharge (60 Hz - 12 kV - 40 W) | •3.78 $\log_{10}$ CFU reduction in *E. coli* population | Klockow and Keener, (2009) |
| Strawberry | Rigid polypropylene | Non-thermal plasma [50 Hz - 60 kV] | •4.99 $\log_{10}$ CFU reduction in total mesophiles and mould population | Misra *et al.* (2014) |
| Tomato | Di-electric barrier discharge | Non-thermal plasma [50 Hz - 70 kV] | •3.1 $\log_{10}$ CFU reduction in *E. coli.*<br>•6.3 $\log_{10}$ CFU reduction in *S. typhimurium.*<br>•6.7 $\log_{10}$ CFU reduction in *L. monocytogenes.* | Ziuzina *et al.* (2014) |
| Orange juice | Rigid polypropylene | Non-thermal plasma [60 Hz - 90 kV] | •5 $\log_{10}$ CFU reduction in *Salmonella enterica.* | Xu *et al.* (2017) |
| Lettuce | Nylon and polyethylene | Non-thermal plasma [2.4 kHz - 34.8 kV] | •Upto 0.9 $\log_{10}$ CFU reduction in *E. coli* O157:H7.<br>•Upto 0.3 $\log_{10}$ CFU reduction in *Salmonella* spp.<br>•Upto 0.9 $\log_{10}$ CFU reduction in *L. monocytogen.*<br>•Upto 1.3 $\log_{10}$ CFU reduction in Tulane virus. | Min *et al.* (2016) |

**Table 5:** Packaging material disinfection/decontamination.

| Package | Microorganism | Treatment details | Observations | References |
|---|---|---|---|---|
| Polycarbonate | *Bacillus subtilis* | Helium based plasma | Complete spore inactivation due to reactive oxygen species with the heat, UV photons, electric field and charged particles respectively. | Deng *et al.* (2006) |
| Polyethylene terephthalate foils | *Aspergillus niger, Bacillus atrophaeus, Bacillus pumilus, Clostridium sporogenes, Deinococcus radiodurans, Escherichia coli, Staphylococcus aureus* and *Salmonella mons* | Cascaded dielectric barrier discharge of plasma | 6 log reduction of vegetative cells. | Muranyi *et al.* (2007) |
| Glass | *Escherichia coli* and *Bacillus subtilis* cell suspension | Helium and oxygen based electric discharge plasma (13.56 MHz) | Cytoplasmic deformation and leakage of *Escherichia coli* and *Bacillus subtilis* cells. | Hong *et al.* (2009) |
| Polypropylene | *E. coli* K12 | One atmosphere uniform glow discharge plasma | 5 log reduction after 24 s exposure. | Gadri *et al.* (2000) |
| Nitrocellulose | *Bacillus stearothermophilus* | One atmosphere uniform | 5 log reduction after 5.5 min exposure. glow discharge plasma. | Gadri *et al.* (2000) |
| Polyethylene terephthalate foil | *Bacillus subtilis* and *Aspergillus niger* | Atmospheric plasma (dielectric barrier discharge) | Four times reduction withinfew seconds. | Heise *et al.* (2004) |
| Glass, polypropylene polyethylene, nylon, polypropylene and paper foil | *Escherichia coli O157:H7,S. typhimurium* and *Staphylococcus aureus* | Low-pressure air plasma | Up to 4-log reduction were observed within 300 s. | Lee *et al.* (2015) |

**Table 6:** Reducing enzymatic activities.

| Crops | Treatment details | Observations | References |
|---|---|---|---|
| Apple cv. Pink lady | Non-thermal plasma | •Reduction in browning due to polyphenol oxidase activity when fresh cut pink lady apple were treated with gas plasma for 10, 20 and 30 minutes.<br>•The treatments also reduced overall metabolic processes significantly. | Tappi *et al.* (2014) |
| Model food system | Non-thermal plasma | •Activity of polyphenol oxidase and peroxidase was studied in a model food system which was treated with atmospheric cold plasma for different time duration.<br>•It was observed that polyphenol oxidase activity was reduced by about 90% after a time of 180s.<br>•Peroxidase was comparatively more stable to plasma and was therefore reduced by about 85% after 240s | Surowsky *et al.* (2013) |
| Tomato | Non-thermal plasma [30, 40 and 50 kV - 10, 20 and 30 min] | •Treatment times and voltage both were found to have a significant effect ($p \leq 0.05$) on inactivating peroxidase enzymes in tomato. | Pankaj *et al.* (2013) |
| Potato and apple tissue | Non-thermal plasma | •Cut pieces of potato and apple tissue was plasma treated for 10 min which showed reduction of polyphenol oxidase up to 77% and 62% respectively.<br>•Peroxidase activity was also reduced by 89% in potato tissue and 65% in cut apple. | Bubler *et al.* (2016) |

**Table 7:** Modification of food properties.

| Crop/product | Treatment details | Observations | References |
|---|---|---|---|
| Parboiled rice | Low-pressure plasma system | •Significant reduction in cooking time of parboiled rice. | Sarangapani *et al.* (2015) |
| Rice | Non-thermal plasma | •Decreased cooking time can be due to textural change or modification in the microstructure.<br>•Due to etching of the rice surface, the penetration of water into the kernel is improved and cooking process is enhanced. | Chen (2014) |
| Cherry tomatoes | Non-thermal plasma | •Plasma treatments did not affect colour, firmness and pH.<br>•Minimum loss in weight and no significant rises in respiration rates. | Misra *et al.* (2014) |
| Blueberry | Non-thermal plasma | •Loss in firmness due to structural disintegrate. | Lacombe *et al.* (2015) |
| Fresh cut celery | Non-thermal plasma | •Loss in firmness due to structural disintegrate. | Berardinelli *et al.* (2016) |
| Legumes | Low pressure cold plasma (1 kHz - 20 kV - 300 W) | •Only very slight change in moisture content of legumes was observed.<br>•No significant change in water soaking, yield and cooking time of legumes were observed. | Selcuk *et al.* (2008) |

**Table 8:** Insecticide and fungicide dissipation.

| Crop/product | Treatment details | Observations | References |
|---|---|---|---|
| Apple | Dielectric barrier discharge (DBD) | Degradation of pesticides in apples. | Heo *et al.* (2014) |
| Maize | Atmospheric cold plasma | GC-MS assay revealed residue minimization of dichlorvos and omethoate. | Bai *et al.* (2009) |
| Strawberry | Atmospheric cold plasma | Successful degradation of residual pesticides. | Misra *et al.* (2014) |
| Blueberries | Atmospheric cold plasma (80 Kv and 5 min) | Degradation efficacy of pesticides were 80.18% for boscalid and 75.62% for Imidacloprid. | Sarangapani *et al.* (2017) |

This produces a short wavelength of ultraviolet light. The phosphor coating inside the tube glows like a lamp.

**Plasma TV display**

A plasma television contains a plasma display panel containing several small plasma cells. These plasma cells have plasma matter present inside it. This plasma gets ionized in presence of the electric field.

**Waste water treatment**

Plasma technology can be effectively used for total purification and decontamination of waste water. Plasma technology is also known to remove colours and off odours from water. In present era, huge amount of water is contaminated with microbes, oils and deadly dye. These colours do not decompose and persist in system flora and fauna. Plasma technology is known to degrade dye including azo derivatives, anthraquinonoid, indigoid, *etc.*

Rowan *et al*. (2007) performed pulsed plasma gas discharge (PPGD) on poultry wash water containing *Escherichia coli*, *Campylobacter jejuni*, *Campylobacter coli*, *Listeria monocytogenes* and *Salmonella* spp. at 4°C. It was observed that there were 8 log reductions of bacteria and their spores.

**Hand dryers**

Cold plasma technology found its application as hand disinfecting agent along with drying of the palm. In developed countries, hand dryers are a part of culture in offices, institution, schools and household. In developing countries, it has application in executive hotels, elite household and executive government offices. It's a part of sanitation movement which not only reduce water wastage but also help to ensure public hygiene. This technology is best suited to neutralize microbes including *Staphylococcus aureus, Salmonella* sp., *E.coli*, norovirus and virus that cause influenza with a success percentage of 99.6% (Anonymous, 2018).

**Advantages of cold plasma technology**

Cold plasma technology is a very worthy technique for the enhancement of shelf life of fresh horticultural produce, cereals, pulses, food and dairy products. Following are the advantages of cold plasma technology:

a. This technique is feasible with all form of matter (solid, liquid and gases).
b. This process ensures a better decontamination of packaging materials without affecting its structure and barrier properties.
c. The products which are modified packaged can also be treated with plasma technology.Microbial inactivation of food products is very effectively done without any sort of heat treatment. Usually the thermally processed foods have a significant nutrient loss and reduction in organoleptic properties (Sampedro *et al*., 2005). Application of non-thermal technologies is very effective at ambient temperature and minimizes all the adverse effects of heat treatment (Tiwari *et al*., 2009).
d. Products decontaminated by this process tend to be more microbial stable.
e. **Bio-film penetration efficiency**

   Non thermal plasma technology can successfully get rid of microorganisms that harbour and perpetuate inside bio-films (Critzer *et al*., 2007). Biofilms are big problems in case of fresh fruits, vegetables, dairy, poultry and meat industry (Jessen and Lammert, 2003). Microorganisms are often found embedded in nutrient-rich environment of biofilms inside which they proliferate naturally without any external stress (Vleugels *et al*., 2005; Simões *et al*., 2010).
f. This process can help to reduce the use of chemical preservatives.
g. Cold plasma does not leave any sort of residue in the treated food.
h. Treatment using cold plasma techniques would also help to minimize fresh water usage.
i. Cold plasma is much cost and energy efficient as its energy expenditure is like a 50 watt bulb.

**Limitations of cold plasma technology**

Like every other thing in our nature, the process of cold plasma technology also has some limitations. The limitations are listed below:

a. The process eventually increases the acidity and firmness of the treated food product which is not always desirable.
b. It is known to slightly reduce the colour of fresh fruits and vegetables slightly.
c. In products containing fat on the surface, plasma treatment can cause lipid oxidation and off-flavour.
d. The entire systems of cold plasma technology have a high installation cost and need a significant amount of technical know-how.
e. Penetration depth is very less in case of plasma technology.
f. The system seems to be non-feasible in Indian agriculture and horticulture system as far as cost is concerned.

## CONCLUSION

Considering all the above things we can easily adopt this new technology in post-harvest sector. This would not only help in loss reduction of perishable horticultural crops but have other qualities of in package sterilization.

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