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# COLD PLASMA TECHNIQUE ITS CURRENT STATUS, APPLICATION AND FUTURE TRENDS IN FOOD INDUSTRY

**Sudhanshu Maheshwari[1*], Raghav Garg[2]**

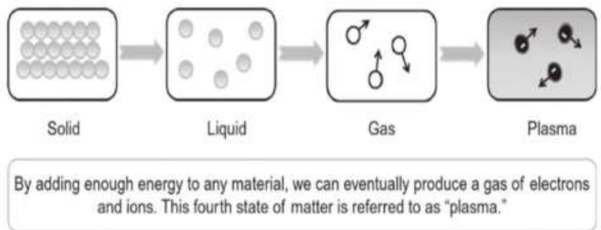
*[1*,2]NH-05, Ludhiana - Chandigarh State Hwy, Sahibzada Ajit Singh Nagar, Punjab,*
*Emails: somani.sudhanshu@gmail.com, raghavgarg4469@gmail.com*,

***Corresponding Author:***
*somani.sudhanshu@gmail.com*

## Abstract-

*Cold plasma has the ability to inactivate germs in the food processing sector. Cold plasma's action mechanisms, as well as its flexibility as a stand-alone or in conjunction with other technologies, makes it a powerful instrument looking forward to continuing innovative ideas. Irving Langmuir first described the state of matter as having nearly equal amounts of ions and electrons in the ionised gas at the electrodes. Since the 1970s, cold plasma treatment has been employed in semiconductor materials. Plasma is the fourth phase of matter, advancing from solid to liquid, then liquid to gas, and finally plasma. Cold plasmas have been produced using plasma technology in sealed plastic containers-in-package. Cold plasma is employed in sectors such as surface treatment, medical equipment sterilisation, and food safety. There are three main cold plasma technology designs being used for food sterilisation. Remote therapy, direct treatment, and close proximity to an electrode are the most common approaches. Plasma has received widespread application in the food sector during the last decade. DBD, Plasma jet, Corona plasma discharge, radio frequency plasma, microwave plasma are some of the techniques that is used in cold plasma delivery according to recent researches. Food processing sectors have been concentrating on energy use and energy savings during the last few years. Plasma processes provide the following advantages: high reliability at cold temperatures, precise plasma creation tailored to the intended application, minimal effect on the internal product matrix, no wastes, and low resource consumption. Cold Plasma is becoming more widely acknowledged as a viable non-thermal technique that can increase food safety with no impact on food quality. The procedure for obtaining regulatory clearance for novel food technology is governed by the nation's legal framework, and requires further study in system design.*

**INTRODUCTION-**
The fourth state of matter, according to certain theories, is plasma. The theory that a phase change occurs by gradually adding energy to a substance. The transition from solid to liquid to gas leads to the idea of the fourth state of matter. The use of cold plasma science and technology to a wide range of agricultural and food industry concerns is increasingly being considered. Cold plasma's action mechanisms, as well as its flexibility as a stand-alone or in conjunction with other technologies, making it a powerful instrument looking forward to continuing innovative ideas. Cold atmospheric plasma has the ability to inactivate germs in the food processing sector, hence enhancing food safety. Growing demand for fresh fruit presents the food business with the difficulty of producing safe food with little processing. Because many items are consumed uncooked, it is critical that they remain free of microbial contamination. Due to which, there is a lot of interest in finding new ways to preserve food and kill microorganisms without harming its quality. The use of cold atmospheric plasma (CAP) therapy is one such promising developing technique. (Bourke et al., 2018a). This review paper provides an overview of cold plasma technology and its potential applications in the food processing sector.




**History**-
Irving Langmuir first used the word "plasma" in 1926, when he described this state of matter as having nearly equal amounts of ions and electrons in the ionised gas at the electrodes, where there are sheaths with relatively few electrons. This results in a very small space charge. Plasma is the name given to this region when ions and electrons have balanced charges. (Langmuir, 1928) Plasma physics evolved as a significant study subject after Langmuir's key work. Townsend was the first to define the idea of self-consistency due to ionization balance during the gas release process and to clarify flow of current through a gas. (Townsend, 1915, 1925). Since the 1970s, plasma processing has been used to etch semiconductor materials (Manos and Flamm, 1989). Plasmas were first used in the computer industry in the 1980s, namely for the manufacture of tiny circuits. Advances in atmospheric plasma have decreased the need for pricey pressure chambers and pumping equipment during the last decade of the 20th century. In recent years, a number of fresh uses for plasma have emerged, including food preservation, water purification, and plasma therapy. Cold plasmas have lately been created within sealed plastic containers in various configurations, which has been referred to as "in-package plasma technology" (*Cold Plasma in Food and Agriculture - 1st Edition*, n.d.).

**Plasma generation**-
Plasma is a phrase that refers to a completely ionised plasma made up of numerous things such as photons and free electrons, as well as excited atoms with a neutral charge. Because it contains an equal amount of positive and negative ions, plasma has a net charge of zero (Kudra & Mujumdar, 2009). Light (photons) and heavy (atoms) species make up plasma (all the other constituents). For keeping such specific properties, forth state of matter is regarded as plasma, progressing from solid to liquid, then from gas to gaseous state, and finally to plasma. (Misra et al., 2011).

**Principles of cold plasma-**
At atmospheric pressure, by moving a process gas through an electric field, cold plasma is produced. Electrons produced by rapid ionisation processes in this area initiate impact ionisation processes. When free e-collides with gas atoms, they exchange energy, resulting in highly reactive species that can interact with the food surface. Cold plasma is employed in sectors such as decontamination technology, surface treatment, medical equipment sterilisation, and food safety. According to (Lacombe et al., 2015), This method processes materials without damaging biological tissues, and it may be used for surface, air, and food disinfection. Cold plasma is classified into two types according on the operating pressure: low-pressure plasma and atmospheric-pressure plasma. The primary idea behind low-pressure plasma is that it is created at low pressures or even in a vacuum. A cold plasma system that runs at radio frequency is the other plasma approach. It generates ionisation by applying quick electrical stimulations at periodic intervals and varying the voltages and powers used to operate the gases in the system. (Niemira & Gutsol, 2011).

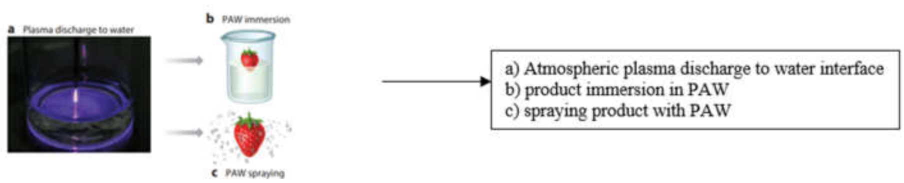
**Cold Plasma Design –**
There are now three main cold plasma technology designs being used for food sterilisation. Direct treatment, close proximity to an electrode, and remote therapy. The surface of the target and the position of the plasma-generating source are used to determine these designs.

- Remote therapy - When using remote therapy, the intended product is not put into the plasma chamber right away. The ionized gas for remote therapy might be air, nitrogen, or a combination of noble gases. The creation of reactive species, which might interact with some other plasma species like charge particle or photon species, is a drawback of the remote treatment concept. In terms of design, however, the distant treatment is preferred above others because to its simplicity, adaptability, and physical form of the objective.

- Direct treatment\Direct therapy, as opposed to distant treatment, uses the plasma needle and thermal plasma tube often and brings the target product into direct touch with the created plasma. et al.(Varilla et al., 2020a). Direct treatments expose more UV radiation since it is closer to the target product. This causes the product to heat up due to conduction, which raises the water content.(Niemira & Gutsol, 2011). This method changes the look and texture of food deteriorates vitamins and minerals in items such as meats
- close proximity to an electrode - The food product is put in close proximity to one of the electrodes in close proximity design. This design exposes the target product to a larger concentration of reactive charged particles, negatively charged electrons, and UV radiation. (Sharma et al., 2000a). The items to be treated or sterilised must be placed between the electrodes for this design to work properly. The technique works well with tiny food items like seeds, berries, and almonds, as well as larger ones like chicken breast.(Varilla et al., 2020a)[(Nwabor et al., 2022)]

**How does the plasma release to the target-**

- **Direct exposure -** As the name implies, this method exposes the meal to the plasma discharge itself. This might be a plasma jet plume or the field between two electrodes. Food interactions with short-lived reactive gas species are enhanced by direct plasma exposure. UV rays and electric fields However, ensuring consistent exposure of complicated surfaces can be problematic. Specifically, pores such as those found in food goods. (Chizoba Ekezie et al., 2017)
- **Indirect or remote exposure -** In this method, the target is positioned some distance away from the plasma discharge. Because so many of the induced species have renominated, only relatively long-lived species may interact with the target. With this method, the negative effects of direct exposure on tissue that is delicate or vulnerable can be reduced. Reactive gas species can be administered more evenly for the treatment of certain goods.(Chizoba Ekezie et al., 2017)
- **Plasma activated water** - This approach uses a fluid to deliver reactive species formed by plasma (usually water). The water is activated for some time after being exposed to a plasma discharge (often direct), during which metastable species concentrations are present. Whenever solutions are exposed to plasma, they produce pretty long by-products like as hydrogen peroxide, nitrates, and nitrites, which can combine to form more cell harmful compounds such as peroxynitrous acid. The PAW can be utilized as an effective decontaminant water wash for food during this busy time. The resulting PAW can be used to immerse and spray products, or it can be frozen as active ice.(Chizoba Ekezie et al., 2017)

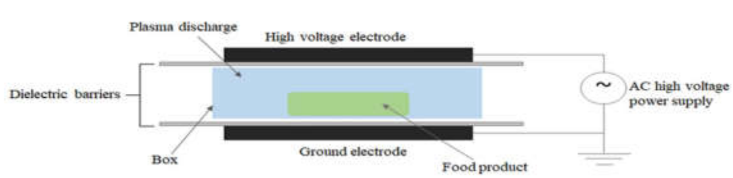



**Techniques used in cold plasma technology-**

Various green technologies have been applied in the food industry to rid production lines and products of pathogens that might degrade product quality, leading to recalls and outbreaks of food contamination. This has resulted in a surge of interest in the use of green technology for preservation and shelf-life extension. Plasma has received widespread application in the food sector during the last decade as a relatively new and promising non-thermal decontamination solution. (O'Connor et al., 2014) (Isbary et al., 2013).

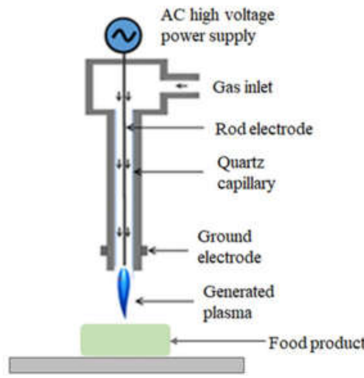
Plasma generating technologies for food processing are classified as dielectric barrier discharge (DBD), plasma jet (PJ), corona discharge (CD), radiofrequency (RF), and microwave (MW). (Laroque et al., 2022a). provided a full assessment of the specifications and application for each. DBD plasma generating systems are of particular interest to researchers because they provide a safe and low-cost option for processing applications.

- **Dielectric barrier discharge (DBD)** - One of the most popular ways to create non-thermal plasma is by using DBD plasma. This type of plasma is prone to chemical reactions because it contains a wide range of high-energy electron, free - radical, active catalytic ions, and excited species. By scattering current flow over dielectric materials between electrodes, dielectric barrier discharge (DBD) can produce plasma. The DBD is ideal for inactivating germs on fresh commodities in packing because reactive nitrogen and oxygen species may be created instantly inside sealed containers. Gas pressures in the 104-106 Pa range and frequencies in the 10-50 MHz range are typical operating conditions. The DBD approach is the most widely used technology for plasma generation because configuration flexibility allows food processing in packaging (including meats, poultry, fruits, and vegetables) and reduces post-contamination.(Ganesan et al., 2020). The clarification of this text is provided in (Fig1.)



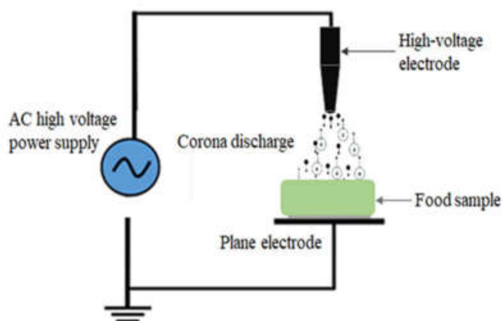

(Fig1.)

➤ **Plasma jet** - The outer electrode is grounded whereas an input gas is transferred between the electrodes while high-voltage power is delivered to the centre electrode to produce valence electrons that collision with gas molecules to create different substances in a plasma jet. The discharge plasma is used in the food product treatment. However, the application is limited in scope. The description of this text is given in (Fig 2.)



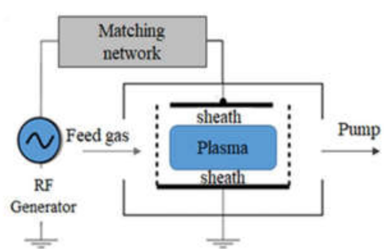

(Fig 2.)

➤ **Corona plasma discharge** - At atmospheric pressure, corona plasma discharge is classified as cold plasma. It happens when current runs from a theoretically high electrode into an area that contains gas or even other gases, ionizing it and forming a zone of plasma surrounding the electrode, as seen in the figure (Fig 3.). It can be powered by pulsed direct current or high voltage alternating current. The electrodes in this arrangement are quite asymmetrical, with a thin wire electrode or a needle electrode facing a thick plane electrode or a cylinder electrode with a big diameter. Moreover, corona discharge arcs are commonly brought on by strong electric fields generated by electrodes with sharp edges, needles, or tiny diameter wires. Corona plasma discharge, in contrast to plasma jets, covers a larger region around the food sample, and it also generates more energizing plasma than DBD.




(Fig 3.)

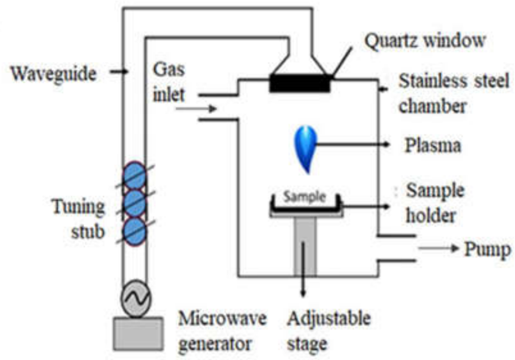
➤ **Radiofrequency plasma (RF)** - radiofrequency (RF) plasma is created by exposing a gas flow to a radio frequency field. There are three types of RF plasmas: sources for helicon waves, capacitively connected plasma, and inductively coupled plasma. The design includes two parallel electrodes spaced by a few centimetres in a sealed chamber. Methodologically, it may be operated in the 1-100 MHz range(Takahashi et al., 2017). Fig 4 can be referred to get a clear idea for this technique.




(Fig 4.)

➤ **Microwave plasma** - Microwave discharge, on the other hand, is generated by a magnetron with an average electromagnetic radiation frequency of around 2.45 GHz. When microwaves are directed into the chamber for treatment, they are taken up by the gas, that warms & ionises, resulting in the release of electrons. Because of inelastic collisions, this causes ionisation processes, which release photons of visible and ultraviolet light in the form of energy.

For various applications, this approach has the ability to produce both quasi-equilibrium and non-equilibrium plasma.(Lebedev, 2010). The following components are included in a microwave plasma configuration: a power source such as a magnetic coil, a circulator, a standing wave ratio metre, a matching loop, and a microwave to plasma applicator. UV radiation and negatively charged particles The items to be treated or sterilised must be placed between the electrodes for this design to work properly(Sharma et al., 2000b). The technique works well with tiny food items like seeds, berries, and almonds, as well as larger ones like chicken breast.(Varilla et al., 2020b). A clear idea of this process can be seen in Fig 5.




(Fig 5.)

| Technique | Theory | Principal | Application | References |
|---|---|---|---|---|
| DBD (dielectric barrier discharge) | Dielectric barrier discharge (DBD) can produce plasma, which is ideal for inactivating germs on fresh commodities in packing. This type of plasma contains a wide range of high-energy electron, free - radical, active catalytic ions, and excited species. Explained in fig1. | Its insulating material describe its principal. To operate a plasma at normal pressure with moderate high voltage amplitudes the discharge gap is typically in the range of 0.1–10 mm. Dielectric materials such as glass, quartz, ceramics, enamel, mica, plastics and silicon rubber or Teflon are used. | • Improving food shelf life<br>• Reducing chemical oxygen demand<br>• Increasing food storage<br>• Reducing food spoilage | (Liao et al., 2018; Subedi et al., 2017) |
| Plasma jet | Plasma Jet is a simple apparatus to form plasma at atmospheric pressure. The plasma produced is touchable by bare hands and can be used for bio-medical, agricultural and surface modification application. Its instrumentation can be seen in fig2. | The plasma jet has been utilized as an energy source to generate a high temp medium for chemical synthesis. | • Sterilization of vegetables.<br>• Sterilization of seeds.<br>• Increasing the germination rate of seeds. | (*Plasma Jet*, n.d.) (Ružbarský & Panda, 2017) |
| Corona plasma discharge | A corona discharge is an electrical discharge created by ionization of a fluid, such as air, around a high-voltage conductor. It denotes a limited zone where the air has experienced electrical breakdown and become conductive, enabling charge to seep off the conductor into the air continually. Fig3 | By ionizing the neutral fluid to produce a zone of plasma surrounding the electrode, a current is flowing from an electrode with a significant potential into the neutral fluid, often air. | • physicochemical properties of banana starch<br>• Manufacture of ozone<br>• Sanitization of pool water | (Bai et al., 2009; Gavahian & Khaneghah, 2019) |
| Radio frequency plasma | The oscillation frequency of an alternating voltage level in the frequency range of roughly 20 kHz to around 300 GHz is referred to as radio frequency (RF). This is about between the upper and lower limits of audio and infrared frequencies, which are the frequency range at which energy from an alternating current may radiate off a conductor. Fig 4 | Automatic management of a rate radiofrequency (rf) plasma source minimizes rf power reflection while maintaining a constant net rf power that equals the forward power minus its reflected power. | • Heating of bread<br>• Blanching<br>• Thawing<br>• Drying<br>• Meat processing | (Piyasena et al., 2003) |
| Microwave plasma | Microwave plasma is a form of plasma that emits electromagnetic radiation at high frequencies in the GHz range. It has the ability to excite electrodeless gas discharges. Fig 5. | Both the hydrocarbons feed and molecule hydrogen are separated using it. 2.45 GHz is typically employed as the excitation source. Electron oscillation in microwave plasma leads to the production of ions through collisions with gas molecules and atoms. | • thermal processing<br>• especially drying<br>• sterilization<br>• pasteurization | (Gallagher & Fridman, 2011) |

**Application of Non thermal technique cold plasma-**

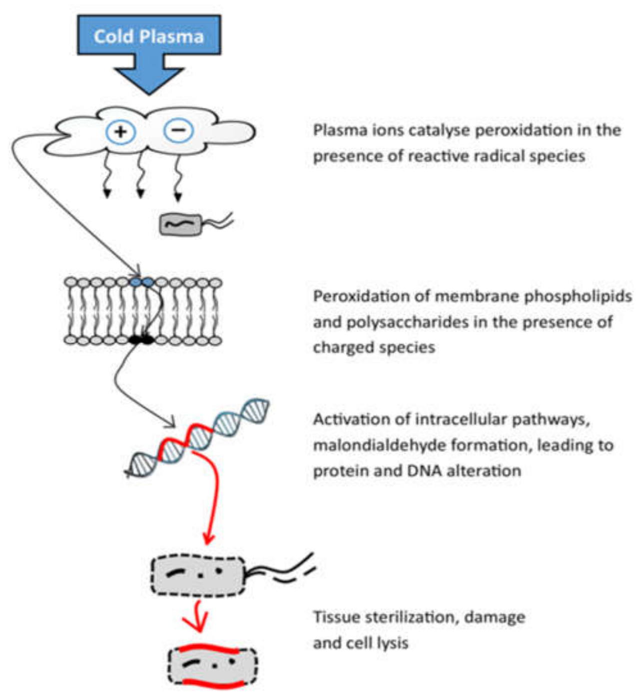
➢ **Packaging** – Food packaging has a lot of promise for plasma technology since it enhances adhesion, polymerization, and processability.(Pankaj et al., 2014). Although polyethylene terephthalate (PET) polymers have a low surface energy and must be activated in order to improve adhesion, printing, and dyeing capabilities, PET polymers have many positive characteristics including toughness, transparency, gas barrier property, formability, and chemically inert. Cold plasma treatment makes it easier to assess how the crystal organization of PET films changes in respect to surface energy. (Jacobs et al., 2011). The active packaging technique was developed to safeguard food quality and increase its shelf life. The method uses physical, chemical, and biological mechanisms to change how a product interacts with packaging materials and even the headspace inside of packages in order to accomplish the desired outcome (Yam et al., 2005). An atmospheric pressure cold plasma reactor was used to complete the active packing of red delicious apples (APCPR). Atmospheric pressure cold plasma was created by raising the voltage between the needle-to-needle arrangement. Vanillin was adopted as monomer and argon as the carrier gas because it can produce plasma polymerized films. To get the apple ready for the proper film deposition on its surface, the chamber placed just below activation zone was utilised. The study found that an even thin layer of coating could be formed upon this apple surface, but nodules appeared when vanillin powder condensed after sublimation.(Fernández-Gutierrez et al., 2010).(Oh et al., 2016) In terms of durability, elongation, and moisture barrier, the edible film treated by cold plasma based on defatted soybean meal performed better than the control.

➢ **Shelf-life extension**- Extension of product shelf life is a recognised global concern to assure food security and reduce waste. Salmonella, E. coli, and L. monocytogenes on cherry tomatoes were reduced to undetectable levels in samples treated for 10, 60, and 120 s with an in-package plasma technique, according to (Ziuzina et al., 2014). In a similar vein, (J. Wang et al., 2016a) demonstrated that in-package plasma treatment with MAP resulted in a 4-log decrease during storage and might increase the shelf life of fresh chicken meat without degrading product quality. Fresh strawberries were subjected to an in-package DBD plasma treatment by(Misra et al., 2015a), who found that the background microflora (aerobic mesophilic bacteria, yeast, and mould) could be decreased by 2 logs with few impacts on colour or firmness. Bourke and colleagues have studied microbiological interactions with cold plasma and processes.(Bourke et al., 2017) Because of its capacity to inactivate germs, CP can postpone food spoiling caused by bacterial and fungal development. Attempts to improve food shelf-life by atmospheric cold plasma have focused on ready-to-eat items such as fresh fruit and vegetables and meat.(Tappi et al., 2016; J. Wang et al., 2016b)

➢ **Inactivation of microorganism**- Cellular envelopes, DNA, and proteins have been identified as possible targets, and the antibacterial efficacy is defined by its multi-target nature even if the underlying plasma-induced inactivation processes are not yet completely understood. Cold plasmas have a wide range of potential applications in the food industry since they may be used to inactivate bacteria, yeasts, moulds, and bacterial and fungal spores on both biotic (food) and abiotic (packaging materials, food contact surfaces) surfaces (López et al., 2019). Cold plasma is used to disinfect fruits, vegetables, and leafy vegetables from pathogens with little treatment or as a chlorine alternative during washing. (Pasquali et al., 2016) investigated the effect of cold plasma on red chicory (Cichoriumintybus) grown at a 70-mm distance from the discharge. The settings were kept steady at 22°C and 60% RH, with only the treatment period varying between 15 and 30 minutes. The initial load of E. coli and L. monocytogenes was 108 cfu/ml and 1.2 x 108 to 1.6 x 108cfu/ml, respectively, after 15 and 30 minutes of treatment. E. coli was decreased to 1.35 log MPN/cm2 after 15 minutes of atmospheric cold plasma treatment, but L. monocytogenes required 30 minutes to reach a final load of 2 log cfu/ml. The length of treatment period had no discernible effect on antioxidant activity or the look of radicchio leaves.( Cold Plasma Processing: A Review, n.d.)

❖ Mechanism of inactivation of microorganism - The impact of plasma sterilisation was originally documented in 1960, and the concept was patented by Menashi in 1968. (Menashi, 1964). When bacteria are exposed to strong radicals bombarding on the cell surface during plasma treatment, the germs lyse. Radical attack results in lesions on the surface of the cell, on which microbes are unable to quickly heal, hastening the death of the living cell. Etching is the term used for this (Bußler et al., 2017a). The accumulation of electrostatic pressures on a living cell's outer surface results in lesions. Two aspects affect the efficiency of non-thermal plasma: the kind of substrate and microbe characteristics including load, sort, and physiological state.(Stratakos & Koidis, 2015) Cell membranes are destroyed, DNA is damaged, and chemical bonds are denaturised by the impact of energetic particles & reactive species in non-thermal plasma, which has an antibacterial effect on the cell. Although the exact way that microbes and plasma species interact is yet understood, several activities, such oxidation and peroxidation, which take place both within and outside of cells and are primarily mediated by plasma ions.(Dobrynin et al., 2009)

Mechanism of microbial inactivation by cold plasma treatment. Adopted from Dobrynin et al.



➢ **Mycotoxin degradation**- Mycotoxins are substances generated by a variety of filamentous fungus. Numerous research on the hazardous effects of mycotoxins on people and animals have been published (Groopman et al., 1988). Mycotoxin-contaminated foods can cause illnesses in humans that damage essential systems such as the neurological and immune systems. Food contamination is exacerbated when it is handled, transported, and stored incorrectly (Hojnik et al., 2017). The US Food and Drug Administration (FDA) presently sets the maximum concentration of mycotoxins for maize and other grains intended for human, poultry, or dairy animal consumption at 20 ppb (*NGFA Publishes Updated Resources on Mycotoxins*, n.d.). Furthermore, fungal spores that create mycotoxin produce heat-stable poisons that may withstand cooking. The best strategy is primary prevention, which should be used before fungi invade and begin producing mycotoxin. According to some writers, treating seeds with plasma can help prevent the growth of further mycotoxin and fungus. Just after half - hour plasma treatment at 60 W,(Devi et al., 2017) saw 99.9% and 99.5% decreases in Aspergillus flavus as well as Aspergillus parasitic spores transplanted over ground nuts. The destruction of organic matters by etching and photo desorption, which are both associated with the breaking of chemical bonds and produce volatile compounds, was discovered by SEM study to be the cause of spore membrane collapse (Hertwig et al., 2015). The authors also reported that plasma treatment reduced AFB1 production by A. flavus by 96.8% and AFB1 production by A. parasitises by up to 95%.

❖ Mechanism of mycotoxin degradation- As an emerging field, the literature on mycotoxin breakdown products and routes during cold plasma therapy is limited. The mechanisms for mycotoxin breakdown during cold plasma therapy are inextricably linked to their molecular structure, the nature of the plasma chemistry, and hence the species interaction with toxin molecules (Pankaj et al., 2018). In polymer science, the presence of aromatic groups in polymers generally slows down the breakdown process during plasma treatments (Klarhöfer et al., 2010; ten Bosch et al., 2017). However, because mycotoxin degradation mechanisms are very tiny molecules, they are significantly diverse throughout plasma therapy. (S. Q. Wang et al., 2015) investigated the chemistry of low-pressure plasma-treated AFB1 and hypothesised breakdown mechanisms based on mass spectrometry. They expected an intermediate to arise with $C_{17}H_{15}O_7$, which is likewise a prominent breakdown product of AFB1 following UV treatment. The cold plasma breakdown of mycotoxins might be directly connected to the free radicals created during the treatments (for example, O• and OH•).

➢ **Enzymatic browning in fruit and vegetable**- Enzymatic browning, which degrades the qualitative characteristics of fresh cut fruits and vegetables, is the main issue. Dielectric barrier discharge atmosphere gas plasma was used by(Tappi et al., 2014) to monitor the metabolic activity of freshly cut apples. The samples were treated for 10, 20, and 30 minutes, with the greatest results showing a 65% decrease in browning area over the course of 30 minutes compared to control samples. The polyphenol oxidase residue was finally reduced by up to 42% when treatment duration was extended. This demonstrates that fresh cut apples treated with plasma had lower metabolic activity than control samples. According to(Bußler et al., 2017b), the polyphenol oxidase and peroxidase enzymes found in apples and potatoes were affected by plasma-processed air. After being exposed to plasma-processed air for 10 minutes, the tissue from chopped apples and potatoes revealed reductions in polyphenol oxidase of up to 62% and 77%, respectively, and peroxidase of around 65% in the apple tissue and 89% in the potato tissue.(*(PDF) Cold Plasma Processing: A Review*, n.d.)

➢ **Allergen removal by cold plasma** – According to (Nwabor et al., 2014) food allergies are increasing rapidly on a global scale. An immune response mediated by immunoglobin (IgE) to antigens, mostly proteins, causes food allergy ((Meinlschmidt et al., 2016)). The epitope site is the area to which an antigen bind. It is possible to reduce allergy responses by altering the epitopes present in food allergens. Linear epitopes can be broken up or genetically altered, while conformational epitopes can be structurally altered by denaturation and cross-linking or chemical modification(Shriver & Yang, 2011). According to several studies ((Boye, 2012), (Sicherer & Sampson, 2006), eight common foods milk, eggs, fish, shellfish, tree nuts, peanuts, wheat, and soybeans are responsible for 90% of all allergic responses. Due to their little impact on food quality indicators, nonthermal procedures have recently been the subject of study into lowering food allergenicity (Huang et al., 2014); (Shriver & Yang, 2011)). According to several writers, proteins that are firmly bonded to solid surfaces can be removed using cold plasma. According to Surowsky et al. (2013), exposure to plasma results in the loss of complex formation like helical and organised -sheet components. Similar to this, studies have shown that the protein architectures are altered by cold plasma (Attri et al., 2015); (Misra, 2015)). According to (Hayashi et al., n.d.)), oxygen radicals created by plasma break down the second-order structure of proteins, which includes -sheets, amide bonds, and side chains. Additionally, it has been noted that plasma species cause etching, cross-linking, and depolymerization. Although the topic of allergenicity is not explored in these experiments, the protein's structural alterations raise the possibility that a plasma therapy might lessen allergens. Few scientists have looked at how well plasma works to reduce allergies. According to (Shriver & Yang, 2011)), a 5-minute direct plasma treatment decreased the allergenicity of shrimp tropomyosin by up to 76%. Additionally, the author noted that cold plasma therapy decreased IgE binding to tropomyosin and shrimp extract.(Shriver & Yang, 2011) was successful in lowering wheat allergenicity by up to 37% using identical settings. Additionally, they suggested that the free radicals produced by plasma exposure may cover up or interfere with the conformational binding epitope, blocking the ability of an IgE-mediated reaction to trigger a negative immunological response. Research by showed that cold plasma was effective in reducing the allergy of both laboratory made as well as ambient allergen aerosols(Wu et al., 2014) Canine allergy Can f 1 exhibited the highest level of inactivation (80%), whereas dust mite allergy Der p 1 exhibited the lowest level of inactivation (30%). Two important fungal allergens also showed more than 50% inactivation. Additionally, they noted that allergens may react with hydroxyl radicals produced during plasma therapy to induce decreases. The shape of the protein structure of the allergens affects how the plasma reacts to them.

❖ Mechanism of allergy removal by cold plasma- Food allergies often contain protein-based structures, and plasma gas-produced reactive species may have an impact. Reactive species are typically in charge of the destruction of allergens, much as the decontamination actions of cold plasma(Wu et al., 2014)(Tolouie et al., 2018). While other processes can potentially affect the reactivity of allergen compounds, it was suggested that the changes in linear and conformational epitopes brought on by the plasma are the primary cause of allergen deactivation in a plasma process. First, protein crosslinking or a reduction in the solubility of the protein can affect conformational epitopes, whereas linear epitopes are altered by fragmentation. Reactive species can also compromise the structural integrity of proteins by dissolving peptide bonds and oxidizing amino acids.(Surowsky et al., 2013). Peptide disulphide bonds may split when a hydroxyl radical is added, forming RSO and RSH at the splitting site. Regarding the precise mechanism and the precise pathway of allergen breakdown by cold plasma, there are, nonetheless, still unanswered questions.(Gavahian & Khaneghah, 2019).

➢ **Pesticide degradation by cold plasma**- Pesticide residues can harm human health and irreversibly harm various organs. This needs the development of efficient methods for removing this potentially hazardous molecule from drinking water, agricultural goods, and food items. In this context, researchers investigated the efficiency of many pesticide detoxification procedures, including Fenton oxidation (Saini et al., 2017), photocatalysis (Patil & Gogate, 2015), adsorption (Abdelillah Ali Elhussein et al., 2018) ultrasonic therapy (Jawale & Gogate, 2018), and membrane filtering (Plattner et al., 2017). However, none of the proposed methods pleased the industry because of the creation of undesired by-products or the inability to completely degrade pesticides. As a result, the viability of pesticide removal by cold plasma has lately piqued the interest of researchers. (Mousavi et al., 2017) used cold plasma to successfully degrade organophosphorus insecticides in apple and cucumber in a recent study. However, according to (Phan et al., 2018a), only a few effective trials for the detoxification of these pollutants in fruits and vegetables have been recorded (Phan et al., 2018a). (Kim et al., 2007) studied the use of an atmospheric pressure plasma for the degradation of parathion and paraoxon, and established the efficiency of this non-thermal technique for pesticide degradation. They proposed that atomic oxygen, the hydroxide radical, and molecular nitrogen are the primary plasma-generated reactive species responsible for the oxidation of paraoxon and parathion. Similarly, it was found that omethoate and dichlorvos, which were sprayed on the surface of maize, were entirely destroyed by two minutes of inductively coupled plasma at a strength of 120 W. Similar to this, (Bai et al., 2010) verified that cold plasma effectively removes dichlorvos. Likewise, (Zhu et al., 2010) found that malathion decomposed completely following a 7-min jet plasma therapy. The scientists noted that plasma therapy broke down malathion by oxidizing phosphorus and sulphur (p-s) bond, as well as the Sulphur and carbon (S-C) bonds. The paraoxon content on the surface of fresh apples was lowered by DBD cold plasma treatment by 96%, according to research by (Heo et al., 2014). (Misra et al., 2014) evaluated the viability of employing in-package gas phase plasma treatment to degrade pesticides on surface of strawberries. Pesticides such as pyriproxyfen, azoxystrobin, fludioxonil, and cyprodinil were used to treat fresh strawberries, and the quantities of these substances in the strawberries' plasma were determined by GC-MS before and after the plasma treatment. The degradation of pesticides, according to the author, is a voltage- & time-dependent phenomenon. Whereas the plasma was operating at an input voltage of 80 kV for 5 minutes, the quantities of cyprodinil, pyriproxyfen, azoxystrobin, and fludioxonil significantly reduced by 45%, 46%, 69%, and 71%, respectively. Researchers examined how well gliding arc discharge plasma broke off pesticide residues that had been sprayed on the surface of mangoes (Phan et al., 2018b). They also looked at how this plasma therapy affected several mango quality traits. They discovered that a carrier gas of argon for 5 minutes successfully lowered the levels of cypermethrin and chlorpyrifos in the plasma by 63% and 74%, respectively. According to the authors, plasma treatment lowered overall phenolic content and titratable acidity while increasing the mango's carotenoid level. Additionally, they noted that the plasma treatment had no effect on the fruit's total soluble solid, texture, or colour properties. (Zhou et al., 2018) investigated the viability of using discharge plasma technology to remove organophosphorus pesticide residue from the surface of wolfberries. According to the scientists, the treatment duration and voltage used had an impact on how well plasma eliminated pesticide residues. According to the scientists, the plasma process ran for a half-hour at a discharge voltage of 10 kV before reaching its peak efficiency (up to 99.6% pesticide destruction). The authors used chemical and Fourier-transform infrared spectroscopy (FTIR) techniques to examine the intermediate compounds generated during the plasma process and found that the organophosphorus residues have been entirely turned into low toxicity constituents when the plasma was applied in the optimum condition.

❖ Mechanism of pesticidal degradation in cold plasma- The concentration of reactive species created and the average energy of the electrons are connected to the effectiveness of cold plasma in destroying pesticides. In ordinary cold plasma gases, the range of the average electron energy is typically 0 to 10 eV. This is why it is anticipated that all organic molecules receiving a plasma treatment would sustain damage due to their identical bond-dissociation and ionization energies to those of plasma gas. Pesticide molecules are first split apart during the cold plasma treatment.(Bai et al., 2010)(N.N et al., 2016)In addition, plasma treatment produces a number of free radicals with high oxidation potentials, such as O3, OH, and H2O2, which may cause the breakdown of pesticides. Finally, the aforementioned reactions release some of the chemical bonds that hold pesticides together and create other, often less dangerous or innocuous molecules. Additionally, plasma gas contains irradiated lights and ultraviolet radiation, which have been shown in the past to be efficient processes for pesticide breakdown (Tsao & Eto, 2018).

- **Cold plasma industrial application**- There are few CP instances in pilot facilities for the treatment of food.

- In a continuous mode for in-package cherry tomato decontamination, (Ziuzina et al., 2016) examined the SAFEBAG technology. Based on a DBD reactor that operates in an open atmosphere, This CP system features a discharge gap that may be adjusted (up to 4.5 cm), an electrode that rises 1 m above conveyor belt, and also an input voltage range of 0 to 100 kV. The use of DBD-ACP in strawberries and spinach leaves under industrial procedures was also studied by (Ziuzina et al., 2020); this technique necessitates additional adjustment of variables such the kind of electrodes used, the dielectric characteristics, and the conveyer belt design.
- According to (Andrasch et al., 2017), MW-CP applied in water and operated with compressed air demonstrated an antibacterial impact on lettuce in a manufacturing process.
- A DBD plasma system was suggested by (Misra et al., 2019) and would be indirectly applied by moving the meat through the tube. The authors suggested a simple design for the equipment to just get rid of micro - organisms. A novel quartz tube DBD-ACP system has been created by (Zhao et al., 2020) to generate plasma directly onto the surface of rolling spherical fruit. The plasma device treats the fruit surface uniformly, and without heating the fruit surface, it was seen that harmful bacteria were effectively killed.

- Today, various businesses all around the world have created CP technology with potential uses in the food industry.

A large selection of plasma treatment equipment is available from Henniker Plasma Company (*Henniker Plasma Treatment - Henniker Plasma*, n.d.), including plasma coating to alter the surface of a material, plasma etching to remove layers of a surface selectively, plasma surface activation to increase adhesion, and plasma surface cleaning to get rid of organic impurities. This business created the ACP robot system for surface treatment, which has a low cost per treatment unit and can treat complicated 3D shapes and micro-channels. The method was developed by Riedel Filter Technik (*Riedel Filtertechnik GmbH — Riedel Filtertechnik*, n.d.) and uses a DBD system operating at 30 kHz to get rid of odour molecules. A roll-to-roll atmospheric CP device that improves PET adherence was patented by Coating Plasma Innovation (COATING PLASMA INNOVATION - Coating Plasma Innovation, n.d.). High voltage, straightforward gazes to graft N2 molecules onto PET film, and speeds between 50 and 500 m/min are needed for plasma treatment. A PAW machine to substitute chlorine and a large gap pin-to-plane atmospheric-pressure plasma reactor used in foods were created by Plasma Leap Technologies (Plasma Leap, n.d.). Other benefits of this technique include lower operating costs due to the air working gas, the elimination of residual chemistry, an extended shelf life, and food safety. However, regulatory permission has not been requested and this equipment is only offered for sale for research and development reasons; a continuing inquiry is being done to see whether it is non-toxic.

- **Impact of cold plasma on environment -**

Any industry that processes food aims to meet customer demand for high-quality meals while also enhancing their level of living through net profits. The food processing sectors have been concentrating on energy use and energy savings during the last few years. This can only be done by using cutting-edge, unconventional technology, as thermal preservation methods utilize a lot of water and are expensive to manage waste water. Numerous writers claimed that compared to thermal processing, non-conventional methods had higher energy efficiency. According to Dalsgaard & Abbots, fossil fuels are the primary source of energy for conventional thermal processing, whereas electricity is mostly utilized for refrigeration and the production of mechanical power for pumps.(Jeremy Hill et al., 2012). According to reports, using cutting-edge, unconventional technologies like PEF and HPP may help minimize the use of cooling systems, which frequently account for almost 50% of all power usage. The employment of non-conventional technologies in the food processing industries of many developing nations is constantly being evaluated because the majority of these technologies not only save energy but also water (water scarcity was already occurred in many of world particularly in developing countries like India).(Rumpold & Schlüter, 2013) shown that plasma therapy is viewed as a viable substitute for other pharmacological or physical treatments (HPP, PEF, and irradiation). Plasma processes have the following benefits: high efficiency at low temperatures, precise plasma generation fit for the intended use, just-in-time production of the acting agent, minimal impact on the internal product matrix, application free of water or solvents, no residues, and resource-efficient. In comparison to conventional air treatment methods, cold plasma technology's main advantage in removing toxic and harmful volatile organic compounds (VOCs) from the food industries is its relatively low energy consumption and generally moderate cost. More importantly, though, is its capacity to treat air with low VOC concentrations at relatively low operating temperatures.(Preis et al., 2013)

- **Future perspective of cold plasma in food industry -**

To be used commercially in the food sector, a suggested technology must be effective and safe. Under ideal circumstances, CP is becoming more widely acknowledged as a viable non-thermal technique that can increase food safety with no impact on food quality (Scally et al., 2021). The procedure for obtaining regulatory permission, however, is still unknown. The procedure for obtaining regulatory clearance for novel food technology is governed by the nation's legal framework. The regulatory issues in the United States to allow a new DBD direct plasma treatment for whole wheat grain with the promise of reducing spoiling were recently discussed by. Three government agencies—the Federal Grain Inspection Service (USDA-FGIS), the US Environmental Protection Agency (EPA), and the US Food and Drug Administration—must debate and approve regulations for cereal grains (FDA)(Bourke et al., 2018b). These organizations are in charge of, in that order, regulatory supervision, treatment efficacy, product labelling, and residue determination. In Europe, the MEMO-15-5875v of the European Commission's Food Safety division outlines the approval of innovative technology. The evaluation criteria for CP technologies, such as risk to public health, nutritional disadvantage, and not deceptive to the customer, require clarity. Additionally, for each circumstance, it is important to carefully research and discuss the operating parameters, electrodes, barrier discharge arrangement, and their material, geometry, form, and wear. Food engineers and technologists may benefit from the knowledge provided in this study, and it has been shown that CP is an effective tool for assisting the food industry in delivering better, safer, and more sustainably produced goods.(Laroque et al., 2022).

- **Conclusion**-

Cold plasma is included in the category of nonthermal processing, which refers to a collection of methods that all strive to provide pasteurization effects without the use of heat. Possibilities for pesticidal action, residual chemical breakdown, product functionalization, and waste pre-treatment are provided by the novel physics and chemistry. Over recent years, cold plasma techniques like for food processing have grown in relevance for the detoxification of food borne pathogens in order to make food items with retained nutritional qualities and prolonged shelf lives. Cold plasma has demonstrated several distinct benefits over older technology in terms of providing answers to contemporary concern of industry in food sector. It is still early to explore cold plasma technology because it is so new in system design, scaling studies, eco-toxicity research, and mechanical insights before it can be used commercially. The implication is that we anticipate plasma processing in the food industry becoming more widespread in the future.

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