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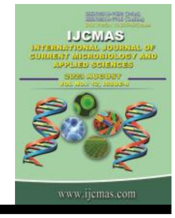

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Application of Cold Plasma in Food Science: A Novel Technique

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ABSTRACT

Fresh and safe food is the demand of customers in past decade, to fulfill this demand various novel technologies are being employed on food, one such technique is being discussed in this review i.e., Cold Plasma. Recently cold plasma has proven to be a budding technique primarily in food preservation sector. The main highlight of this technique is minimum heat damage, also the processing time to kill pathogens is considerably low as compared to other techniques. It is being utilized in killing pathogenic micro-organisms in various sectors of food. In this review we will see the mechanism behind generation of cold plasma as well as its types. The paper also summarizes its effect on different food sectors such as milk, meat, packaging, fruits, vegetables etc. Cold plasma is also being utilized in altering the food components as well as packaging materials. Despite being a promising option, the technique still is under scrutiny due to challenges faced by researchers which will be discussed briefly.

Introduction

There are 3 states of matter, solid, liquid and gas, but there is a fourth state of matter known as "Plasma" today, which was discovered in 1879 by Sir William Crookes. But it was given the term "Plasma" by Langmuir in 1928. Plasma does not occur naturally on earth but the universe is majorly made up of plasma, so it can be called as the most common state of matter. It's a misconception to believe that "Plasma" is always hot, it can exist in both thermal as well as non-thermal form. The non-thermal plasma can be referred to as Cold Plasma or Cold Atmospheric Plasma (Coutinho *et al.,* 2018)

Cold plasma technique is a novel technology which is being used in various food sectors as well as medical sector such as oncology studies. This technique is majorly used in inhibiting microbial attack on food as well as targeting the enzymes which is cause of enzymatic browning of many fruits and vegetables such as Polyphenol oxidase and peroxidases. It can be utilized in sterilization of heat sensitive materials (Thirumdas *et al.,* 2018). Plasma is considered as ionized gas, but it would not be right to say that all ionized gases as plasma (Adhikari and Khanal, 2013).

Cold Plasma is rapidly gaining influence as a novel technology in various sectors of food such as animal origin products such as milk and meat along with fruits and vegetable industry (Ziuzina *et al.,* 2014), it can be used for surface modification in several food products (Dong *et al.,* 2017), packaging industry (Jaobs *et al.,* 2011), which will be discussed in this review. Cold Plasma is also being used in several other fields such as to reduce anti-nutritional effect of cereals, food allergy, germination of seed etc.

As we already know, thermal technology is being used in various industry to battle with pathogenic micro-organisms, but often the heat damages the products sensory quality, so producers are continuously looking for other techniques such as HPP, Ultrasonication, Pulse Electric Field, Ohmic heating etc. instead of using heat induced methods (Mandal *et al.,* 2018), cold plasma has proven its worth in killing pathogenic microbes in various types of food, its main advantage is the short duration of exposure protects the food quality and minimizes textural losses which was investigated by various researchers.

In this paper we will discuss about the generation of cold plasma, how and which gases are used to generate reactive species and how these species can help in killing pathogenic microbial cells (Figure I and II).

We will also review numerous types of cold plasma techniques as well as their design elements. Next, we will discuss the effect of cold plasma in various food sectors and evidence of its effectiveness by previous literature. At last, we will discuss the future of plasma based on the study. The challenges of this technique will also be discussed briefly.

Generation of Cold Plasma and its Mechanism

Cold Plasma can be generated by various methods namely Corona discharge, plasma jets, DBD (Dielectric barrier discharge) (Surowsky *et al.,* 2013). In DBD method two electrodes are used between which a carrier gas moves and as it passes through it gets ionized, which in turn creates Plasma. Presence of high voltage is necessary in order to create plasma. The electrodes used in this technique can be cylindrical, flat or in some cases only one electrode is present.

In normal setup out of 2 electrodes one is grounded but in floating DBD setup one electrode is not grounded, it can be human skin or any organ. Another method is Plasma Jet or APPJ (Atmospheric Pressure Plasma Jet) in which electrodes are arranged in coaxial form between which gas travels (Hoffmann *et al.,* 2013). Other sources include glow discharge, radio frequency discharge etc. Various forms of energy can be used to ionize gases to create plasma such as electricity, heat, radiation etc. one of the advantages of non-thermal plasma is that it does not cause heat damage to food (Niemira, 2012).

Formation of reactive species is another characteristic feature of plasma generation. Reactive species include reactive oxygen (O, O_3) and nitrogen species (NO, N_2, NO_2, NO^+) These emerge as products of plasma generation. Exposure of contaminants to these reactive species leads to reaction with cell contents such as lipids, carbohydrates, nucleic acid which can cause cell lysis and ultimately death of cell. This feature is used as anti-microbial effect on food. Decontamination of food by cold plasma is dependent on several factors such as time of exposure of target, chemical nature of gas used for plasma generation and power used for plasma generation (Priya Arjunan and Morss Clyne, 2011)
The manner of exposure of food to plasma is also a

matter of interest among researchers. There is Direct Exposure, Indirect Exposure or use of Plasma activated water. All the above-mentioned delivery systems influence food in different ways.

Direct exposure requires food to be placed directly in path plasma discharge which leads to exposure of food to reactive species while indirect approach requires exposing the target to plasma discharge from a certain distance.

This is advantageous over direct method as it limits the damage in textural properties of food. Another method is introducing food to plasma activated water, food can either be immersed in PAW or it can be sprayed on the surface of food. This Plasma activated fluid can be stored for future purpose (Sarangapani *et al.,* 2018).

Cold Plasma technology is an eco-friendly novel technique which is being used in various sectors of food such as sterilization of food, surface modification of food for improvement in textural properties, Rheological studies in cereal food, diary industry, fruits and vegetable industry, packaging as well as in meat industry (Mir *et al.,* 2016). In this review we will study the applications of plasma in various food groups.

Types of cold plasma

DBD

The first person to conduct experiments on Dielectric Barrier Discharge was Seimens in 1857. DBD research was first done with the idea of production of Ozone, so it was also called as Ozone discharge (Li *et al.,* 2019). Another term which was associated with DBD was silent discharge which was used in various literatures. Sometimes the term “Corona Discharge” is also used but mostly when there is no involvement of Dielectric barrier material. As discussed earlier a typical DBD setup at least requires one dielectric barrier in the configuration. The dielectric barrier can be made up of ceramic materials, glass, silica or polymers etc. The operating electric field should be high in order to facilitate the breakdown of the carrier gas to form reactive species (Kogelschatz, 2003). Osawa and Yoshioka (2011) demonstrated the generation of plasma using alumina as discharge material in DBD setup. The frequency ranged from 10Hz to 1.1 kHz with air, oxygen, helium and nitrogen as carrier gas. The DBD setup is shown in Figure III and IV.

APPJ: Atmospheric Cold Plasma jet

As discussed above that APPJ gives a jet like appearance to the plasma. It is used directly on the substrate (Hertwig *et al.,* 2018). APPJ works at atmospheric pressure. The Typical design of APPJ consist of Co-axial or concentric electrodes in middle of which the target gases like helium, nitrogen etc. flows as shown in Figure V. It can operate on AC, DC or RF power. The plasma generated by this device exits through a nozzle and falls on the substrate.

The working temperature of APPJ can be 50 degree C to 300-degree C (Nehra *et al.,* 2008). The major difference of APPJ with DBD is that it can used to modify the three-dimensional structure unlike DBD or Corona discharge (Mandal *et al.,* 2018). In one of the recent research projects, a pilot APJ system was designed to kill the surface microflora of rice, sesame, and black pepper powder. They also studied changes in antioxidant properties of the sample food. The result showed decrease in the microbial content and no change was observed in the antioxidant property of the sesame and black pepper (Lee *et al.,* 2021).

PAW: Plasma Activated Water

Plasma activated water is another type of cold plasma technique on food used as disinfection agent of fresh food to reduce surface micro-flora. It can be referred as “Plasma Acid” or Plasma activated liquid (Figure VI). The main advantage of PAW over other methods of plasma application is that it is lot more convenient to apply and maintain. PAW can be generated by directly inducing plasma into water or by streaming it with water. During PAW generation there is generation of various acidic species which in turn make the water acidic, which in turn make the water acidic hence the name “Plasma Acid” (Thirumdas *et al.,* 2018). The acidic nature may be responsible for the anti-microbial effect of the water. Plasma acid was also known to be used in agriculture studies along with its application in food (Shainsky *et al.,* 2012).

Applications of Cold Plasma in Food Sector

Animal origin Products

Milk being a perishable food is a hub of different pathogenic microbes such as *Yersinia enterocolitica, Listeria monocytogenes Salmonella, E.coli*, etc. which is responsible for various type of diseases in human body, so it is necessary to treat milk to inactivate or kill these pathogens. Common methods used for pasteurization or UHT. UHT is far less acceptable than other technique as it leads to change in textural properties of milk.

Cold plasma can be a good substitute for sterilization of milk. Many Scientists have been studying effects of cold plasma in milk (Ahmad *et al.*, 2019). Gurol *et al.,* (2012) investigated possibility of using low temperature plasma technology for destruction of *E.coli* infected milk with variable fat content.

There was significant decrease in population of *E. coli* from 7.78 log CFU/ml to 3.63 log CFU/ml in 30-minute treatment of whole milk. Similar findings were observed in both skim milk and semi skim milk as well.

Another industry which uses Cold Plasma is the meat industry. As a perishable food affected by microbial spoilage Meat industry is in need of novel technologies to beat microflora like *Listeria monocytogenes, Salmonella sp.* and other pathogenic micro-organisms (Misra and Jo, 2017). Frohling *et al.*, (2012) studied effects of indirect APP used on fresh Pork using a microwave plasma set up and was successful in reducing the microbial count. Similar effects of Plasma treatment in animal origin food products can be seen in other work which is given in Table 1.

Fruits, vegetables and their value-added products

Fruits and vegetable sector is also known to be using this new technique for various functions such as surface modifications, sanitization of surface micro flora present in fruits & vegetables. Several vegetables & fruits have been investigated to check effects of plasma treatment on *E.coli* strains and other pathogenic micro-organisms. Bermúdez-Aguirre *et al.*, (2013) investigated use of APCP on *E.coli* inoculated produce such as tomato, lettuce, carrot etc. and significant result can be seen his experiments.

Cold plasma is also being researched for its use in surface modification of food. Another experiment is done by Bußler *et al.*, (2015) in which cold plasma has been used to increase the moisture binding ability of the protein present in *Pisum sativum*. Other applications are summarized in Table 2.

Other applications in the Food sector

Along with the applications of CP in food, it is also used in modification of starch as well as in improvement of packaging materials. Charoux *et al.*, (2021) also mentioned about different types of applications of plasma such as its effects in the mycotoxin level of rice, but there is still need for extensive study to know exact pathway of destruction of mycotoxins. Plasma is also being investigated for reduction of food allergens such as a-casein, tropomyosin, a-lactalbumin, Trypsin inhibitor etc. (Gavahian and Khaneghah, 2020).

In Packaging Industry, the main focus was improvement in barrier property of the material and effect of plasma on adhesion property is also discussed in various literature. Some other applications of Cold plasma are given in Table 3.

Table.1 Application of cold plasma in animal origin food

S. No.	Food type	Target micro-organism	Treatment	Dose and exposure time	Effect	Reference
1	Whole milk	*E. coli*	ACP (Atmospheric corona discharge)	9 kV AC for 3 minutes	Reduction of *E. coli* from 7.78 log CFU/ml to 3.63 log CFU/ml	(Gurol *et al.*, 2012)
2	Whole milk	*E. coli*	DBD plasma discharge	15 kHz for 5 to 10 minutes	Reduction from 6.28 log CFU/ml to 3.85 CFU/ml	(Kim *et al.*, 2015)
3	Whole milk	*L. monocytogenes*, *S. typhimurium*	DBD plasma discharge	15 kHz for 5 to 10 minutes	For *L. monocytogenes* Reduction from 6.43 log CFU/ml to 4.03 log CFU/ml For *S. typhimurium* Reduction from 6.21 log CFU/ml to 3.75 log CFU/ml	(Kim *et al.*, 2015)
4	Pasteurized milk	*E. coli*	Liquid plasma	4kHz for 2 minutes	6.57 Log CFU/mL reduced to 0	(Ponraj *et al.*, 2015)
5	Raw milk	*E. coli*	Liquid plasma	4kHz for 2 minutes	6.06 Log CFU/mL reduced to 0	(Ponraj *et al.*, 2015)
6	Whey Protein Isolate (WPI)	--	ACP treatment	70 kV for 1 to 60 minutes	- Increase in yellow colour - Reduction in p^H due to formation of reactive species during treatment - 15-minute treatment leads to increase in carbonyl group - Increase in emulsifying capacity - Foam stability improved on extended treatment	(Segat *et al.*, 2015)
7.	Fresh pork		APP (Indirect treatment)	1.3 kW at 2.45 kHz for 5-2 min	Indirect Plasma treatment was successful in holding	(Fröhling *et al.*, 2012)

					microbial count after 20 days storage at 10^2 CFU/g	
8.	Chicken breast	*L. monocytogenes*, *S. typhimurium*	Cold Plasma (DBD)	2W at 15 kHz (0 to 10 min)	Decrease in aerobic count of *L. monocytogenes* by 2.14 log cfu/g, *E. coli* by 2.73 log cfu/g and *S. typhimurium* by 2.71 log cfu/g	(Lee *et al.*, 2016)
9.	Pork	Total Plate Count Yeast and mold count	Cold Plasma (N_2, Argon and Helium Plasma Gas)	1.2 kVA at 20-100 kHz (10 min)	**Helium Plasma Treatment: -** reduced total microflora by 2 log CFU/cm^2 and psychrotrophs by 2.7 log CFU/cm^2 after 10-minute treatment **Argon plasma treatment**: - Psychotrophs reduced by 2.1 log CFU/cm^2, total bacterial count reduced by 2.3 log CFU/cm^2 and Yeast and mold count reduced by 2.6 log CFU/cm^2 after 10-min treatment **N_2 plasma treatment**: -yeast and mold count decreased by 0.5 to 1.0 log CFU/cm^2	(Ulbin-Figlewicz *et al.*, 2015)
10	Bacon	*E. coli*, *L. monocytogenes* & *S. typhimurium*	APP	75-125 W at 13.56 MHz (rf) for 60-90 sec (Helium and He+O_2 mixture)	**He+ O_2 mixture: -** Total aerobic count reduced to 2.5 Log CFU/g after 60s Treatment. *E. coli* count reduced to 4.80 log CFU/g after 90s treatment *L. monocytogenes* count reduced to 5.76 log CFU/g after 90 sec. *S. typhimurium* count	(Kim *et al.*, 2011)

					reduced to 6.46 log CFU/g after 90s treatment	
11.	RTE meat (Bresoala)	*L. innocua*	CAPP (Cold atmospheric pressure plasma)	15-62 W at 27.8 kHz (2-60 sec)	Decrease in population of *L. innocua* by 1.6 log CFU/g	(Rød *et al.*, 2012)
12.	Chicken Breast and Ham	*L. monocytogenes*	APPJ (Atmospheric pressure plasma Jet)	2kV at 50 kHz for 2 min (He, He+O_2, N_2 and N_2 +O_2)	Effect on *L. monocytogenes* population **He treatment: -** Decrease by 0.87 log units **He+O_2 treatment: -** Decrease by 4.19 log units **N_2 treatment:-** Decrease by 4.26 log units **N_2 + O_2 treatment:-** Decrease by 7.59 log units (most effective among all)	(Lee *et al.*, 2011)
13.	Raw poultry (Chicken breast and Chicken thigh)	*S. enteric, Campylobacter jejuni*	Cold Plasma (DBD)	30 kV at 0.5 kHz (0 to 30 sec)	*S. enterica* and *Campylobacter jejuni* was exposed to 30 s treatment by plasma using DBD which resulted in decrease on microflora by 0.85 and 0.21 log units respectively	(Dirks *et al.*, 2011)
14.	Cured Beef (Pastirma)	*Listeria monocytogenes* and *Staphylococcus aureus*	CAP	25 kV at 45kHz (180s and 300s exposure given to each sample) was used. Ar and Oxygen used to create plasma	*S. aureus* decreased from 5.78 log cfu/cm^2 to 0.85 log cfu/cm^2. *L. monocytogenes* reduced from 5. 71 log cfu/cm^2 to 0.83 log cfu/cm^2	(Gök *et al.*, 2019)

Table.2 Application of cold plasma in Fruits and vegetable sector

S.no	Food Type	Treatment	Dose and Exposure time	Effect	Reference
1.	Lettuce, Tomato and Carrot	APCP	3.95 kV to 12.83 kV at 60 Hz (30 sec – 10 min)	Decrease in *E. coli*population in all vegetables, Highest reduction was recorded in tomato.	(Bermúdez-Aguirre *et al.*, 2013)
2.	Pea (*Pisum sativum*) Protein	CAPP (Surface Dielectric barrier discharge)	8.8 kV at 3.0 kHz for 10 min	Increase in water and fat binding capacity of protein	(Bußler *et al.*, 2015)
3.	Sour cherry Marasca Juice	Cold Atmospheric Pressure Gas Phase Plasma	4 W at 20 kHz (3 to 5 min)	Increase in anthocyanin as well as Total phenolic acid content in plasma treated sample in comparison to pasteurized juice sample	(Garofulic *et al.*, 2014)
4.	Cashew apple juice	Indirect Cold Plasma treatment	Plasma in N_2 at 80 kHz for 5 to 15 minutes	Initial increase in Vitamin C and Total phenolic content of the product but overexposure tends to destroy the bioactive components	(Rodríguez *et al.*, 2017)
5.	Hazelnut, Pistachio and Peanuts	LPCP (Low pressure Cold Plasma) using air gas and Sulfur Hexafluoride gas (SF_6)	300 W (5 to 10 min)	Decrease in population of *A. parasiticus* population (1 log reduction in 5 min) & aflatoxin content by 50 %	(Basaran *et al.*, 2008)
6.	Zein powder (Protein)	ACP treatment (Dielectric barrier Discharge)	1 ± 0.2 A and 50 V to 125 V for 2 minutes at 45% RH	-Enhance the adhesion and Functionality of the protein polymer (Diameter of Zein protein reduced by 34 nm) - Solubility of the protein was improved in acidic and neutral solutions after treatment	(Dong *et al.*, 2017)
7.	Blueberry	ACP (Plasma jet)	549 W at 47 kHz from 0 to 120 sec	-Reduction in Aerobic plate count of Bacteria and Yeast and mold count. - APC< 1.5 log CFU/g after 60 sec treatments.	(Lacombe *et al.*, 2015)

				-More than 60 sec treatment leads to reduction in firmness of the fruit	
8.	Cabbage, Lettuce and dried Fig	CPT (Cold plasma treatment using N_2 gas or He- O_2 gas)	400-900 Watt at 667 Pascal for 1-10 minutes	Reduction in population of microbes -On Cabbage and lettuce CPT N_2 treatment reduced *S. Typhimurium* Population by 1.5 log Cfu/g -On cabbage the CPT He-O_2 treatment reduced *L. monocytogenes* population by 2.1 log CFU/g -On dried fig 10 min CPT treatment reduced *E. coli* population by 1.1 log CFU/g and *L. monocytogenes* Population by 1.3 log CFU/g	(Lee *et al.*, 2015)
9.	Strawberries	In package Treatment (ACP) using Dielectric barrier discharge	60 kV at 50 Hz for 5 minutes	Reduction in population of Total Mesophiles by 80 % and Yeast and mold count by 90 % -Mesophiles count (Reduced from 4.99 to 2.56 log CFU/g) -Yeast and mold count (Reduced from 4.96 to 1.56 Log CFU/g)	(Misra *et al.*, 2014)
10.	Red chicory (Radicchio Leaves)	ACP (DBD treatment)	15 kV at 12.5 kHz (15-30 min)	-Reduction in *E. coli* population by 1.3 log MPN/Cm^2 by 15 min treatment -Reduction in *L. monocytogenes* population by 2.20 log CFU/cm^2	(Pasquali *et al.*, 2016)
11.	Mango and melon	CAP	16 kV at 30 kHz for 5 to 30 sec	Reduction of microflora population of *E. coli, S. cerevisae, Pantoea agglomerans and Gluconacetobacter liquefaciens*	(Perni *et al.*, 2008)
12.	Mushroom and horseradish	CAPP	0 to 360 sec	Reduction in activities of PPO and POD enzymes and *Agaricus bisporus* and Horseradish	(Surowsky *et al.*, 2013)
13.	Apples	Atmospheric gas plasma treatment (DBD)	150 W (10, 20 & 30 min)	Influence Polyphenol Oxidase activity	(Tappi *et al.*, 2014)

14.	Strawberries and Cherry Tomato	ACP (DBD treatment)	70 kV (RMS) 10 to 120 sec	Reduction in *Salmonella, E. coli and L. monocytogenes* population by 3.8. 3.5 and 4.2 log CFU/sample respectively	(Ziuzina *et al.*, 2014)
15.	Brown Rice	Low Pressure cold plasma	40 W for 5 minutes and 50 W for 10 minutes	Reduction in cooking time of the rice by 8 minutes due to increase in gelatinization degree The water holding capacity was also enhanced by 7.2 % post treatment The hardness as well as chewiness of rice also seem to be reduced	(Thirumdas *et al.*, 2016)
16.	Tender Coconut water	High Voltage ACP	90 kV for 120 seconds	The population of *Salmonella* enterica serovar typhimurium LT2 was reduced uoto 5 log with addition of 400ppm of citric acid.	(Mahnot *et al.*, 2019)
17.	White Grape juice	High Voltage ACP	80 kV for 4 minutes	The population of S. cerevisiae was reduced upto 7.4 log cfu/ml of juice	(Pankaj *et al.*, 2017)
18.	Apple juice	Cold Plasma	1.32 kV with gas flow rate of 130ml/min for 60s.	The population of *A. acidoterrestris*was reduced to 99%.	(Ding, Hao, *et al.*, 2023)

Table.3 Other applications of cold plasma

S.no.	Substrate	Treatment	Dose and Exposure time	Effect	Reference
1.	Corn Starch	Cold Plasma (DBD)	75 W for 10 minutes	Change in rheological properties of starch: - -Conversion of Non-Newtonian behavior to Newtonian fluid, decrease in paste viscosity. -Treatment from 0 to 10 min led to reduction in consistency coefficient by 86%	(Bie *et al.*, 2016)
2	PET Foils	Low Pressure microwave plasma	2.45 GHz at 1–10 Pa	Improvement in barrier properties	(Schneider *et al.*, 2009)
3.	PET Foils	Low Pressure microwave plasma	850–5100 W at 2.45 GHz for 0.5 sec to 3.0 sec	Decrease in population of *B. subtilis* by 4 orders of magnitude on few seconds of treatment.	(Schneider *et al.*, 2005)
4.	LDPE film	Low-pressure glow discharge Plasma	RF discharge (13.56 MHz, 0-100 W) for 15-90 sec	Increase in adhesive properties post plasma treatment due to change in surface topology and morphology	(Ataeefard *et al.*, 2009)
5.	PP (Polypropylene)	Atmospheric Cold Plasma (DBD)	50-150 W at 18 kHz for 10-40 sec	Roughness of the surface is increased post treatment which in turn increases	(Wang and He, 2006)

				wettability	
6	BOPP	Low Pressure plasma Treatment	0 to 100 W at 13.56 kHz for 0 to 300 sec	RMS Roughness of the surface is increased post treatment from 36 Å to 69 Å	(Mirabedini *et al.*, 2007)
7	PET	Cold Plasma (DBD)	1.9 to 2.1 W at 5 kHz.	surface roughness increased by plasma treatment	(Jacobs *et al.*, 2011)
8.	*Salmonella enterica serovar typhimurium*	CAP	1 W at 1 kHz for 15 minutes	Reduction in the microbial population by 2.71 log cycles	(Fernández *et al.*, 2013)
9.	Oyster mushroom substrate	DBD-CP	60 kV for 0-25 minutes.	The microbial colonies reduced from 1.0^{9} CFU/ml to 1.5^{8} CFU/ml within 0-25 minutes.	(Linda *et al.*, 2020)
10.	Edible films **(**gelatin-carboxymethyl cellulose films)	Cold Plasma	19kV at 80 kHz with flow rate of 22.5 L/min	The viscosity of film decreased while its stability, surface roughness and gel voids increased.	(Zhang *et al.*, 2023)
11.	Zein film with PLA coating	DBD Cold Plasma	60 V and 1.5 Ampere current for 60s and 120s	Film resulted with better porous structure, increased biodegradability, more thermal stability, fracture resistance and surface hydrophobicity.	(Chen *et al.*, 2020)

Fig.1 States of Matter

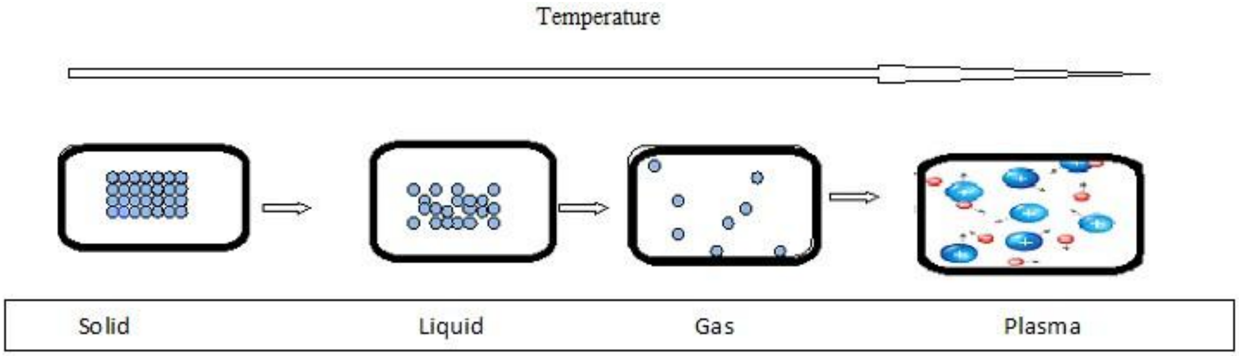


Figure 1 (States of matter)

Fig.2 Effects of Plasma on cell

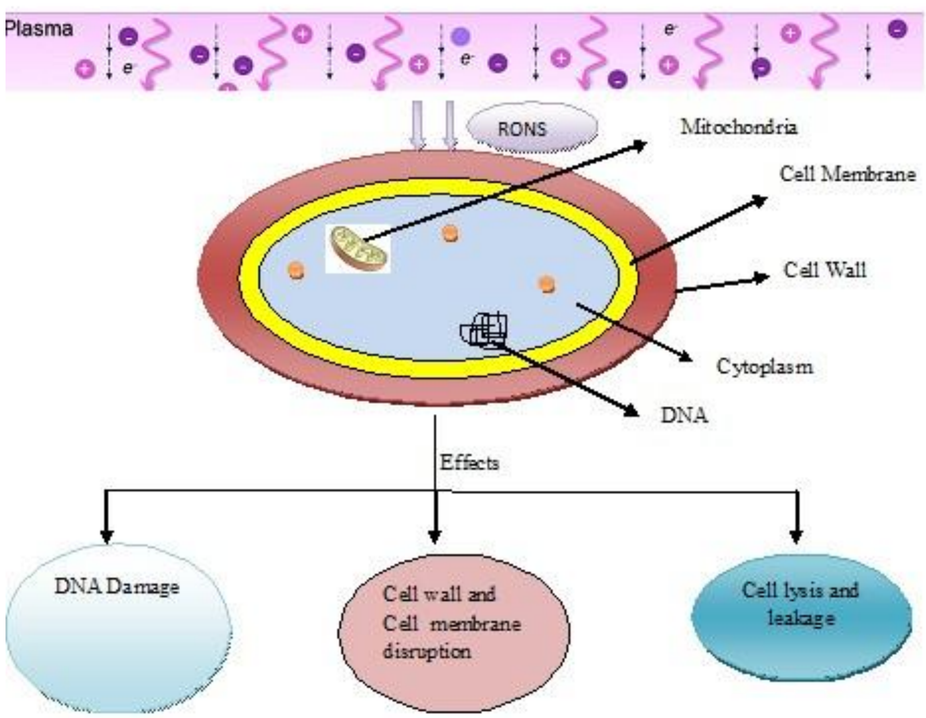


Fig.3 DBD setup

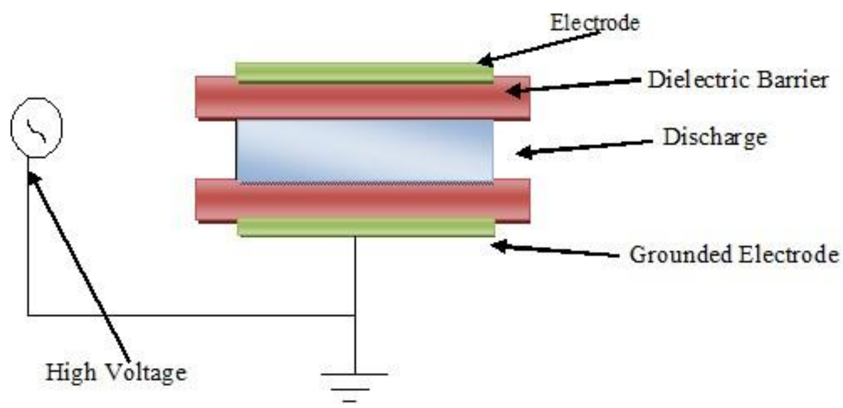


Fig.4 Floating Type DBD

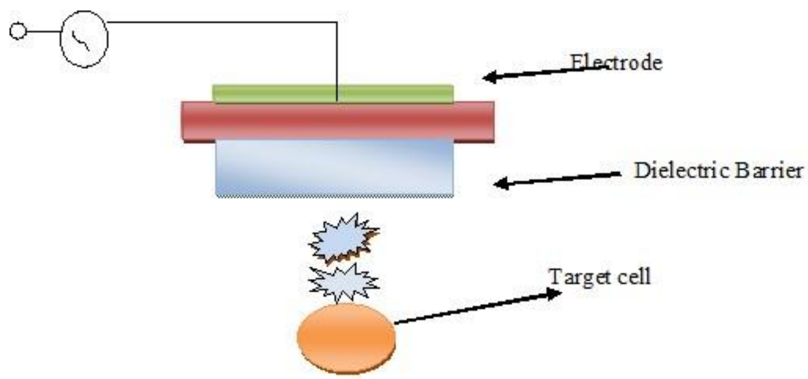


Fig.5 Atmospheric Plasma Jet

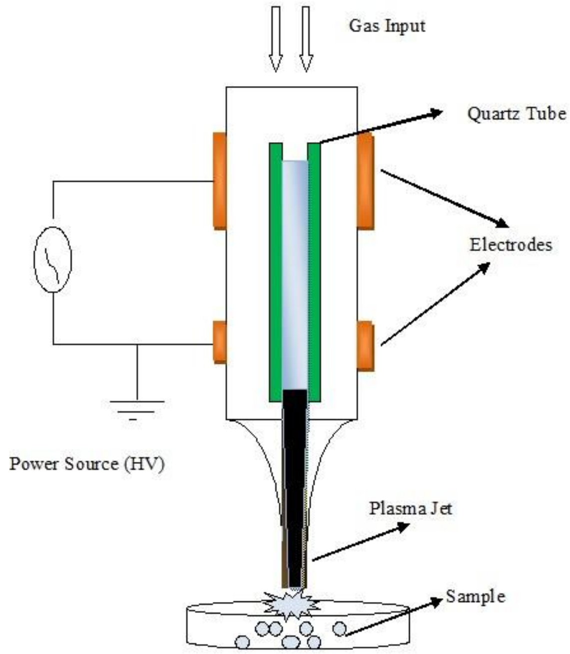
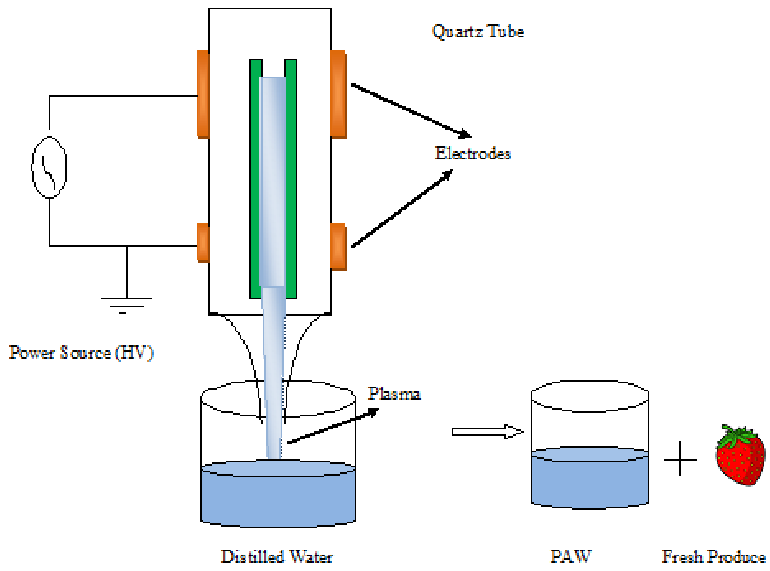


Fig.6 Plasma Activated Water



Challenges of Cold Plasma Technology

Significant Research has been going on application of plasma in different sectors of food as well as in other fields such as biomedical applications. Despite its successful application in food, plasma generation remains dependent on various factors such as flow rate of gas, temperature, humidity, the molecular composition of target gas, power distribution, electrode design (Co-axial or co-planar), distance between electrodes used in the system etc. These factors are to be considered for various types of food (Cullen *et al.,* 2018). In recent years several factors are driving people to explore plasma technique for minimization of food waste, increase in shelf life of food without chemicals, conservation of energy, need for green technology. All these factors are responsible for the interest of people in Cold Plasma, HPP (High Pressure processing Technology), Ultrasonication and other novel techniques (Keener and Mishra, 2016). Cold Plasma technique is being used in various other fields such as polymer technology.

Some challenges faced by researchers due to cold plasma such as Ekezie *et al.,* (2017) mentioned about toxicity of plasma generated food, the change in texture profile and colour on exposure to plasma, increase in acidity etc. Another negative impact is mentioned by Varilla *et al.,* (2020) that the reactive species generated during plasma application led to lipid oxidation in certain food which in turn affects its shelf life and ultimately overall acceptability. There were also reports of degradation of oligosaccharide by excessive treatment. Gavahian *et al.,* (2020) also reported that although the reactive species generated by cold plasma is effective in killing microbes but it also starts lipid oxidation due to presence of free radicals. It was also reported that DBD-ACP used on foxtail millet for storage damaged its carotenoid content if the treatment was 35kV (Wang *et al.,* 2022).

We came to conclusion that plasma can be a promising technique to replace the traditional food processing techniques, its applications in food as well as in other sectors make it a good technique for scale up applications. But there are some negative impacts reported by authors mentioned above, along with the negative impacts, some other concerns are about the limited data on its effect on sensory quality of food, also concerns about its commercialization is present. There also need to study in detail about effects of this technique on individual components of food and changes during the long-term exposure of food. Since food safety is the most important concern while applying any new technique, so role of government bodies in regulation making and implementation is most important in commercialization of the technique.

COI Declaration

The authors declare that the review was conducted without any form of financial or commercial relationships which could be a potential conflict of interest.

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