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Recent Advances in Cold Plasma Technology for Food Processing

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Abstract
Cold plasma (CP) is a novel non-thermal technology and has marked a new trend in both the sectors of agriculture and food processing for their safety and quality. This review describes an overview on the effects of CP with respect to microbial decontamination, enzyme denaturation, pesticide degradation, food allergens, polyphenols, food packaging, and many other physiological processes. Furthermore, mechanisms and applications involving different aspects related to cold plasma are discussed. The recent studies on cold plasma referred mainly with the interactions of reactive species and target food commodity. Finally, the future prospects and challenges that could help in rendering substantial benefits of CP to the food industries and researchers, particularly in upscaling this eco-friendly technology, are discussed.

Keywords Cold plasma · Antimicrobial effect · Food quality · Nutritional characteristics · Food sector

Introduction

Over a decade, non-thermal plasma has gained interest by food processing researchers. The reason for this could be its economical, eco-friendly, and versatile performance. At present, food safety is a major concern, and this could be more useful if maintained without affecting its nutritional, sensorial, and shelf-life properties. In this regard, non-thermal plasma possesses all the features to process the food economically without affecting their properties [1]. Let us go to the basics of plasma. When a gaseous substance is subjected to a high level of energy, it transforms into an ionized state of matter and is known as "plasma." The term "plasma" was first coined by Irving Langmuir in 1927 [2]. All types of plasma are basically ionized gaseous entity consisting of variety of elements, such as electrons, photons, ions, and free radicals. Elements like photons and electrons constitute the "light" species, and the rest of the elements are considered as "heavy" species [3–5]. On the basis of the temperature, there are two types of plasmas: non-thermal and thermal. Thermal plasma is generated under high power (≈50 MW) and extremely high pressures ($\geq 10^5$ Pa). Thermal plasma exhibits a thermodynamic equilibrium between the "heavy" species and the electrons. It ensures an overall consistent plasma temperature [4, 6]. On the other hand, non-thermal plasma can be obtained under low pressures and low power. These plasmas are also called non-equilibrium plasma in which the electrons exhibit much higher temperature compared to the gas at macroscopic level [4]. Therefore, no thermodynamic equilibrium is observed between the "heavy" species and the electrons. In this review, cold plasma and non-thermal plasma have been used interchangingly for low-temperature plasma.

Food consumption provides nutrition and development to an organism. In the current situation, food quality and safety have been a major concern for the food industry and food researchers. Therefore, tackling some food-related issues is the need of hour-like microbial contamination or any kind of enzymatic degradation in perishable food products [7, 8]. Moreover, there have been several studies on the existence of various types of food contaminants, such as mycotoxin [9–11], heavy metals [12, 13], and polycyclic aromatic hydrocarbons [14]. In this regard, pesticides and

Highlights

- Cold plasma exhibits antimicrobial effect and enzyme denaturation property.
- Cold plasma ensures food quality, better food safety, and food packaging.
- Cold plasma is an eco-friendly solution for food and agriculture industry.
- Cold plasma-treated food retains texture, nutritional, and sensory characteristics.
- Future scope of cold plasma technology in food sector.

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allergens deserve a special note on the account of exhibiting the most prominent effects among all the food contaminants [15–19]. Previously, several thermal techniques have been used for food processing and sterilizing, such as freezing, drying, and heating [20–22]. Other sterilization approaches, such as chemical treatments, are often tedious and leave behind the toxic residues [23]. Furthermore, in terms of food packaging, several conventional substances such as papers and metals have been replaced by polymers [24]. In addition to providing functional characteristics similar to those of the conventional substances, the polymeric substances give more flexibility, are essentially inert, much cheaper, and exhibit lower specific weight. For food packaging, multi-layered materials are in high demand. However, the production of multi-layered polymers necessitates the surface sterilization or modification of these materials. The surfaces of polymeric materials are usually hydrophobic and have low surface energy [25]. This characteristic renders the conventional strategies useless during surface sterilization of the polymers.

Cold plasma (CP) technique employs versatile application. CP has grabbed lot of awareness in the field of food safety and processing. It was initially used for other industries such as electronic and polymer industries. CP was used to enhance the surface energy of the materials, properties of paper and glass, and printing and adhesion properties of polymers [4, 26]. However, it has recently been recognized as a potentially useful in the domain of food safety and processing. It offers wide range of applications along with very short processing time without leaving any toxic residues [27]. Several researchers have shown that the presence of reactive species within the plasma makes it a good medium for the inactivation of microbial species. Therefore, sterilization using plasma would not only reduce the surface contamination of the food products but also increases their shelf-life [8, 28–35]. There are handful of studies describing the applications of cold plasma to imrpove food quality through enzyme degradation [36–40]. In addition, CP has been reported to enhance the characteristics of various food packaging materials [24, 41–43]. CP has also been reported to enhance several functional aspects of food products, such as seed germination [44–46], physico-chemical properties of grains [47, 48], hydrogenation of vegetable oils [49, 50], inactivation of anti-nutritional factors [51], and high-quality mung bean sprout [52].

Therefore, this article gives a synopsis on recent developments in the application of cold plasma (CP) for food processing industry in terms of food safety and quality maintenance. It includes background of plasma generation and its sources as well as types of setups and apparatus in current use. Mechanism and application of non-thermal plasma in different approaches of food processing are discussed for different targets. Furthermore, limitations and future prospects of CP have also been discussed. The recent understanding and potential use of CP, a green and eco-friendly technology, will provide new opportunities for boosting and sustaining food sector.

Basics of Cold Plasma Technology

Plasma Generation

Usually, plasma is produced by the application of energy to a gaseous substance. The energy can be applied via different approaches, such as electric current (direct or alternating), thermal energy, magnetic fields, microwave, or radiofrequencies. Such energy sources can impart energy to the gaseous atoms and molecules by, essentially, increasing the kinetic energy of the electrons within them. Such an increase in the kinetic energies of the electrons causes them to move from lower energy states to higher energy states, which leads to the generation of ions. In addition, it results in more frequent collisions between the electrons and the “heavy species” that release several types of radiations [53]. Although several sources could be employed for the energy input in plasma generation for food processing, an electrical discharge is preferred to produce the non-thermal plasma [54]. This is because the electric discharge approach helps in better regulation of the plasma temperature. Low temperature is the primary requirement of the plasma for use in food products processing [4]. The type of gas employed for plasma production as well as the frequency and magnitude of the electric current chiefly determine the type of active species present in it [55]. Plasma can be produced via various sources, such as corona discharge, dielectric barrier discharge (DBD), gliding arc discharge (GAD), microwave frequency, and radio frequency. However, with respect to food products and food processing industry, jet plasma and the plasma generated from DBD are the most commonly used plasmas [56].

Broadly, plasma works on the principles of ions collision in the substance without generating heat. On the application of electric energy between two electrodes, the kinetic energy of the gas molecules is increased. During the process, electrons are released from the cathode surface and accelerated towards the anode. Hence, ionization of gas molecules continues till the inelastic collision reached. In the process, dissociation of molecules may happen and releases the ions (Fig. 1). Hence, the process would bring out the changes in the materials under consideration.

Plasma Characteristics

As already mentioned, the intensity and the frequency of the electric current primarily determine the energy of the

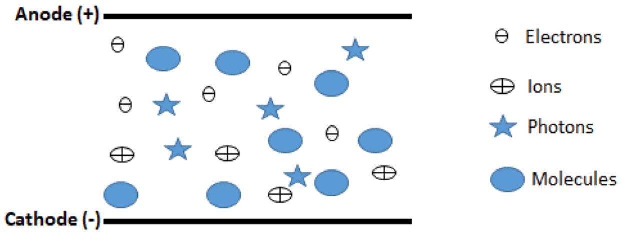


Fig. 1 Basic principles of plasma. On energy applications, ions generated lead to the collision of molecules and bring out the transformations

plasma and the type of active species present in it [1, 4]. Another important factor involved in the determination of the plasma characteristics is the composition of the source gas. The type of gas used decides the type of active species produced. Modified atmospheric packaging is extensively used to avoid food contamination. Misra et al. [57] reported a 3-log reduction in strawberries upon plasma treatment in sealed package containing oxygen, nitrogen, and carbon-dioxide. Moreover, type of exposure (direct or indirect) also defines the effect of generated reactive species [4, 55].

Target Characteristics

With respect to food safety, the antimicrobial effects of plasma have been studied extensively. The internal characteristics of the microbes are majorly influencing the efficiency of the plasma treatment. Different species and strains of microbes exhibit variable sensitivities to plasma exposure [58, 59]. Furthermore, gram-positive bacteria exhibit higher resistance to plasma treatment compared to gram-negative bacteria [58, 59]. Sporulated bacteria also exhibit higher resistance against the plasma treatment. Liang et al. [60] reported higher resistance of fungi to plasma because of the chitin present in their cell walls, and is imparting them more rigidity.

Other Factors

Several surrounding physical factors also determine the efficiency of plasma treatment, including the pH of the medium, temperature, relative humidity, and treatment time. The presence of humidity usually enhances the impact of plasma due to the formation of higher levels of hydroxyl radicals. Furthermore, solid and liquid matrices react differently against the plasma treatment. In fact, different matrices of the same state show variable interactions with the plasma species. For instance, plasma treatment can decontaminate an agar plate or a filter membrane more rapidly compared to a fruit surface [59].

Augmentation of Plasma Efficiency

All the above factors seem to be affecting the efficiency of plasma treatment and open up a wide domain of approaches to enhance the effect of plasma. Moreover, several techniques could be used in conjugation with plasma treatment to further improve the impact of plasma.

In general, food products are packaged under different mixtures of gases, which help in enhancing the shelf life of food products, minimize microbial contamination, and act as a preservative. Since the surrounding environment of the target plays an important role during plasma interaction, exposure to CP in the presence of these mixtures of gases has been exploited and found to enhance the sterilization efficiency of plasma [57, 61, 62]. Furthermore, the pH of the medium could be altered to enhance the plasma sterilization efficiency. For instance, use of sanitizers, plasma-activated water (PAW), and essential oils, in conjugation with CP treatment, has been shown to enhance CP efficacy [63, 64]. Moreover, Mehta et al. [62] also reported enhancement in polyphenolic components in strawberry juice when cold plasma processing was coupled with hydrothermal treatment. Furthermore, external magnetic fields have also been reported to enhance the efficacy of plasma by increasing its density [65].

Types of Plasma

Plasma consists of several species that are present either in excited or in their fundamental state but with an overall neutral charge [66]. CP is a type of non-thermal plasma that can be generated via various approaches at both atmospheric pressure and reduced pressure. For utilization in the food industry, CP at atmospheric pressure is preferred to minimize the risk of degradation of food products. Schematic diagram of different types of plasma is shown in Fig. 2.

Dielectric Barrier Discharge (DBD)

DBD setup includes two metal electrodes kept close to each other and separated by a dielectric material. Commonly used dielectric materials include quartz, ceramic, polymer, or plastic [67]. The gap between the discharge material ranges from 100 mm to a few centimeters. An alternating current is emitted by the electrodes to generate plasma [68]. The dielectric barrier essentially acts as a stabilizer that helps to create several micro-discharges [56]. Recently, a novel model of DBD plasma, known as “in-house” or “encapsulated” plasma has been employed. In the latter, the food for sterilization is enclosed in a plastic packaging material and kept in place of the dielectric materials [59, 69, 70]. DBD approach offers several advantages such as simple design, flexibility

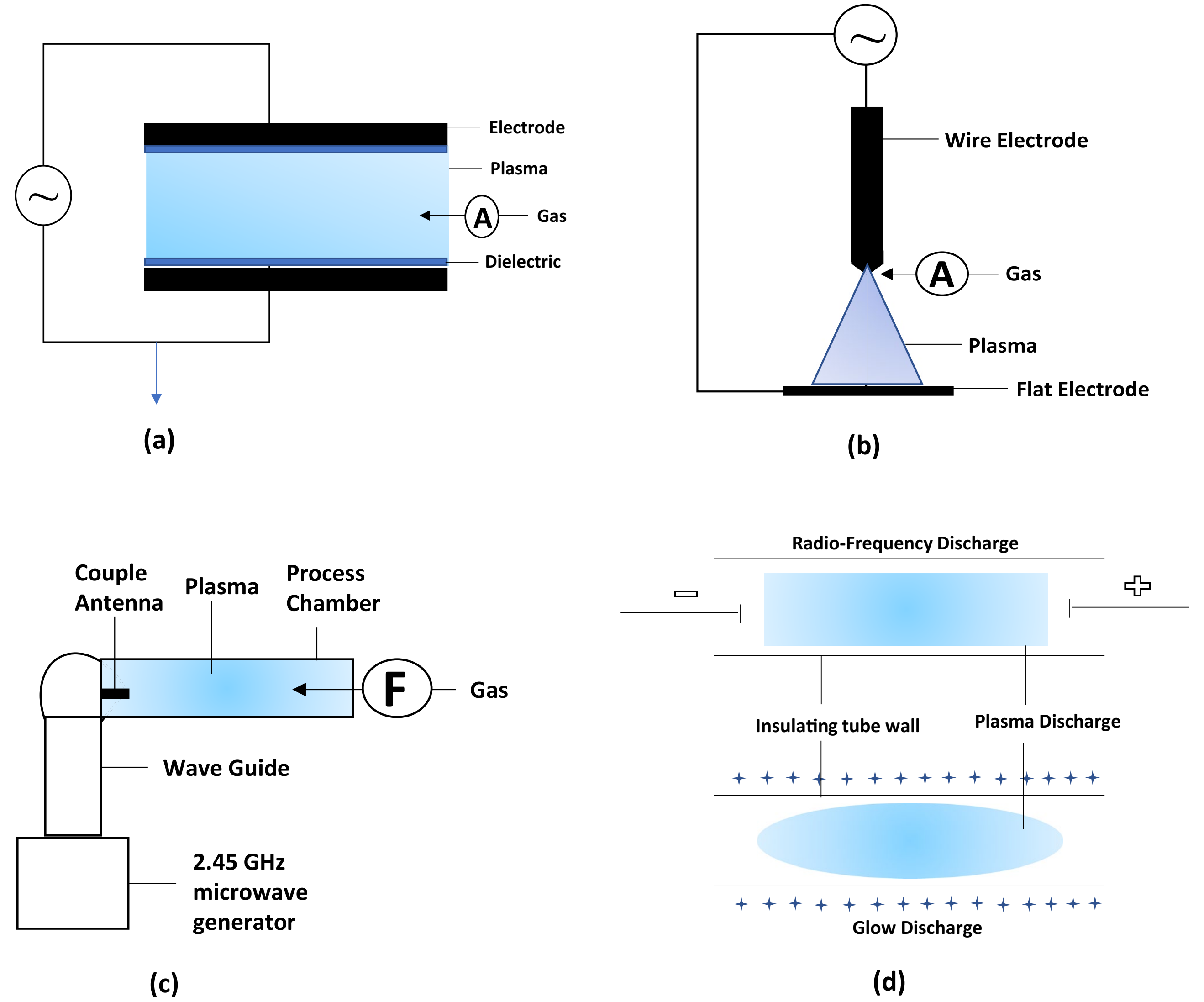


Fig. 2 Schematic diagram of different types of plasma. **a** Dielectric barrier discharge. **b** Corona discharge. **c** Microwave discharge. **d** Radiofrequency discharge

in terms of choice of gas and size of electrodes, and uniform discharge ignition. However, DBD plasma is produced at high ignition voltage of 10 kV and, hence, requires technical expertise and caution. A high level of energy is required to sustain DBD plasma, produced at atmospheric pressure. DBD plasma has also been used for UV generation, CO_2 lasers, and ozone generation [4].

The breakdown voltage as a function of pressure and distance between the electrode is represented by Eq. (1).

$$V_B = \frac{B(pd)}{C + log\ (pd)} \tag{1}$$

where $C = log\left\{\frac{A}{log\ (1+1/y)}\right\}$ and $V_B = \text{Ed}$, the total voltage applied between two electrodes. A and B are the constants depending on the gas used. The secondary emission coefficient (γ) depends on the material of cathode, the state of its surface, type of gas, and reduced electric field.

Gliding Arc Discharge (GAD)

GAD is created using two or more diverging metal electrodes and operates at a high potential difference (~9 kV). Approximately, 100 mA of electric current is passed through the electrodes, which leads to an arc formation in the narrower region between the electrodes. The inlet gas, carrying the humid air, flows from the narrow to the wider region between the electrodes and causes the arc to glide along with it. Based on the conditions, GAD could produce both thermal and non-thermal plasma at atmospheric pressure.

GAD setup could be used to produce a high concentration of short-lived active species by applying high electric power [71]. GAD can also be used to produce high density plasma. Since there is no thermodynamic equilibrium between electrons and other plasma components, it is classified as non-thermal plasma [3]. GAD plasma can be used for both liquid and surface sterilization. It has previously been used for organic compounds degradation, bacterial decontamination, and water purification [4, 72]. The Arrhenius equation used to express the radical reaction rate and describe the effective rate of associative ionization in the plasma is represented by Eq. (2).

$$R_e = \frac{n_e}{\tau_i} \exp\left(-\frac{E_a}{T_g R_u}\right) \tag{2}$$

where $\boldsymbol{\tau i}$ is a pre-exponential factor, $\boldsymbol{E_a}$ is the effective activation energy, $\boldsymbol{R_u}$ is the universal gas constant, and $\boldsymbol{T_g}$ is the gas temperature.

Corona Discharge Plasma

Corona discharge plasma refers to the plasma that is produced when an ample amount of electric field around a sharp electrode ionizes the electrons in the atoms or molecules of surrounding gases [6]. It is only produced at high voltage, and its applications are limited to non-homogenous medium. However, its design is simple and relatively less costly. This technique has been employed previously for the surface sterilization, microbe elimination, and electro-precipitation [4, 73]. Corona discharge gives the current in the gas, and the total current flowing between the electrodes in the discharge region is described by Eq. (3).

$$I_{tot}(t) = I_{ion}(t) + I_{disp}(t) \tag{3}$$

where $\boldsymbol{I_{ion}}$ is the ionic current component, and $\boldsymbol{I_{disp}}$ is the displacement current component.

Plasma Jet

The plasma jet device consists of two concentric electrodes, and a gas or a mixture of gases is flown between the electrodes. The inner electrode is subjected to a high radio frequency (~13.56 MHz), and a potential difference of 100–250 V is maintained between the electrodes that leads to ionization of the gas. The ionized gas molecules are directed out through a nozzle towards the surface of a food product located at a distance of few millimeters [28, 56, 74]. The ionized gas flows out through the nozzle in the form of a jet and hence, the name plasma jet. Plasma jet may also be generated by applying low-frequency kHz, nanosecond pulses, etc.

Capacitively Coupled Plasma (CCP)

CCP is most commonly used at the industrial level. CCP setup consists of two closely placed metal electrodes in a gas-filled chamber. One of the electrodes is attached to a radio frequency power supply and the other is grounded. The potential difference between the electrodes leads to the ionization of the gas. Since this setup resembles a capacitor, the plasma produced by it is termed as capacitively coupled plasma [75, 76]. CCP has a wide range of applications [24, 77].

Others

Inductively Coupled Plasma (ICP)

ICP refers to the plasma that is produced by the ionization of gas using the energy imparted by the electric current which is produced via electromagnetic induction [78]. Structurally, ICP setup is broadly classified into two categories: cylindrical and planar. In planar design, a spiral-shaped coil of flat metal is used as an electrode. In cylindrical design, the metal electrode is in the shape of a helical spring. With the passing of an electric current through the electrode, a magnetic field is created that induces the electric current into the target gas and ionizes it into plasma. Since the electric current is produced in the gas via a magnetic field, there is no need for the electrodes to be in direct contact with the gas and, hence, the electrodes are placed outside the reaction chamber [24].

Microwave Plasma/Electron Cyclotron Resonance Plasma (MP/ECR Plasma)

The MP plasma is generated using electromagnetic waves with high frequencies. Contrary to the electrode-based methods, a magnetron is used to produce microwave discharges in a process chamber. The heat produced by the microwaves causes ionization of the gas molecules. The major advantage of MP is the non-requirement of electrodes that allows ionization of the gas in free air and reduced the level of gas required to produce the plasma. However, the main limitation of ECR is that it cannot be used over a large area unless an array of discharges is used [4, 79]. Some basic magnetic circuits can be used are horseshoe magnet with iron keeper (low-reluctance circuit), horseshoe magnet with no keeper (high-reluctance circuit), electric motor (variable-reluctance circuit), and pickup cartridge (variable-reluctance circuits).

ECR plasma is a type of MP, produced by using microwaves with 2.45 GHz [80]. Electrons trajectory is in the form of a vertical spiral along the magnetic field lines. In ECR design, the electrons flow along the magnetic lines in a vertical spiral and ionize the gas molecules to produce plasma. This type of plasma is more efficient for surface treatments, such as surface deposition, surface functionalization, and surface etching [24, 81, 82].

Basically, an ECR and microwave ion source comprises of a multimode cavity. This cavity serves as the plasma generation and containment cavity. In the plasma drifts down the axial magnetic field gradient, the electrons are resonantly excited by the high-frequency field at a frequency explained through the following Eq. (4).

$$\omega_{RF} = \omega_C = \frac{eB}{m_e} \tag{4}$$

In this, ω_{RF} is the excitation frequency, ω_c is the electroncyclotron frequency, e is the magnitude of the electronic charge, B is the magnetic flux density, and m_e is the electron mass.

For more complete description of these phenomena, please see the following articles [83–85].

Mechanism and Applications of Plasma

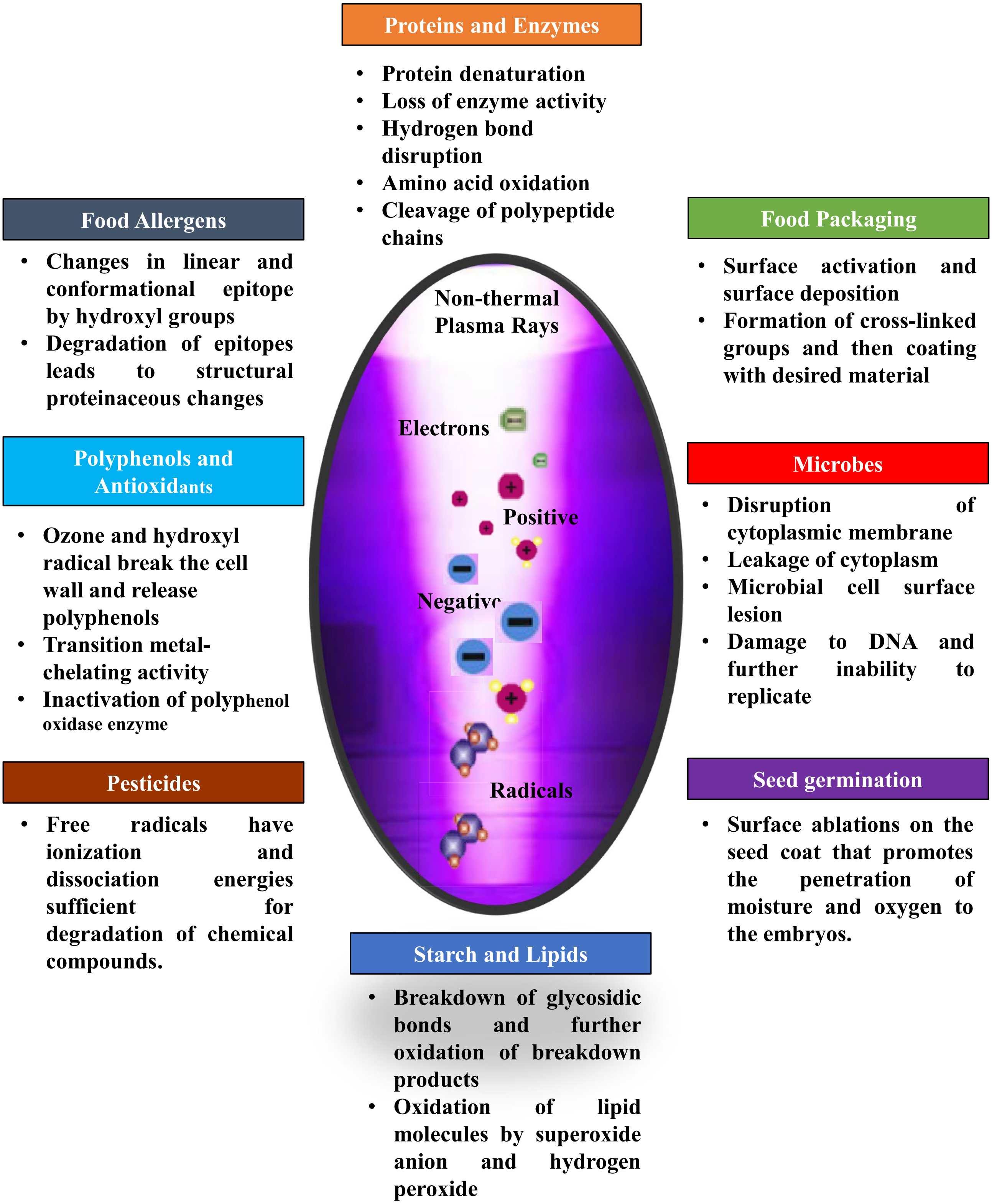
All the entities present in the plasma, whether charged or neutral, play a significant role in its action. Apart from physical particles (ions, free radicals, electrons), plasma also comprises of radiations, such as UV. For various applications of the plasma, different plasma components are needed. Various hypotheses have been given to explain the mechanism of action by reactive species generated by cold plasma. For instance, cold plasma generates reactive and charged particles that induce numerous chemical reactions owing to the possession of sufficient electrical energy to break covalent bonds that lead to the breakdown of cell membrane via hydrolysis [86]. Another mechanism could involve the erosion of tissues and release of the bioactives accumulated in central vacuoles of guard cells under the effect of reactive oxygen species such as $\cdot$OH, O, and O_2 [62, 87]. However, the mechanism of action of each plasma component remains more or less similar (Fig. 3). Applications of cold plasma are discussed under the following headings, viz, microbial inactivation, enzymes inactivation, stability of polyphenols, pesticide degradation, food allergen degradation, food packaging, effect of CP on starch, vitamins, and lipids, and seed germination.

Microbial Inactivation

During microbial decontamination, the cytoplasmic membrane of the microbe plays a crucial role. The efficiency of sterilizing agents and techniques majorly depends on their ability to penetrate the cytoplasmic membrane of the microbes and eliminate them. Interestingly, in terms of disruption of the cytoplasmic membrane, the oxidizing potential of the sterilization agent has been shown to be very crucial [33]. Therefore, the oxidizing agents in the plasma play a critical role in eliminating the microbes. In addition, several mechanical effects of plasma have also been reported to be mediated by the free radicals present in it, such as $OH^\bullet$ and $NO^\bullet$ radicals [53, 88, 89]. During plasma treatment, several such free radicals interact with the microbial cells and cause surface lesions. Due to the high frequency of the formation of these lesions, the cell does not get enough time to repair itself and get destroyed. This process is termed as “etching” [90]. The most widely accepted mechanism of plasma-induced DNA damage includes the formation of reactive oxidative species (ROS) by plasma elements in the microbial cells that damage their DNA molecules. The major plasma-induced ROS include H_2O_2, superoxide anion, and hydroxyl radicals [53]. The most prominent mechanism of plasma-induced microbial destruction includes the reaction of plasma elements with the water molecules inside the microbial cells that leads to the generation of hydroxyl radicals and responsible for most of the DNA damage [53]. Studies have also proposed that the accumulation of charged particles within the microbial cells induces the apoptosis, electroporation, and electrostatic disruption [31, 58].

Several studies have demonstrated the antimicrobial effects of CP [34, 91–94]. Recently, CP treatment has been reported for decontamination of tofu [28] and black pepper grain [91]. Moreover, reduction in microbial content has also been reported in chicken breast [70] and pork jerky [35]. Also, decontamination of dried squid has been performed using corona discharge plasma [73]. A study has also revealed the decontaminating effects of microwave-induced CP on onion powder without any visible effects on their sensory characteristics [95]. Wan et al. [96] have successfully used the CP technique for the decontamination of egg shells. Similarly, microwave-induced CP has been used to eliminate *E. coli* from lettuce with a 90% efficiency [97] and from radish [98].

As mentioned above, the efficiency of the plasma depends on the sample characteristics as well. CP is much more effective against *Botrytis cinerea* compared to ozone or UV-C exposure [99]. CP showed effective decontamination of fresh produce within 10 s of exposure, while the same efficacy of CP was attained for decontamination of strawberries after 300 s of exposure [100]. The in-package sterilization technique has been shown to be highly advantageous because the sealed sample can be directly exposed to the plasma without any leftover contamination after the process [33, 101, 102]. Indirect air plasma, such as plasma jet, has been used to create plasma-activated water (PAW) that has an acidic pH and contains several active species [103]. PAW, in turn, has been shown to exhibit antimicrobial effects [104]. Synergistic effects of pH and plasma species have been proposed to be responsible for



Proteins and Enzymes

- Protein denaturation
- Loss of enzyme activity
- Hydrogen bond disruption
- Amino acid oxidation
- Cleavage of polypeptide chains

Food Allergens

- Changes in linear and conformational epitope by hydroxyl groups
- Degradation of epitopes leads to structural proteinaceous changes

Polyphenols and Antioxidants

- Ozone and hydroxyl radical break the cell wall and release polyphenols
- Transition metal-chelating activity
- Inactivation of polyphenol oxidase enzyme

Pesticides

- Free radicals have ionization and dissociation energies sufficient for degradation of chemical compounds.

Food Packaging

- Surface activation and surface deposition
- Formation of cross-linked groups and then coating with desired material

Microbes

- Disruption of cytoplasmic membrane
- Leakage of cytoplasm
- Microbial cell surface lesion
- Damage to DNA and further inability to replicate

Seed germination

- Surface ablations on the seed coat that promotes the penetration of moisture and oxygen to the embryos.

Starch and Lipids

- Breakdown of glycosidic bonds and further oxidation of breakdown products
- Oxidation of lipid molecules by superoxide anion and hydrogen peroxide

Fig. 3 A scheme to show the action of cold plasma on different aspects of food functionality and food safety

Table 1 Effect of CP on microbes

Sr. no	Food product	Microbe	Plasma source	Observation	Reference
1	Tofu	*S. enteritidis* and *E. coli* O157:H7	Plasma jet	Log_{10} reductions attained ranging from 0.2 to 0.6 $\log_{10}$	Frías et al. [28]
2	Black pepper grains	*Bacillus subtilis* vegetative cells and spores	Plasma jet	1-log reduction was achieved in the case of black pepper inoculated with spores	Charoux et al. [91]
3	Chicken breast	Mesophiles, psychrotrophs and *Enterobacteriaceae*	DBD	1.5, 1.4, and 0.5 log lower than the control	Moutiq et al. [70]
4	Red pepper	*Aspergillus flavus&Bacillus cereus*	MCPT	Reduction of spore count by 0.7 ± 0.1 and 1.5 ± 0.2 log spores/cm^2	Kim et al. [79]
5	Pork jerky	*Staphylococcus aureus* and *Bacillus cereus*	DBD	Reduction in both bacterial content	Yong et al. [35]
6	Blueberry	***Botrytis cinerea***	DBD	Effectively inhibited the growth of *Botrytis cinerea*	Zhou et al. [99]
7	Chicken breast meat	*Campylobacter* and *Salmonella*	DBD	Growth was inhibited after treatment	Zhuang et al. [102]
8	Pepper powder	*E. coli*	DBD & RF	Reduction of E. *coli* to 9 log CFU/g	Choi et al. [89]
9	Apple juice	*E. coli*	DBD	3.98 to 4.34 log CFU/mL reduction	Liao et al. [172]
10	Tangerine juice	*E. coli*	HVACP	*E. coli* was reduced by 4.8 $\log_{10}$ CFU/mL	Yannam et al. [34]
11	Apple juice	*Zygosaccharomyces rouxii*	DBD	5-log reduction	Xiang et al. [173]
12	Mandarin	*Penicillium italicum*	MP	Reduction in incidence of disease	Won et al. [174]
13	Chicken eggs	*Salmonella enteritidis*	HVACP	Reduction of 5.53 log CFU/egg	Wan et al. [96]
14	Lamb meat	*Brochothrixthermosphacta*	DBD	Reduction by 2 log cycle	Patange et al. [175]
15	Radish sprouts	*Salmonella typhimurium*	MP	Reduction of 2.6 ± 0.4 log CFU/g	Oh et al. [98]
16	Egg shells	*Salmonella Enteritidis*	Jet plasma	Reduction up to 2.7 log CFU/egg	Moritz et al. [176]
17	Romaine lettuce	*Escherichia coli*	DBD	Decrease of 0.4–0.8 log CFU/g	Min et al. [177]
18	Tomatoes	*Escherichia coli*	DBD	Decrease of 6 log CFU/g	Prasad et al. [33]
19	Onion powder	*Aspergillus brasiliensis, Escherichia coli, Bacillus cereus*	MP	Reduction of 1.6, 1.9, and 2.1 log spores/cm^2, respectively	Kim et al. [95]
20	Groundnut	*Aspergillus flavus, Aspergillus parasiticus*	RFP	99.3% and 97.9% reduction, respectively	Devi et al. [178]
21	Dried squid	Marine bacteria, *Staphylococcus aureus, Aerobic bacteria*	Corona discharge plasma	Reduction of 1.6, 0.9, and 2.0 log units, respectively	Choi et al. [73]
22	Hazelnuts	Aflatoxigenic fungi (*Aspergillus flavus* and *Aspergillus parasiticus*)	Atmospheric pressure fluidized bed plasma	Significant reductions of 4.50 log (CFU/g) in *A. flavus* and 4.19 log (CFU/g) in *A. parasiticus*	Dasan et al. [179]
23	Celery, radicchio and deionized water	*L. monocytogenes and E. coli*	DBD plasma	6-log CFU/mL reduction in deionized water and reduction up to 2.5 and 3.7 log CFU/cm^2 for *L. monocytogenes* and *E. coli* in liquid medium vegetables, respectively	Berardinelli et al. [88]

Table 1 (continued)

Sr. no	Food product	Microbe	Plasma source	Observation	Reference
24	Pork butt and beef loin	*Listeria monocytogenes, Escherichia coli O157:H7, and Salmonella Typhimurium*	DBD	Microbial reductions were 2.04, 2.54, and 2.68 log CFU/g in pork-butt samples and 1.90, 2.57, and 2.58 log CFU/g in beef-loin samples, respectively	Jayasena et al. [30]
25	Fresh lettuce	*Escherichia coli* O157:H7 and *SalmonellaTyphimurium*	MP	Effective in reduction of microbial growth	Song et al. [97]

APP atmospheric pressure plasma, *HVACP* high-voltage atmospheric cold plasma, *MP* microwave plasma, *DBD* dielectric barrier discharge, *RFP* radiofrequency plasma, *MCPT* microwave-combined plasma treatment

the non-thermal sterilization by PAW [105]. Application of plasma-activated water (PAW) has been documented for food decontamination [106]. Some antimicrobial effects of CP are listed in Table 1.

Enzymes Inactivation

Majority of enzymes found in the food products are proteinaceous in nature. Hence, the mechanisms of action of CP on enzymes and other proteins are similar. Plasma-induced changes in the protein structure are primarily attributed to the active plasma species. For instance, protein inactivation induced by helium/oxygen plasma is mainly due to nitric oxide and atomic oxygen. Atomic oxygen in the plasma is able to remove the hydrogen from the protein backbone. This has led to the generation of radical sites and hence the cleavage of polypeptide chains [38]. Hydroxyl, hydroperoxy (HO_2), nitric oxide, and superoxide anion radicals in the plasma could also modify the side-chains and aromatic rings of amino acids, leading to enzyme inactivation [107]. While the oxygen-based plasma species can cause structural changes in protein by converting C–N, N–H, and C–H bonds to NO_2, H_2O, and CO_2, respectively. Plasma species such as O^{2-}, H_3O^+, and O^{2+} are able to increase the polarity of zein molecules, a major protein found in maize [108].

Enzymatic browning has been a major problem in the food industry. CP has been used for the inactivation of several enzymes, such as polyphenol oxidase (PPO), pectin methylesterase (PME), superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), lysozyme, alkaline phosphatase, a-chymotrypsin, and lipase [7]. Recently, inactivation of peroxidase enzyme in green coconut juice and amazonia juice has been reported upon CP treatment [38, 109, 110]. Moreover, lipase and lipoxygenase enzyme in wheat germ have been reported to be inactivated by CP [40]. Also, CP can be used for the extension of the storage time of potatoes and apples by inactivation of POD and PPO enzymes [36]. Furthermore, mild inactivation of PME, a cell wall-bound enzyme, has been documented using DBD in fresh-cut melon [39]. Their results have concluded that different enzymes are exhibiting different sensitivities to CP based on their structures. A significant decrease in alkaline phosphatase activity was observed within seconds after treatment with CP [111]. Similarly, a 70% and 10% decrease in PPO activity has been documented in the CP-treated guava pulp and whole fruit, respectively [53]. However, CP treatment is not effective for all types of enzymes. CAT and SOD activities were increased upon CP treatment in blueberries [99], while PAW was inefficient for the inactivation of the SOD enzyme in button mushrooms [112]. Some food enzymes affected by CP treatment are listed in Table 2.

Stability of Polyphenols

Antioxidants pose a problem during plasma treatment owing to the fact that they exhibit the opposite action to that of free radicals. They protect the cells against reactive oxygen species (ROS). However, the ozone and hydroxyl radicals present in the plasma could degrade flavonoid compounds [62]. Similarly, an increase in the level of polyphenols was observed on the treatment of sour cherry marasca juice with CP [87].

Studies have shown a decrease in the level of phenolic compounds in various food products such as orange juice, lamb's lettuce, and white grape juice after treatment with CP [113, 114]. In contrast, de Castro et al. [110] and Rana et al. [115] applied cold plasma and reported an increase in phenolic compounds in camu-camu juice and strawberry fruit, respectively. Also, cold plasma has enhanced the phenolic compounds in tomato-based beverage, siriguela juice, and blueberry juice [62, 74, 86]. Moreover, Rodríguez et al. [116] and Sarangapani et al. [117] reported an increase in the content of phenols upon CP treatment in cashew apple juice and blueberries, respectively. These varied results have necessitated further research on the CP effects and mechanism of actions of different phenolic compounds. Thus, the

Table 2 Effect of CP on enzymes

Sr. no	Food product	Enzyme	Plasma source	Observation	Reference
1	Green coconut water	Peroxidase	DBD	Inactivation of peroxidase enzymeon application of higher frequencies	Porto et al. [38]
2	Amazonia juices	Peroxidase and polyphenol oxidase	Glow plasma	Higher reduction in enzyme activity	Castro et al. [109]
3	Potato	Polyphenol oxidase	MCPT	Inactivation of polyphenol oxidase by 49.5%	Kang et al. [37]
4	Tender coconut water	Peroxidase and polyphenol oxidase	DBD	Inactivation of both enzymes. Peroxidase was found more resistant than polyphenol oxidase	Chutia et al. [180]
5	Blueberry	Peroxidase activity and ascorbate peroxidase	DBD	Initially increased and then decreased in stored blueberries	Zhou et al. [99]
6	Wheat germ	Lipase and lipoxygenase	DBD	Higher voltage and treatment time led to higher inactivation	Tolouie et al. [40]
7	Apples	Polyphenol oxidase	DBD	Decrease in the level of browning	Tappi et al. [181]
8	Tomato slices	Polyphenol oxidase	DBD	Inactivation of peroxidase enzyme by more than 90%	Khani et al. [182]
9	Apple slices, potato cubes	Polyphenol oxidase, Peroxidase	MPT	Polyphenol oxidase activity was reduced by about 62% and 77%, respectively, and peroxidase activity reduced by about 65% and 89%, respectively	Bußler et al. [36]
10	Orange juice	Pectin methylesterase	DBD	Reduction in pectin methylesterase activity by 74% in air and 82% in modified atmosphere packaging	Xu et al. [94]
11	Germinating mung beans	Phytase	RFP	Amylases and proteases activity got enhanced after the treatment	Sadhu et al. [169]
12	Melons	Peroxidase	DBD	Exposure time-dependent decrease in activity	Tappi et al. [39]
13	Melons	Pectin methylesterase	DBD	94% residual activity after 30 + 30-min treatment	Tappi et al. [39]
14	Mushrooms	Superoxide dismutase	Plasma jet	Increase in activity during storage	Xu et al. [112]
15	Raw milk	Alkaline phosphatase	DBD	90% inactivation of enzyme	Segat et al. [111]
16	Brown rice	Lipoxygenase	DBD	9.2% inactivation of enzyme	Chen et al. [183]

DBD dielectric barrier discharge, *RFP* radiofrequency plasma, *MCPT* microwave-combined plasma treatment, *MPT* microwave-driven plasma torch

plasma source, the food products, mode of exposure, and other treatment parameters have been observed to be critical for the impact of CP on polyphenolic compounds. Effects of CP application on the polyphenols/antioxidant components of food matrix are tabulated in Table 3.

Pesticide Degradation

Pesticides present in the food stuff are difficult to degrade and eliminate. As a result, they enter the food chain and accumulate in the bodies of the animals, soil, and water bodies. This process is termed as “bioaccumulation” and is regarded as an ecological hazard due to the toxic nature of the pesticides. Importantly, the source gas composition and the overall plasma energy are critical to be involved in plasma-mediated pesticide degradation [117]. Organic molecules of the pesticides possessed similar ionization and dissociation energies to those of the electrons in CP. Therefore, they are easily dissociated upon plasma applications [118, 119]. In addition, the high oxidizing potential of free radicals in the plasma also makes them to participate in the degradation of pesticide molecules, and releasing fewer toxic compounds [118].

Different plasma species show varied efficacies on different types of pesticides. For instance, in the degradation of dichlorvos and organophosphorus pesticides, free radicals and electrons have been deemed to be most effective [118–120]. Several methods of pesticide degradation, such as photocatalysis, adsorption, ultrasound, Fenton oxidation, and membrane filtration, have been explored [121–125].

Table 3 Effect of CP on polyphenols

S. no	Food material	Plasma source	Observation	Reference
1	Tofu	APP	Retention of 80% of total phenolic content	Frías et al. [28]
2	Camu-camu juice	DBD	Significant increase in phenolic compounds	de Castro et al. [110]
3	Strawberry fruit	DBD	Increase in concentration of individual and total polyphenolic compounds	Rana et al. [115]
4	Green coconut water	DBD	Slight changes in phenolic compounds	Porto et al. [38]
5	Strawberry juice	DBD	Increased concentration of individual and total polyphenolic compounds when coupled with hydrothermal treatment	Mehta and Yadav [69]
6	Apple juice	Spark and glow discharge plasma	Increment in total phenolic content	Illera et al. [184]
7	Olive oil	Plasma jet	No adverse changes in phenolic content	Amanpour et al. [185]
8	Tomato-based beverage	DBD	Enhanced individual and total phenolic content	Mehta et al. [62]
9	Siriguela juice	Glow discharge plasma	Increased total phenolic content	Paixão et al. [86]
10	Blueberry juice	Plasma jet	Enhanced phenolic content	Hou et al. [74]
11	Fresh-cut apples	DBD	Increment in phenolic compounds after 10-min treatment	Tappi et al. [186]
12	**Apple, orange, tomato juices, and sour cherry nectar**	Plasma jet	Higher phenolic content in comparison with untreated	Dasan and Boyaci [187]
13	Cashew apple juice	Indirect plasma mode	Higher polyphenolic content after longer exposure	Rodríguez et al. [116]
14	White grape juice	DBD	Decrease in total phenolic content	Pankaj et al. [114]
15	Blueberries	DBD	Increased polyphenolic content	Sarangapani et al. [117]
16	Chokeberry juice	Gas phase plasma	Increased concentration of hydroxycinnamic acids	Kovačević et al. [188]
17	Orange juice	DBD	No changes in total phenolic content	Almeida et al. [113]

DBD dielectric barrier discharge, *APP* atmospheric pressure plasma

However, these methods are not feasible for industrial applications due to either incomplete pesticide degradation or generation of undesirable by-products. Recently, the focus has been turned in this regard to the plasma technique.

The use of "plasma-activated water" (PAW) has been reported effective in the degradation of pesticides on tangerine and grapes [119, 126]. Also, the reduction of pesticides like chloropyrifos, carbaryl, and cypermethrin has been documented by DBD plasma [71, 127, 128]. Furthermore, Mousavi et al. [129] showed a complete degradation of organophosphorus pesticides in cucumbers and apples using CP treatment. Similarly, use of high efficiency of CP at atmospheric pressure has been suggested in the degradation of paraoxon and parathion [130]. It has been suggested that hydroxide radical, molecular nitrogen, and atomic oxygen are the primary plasma species responsible for achieving such effects. A mixture of fludioxonil, pyriproxyfen, cyprodinil, and azoxystrobin pesticides applied on strawberries and subjected them to in-package plasma exposure at various voltages and treatment durations. The plasma treatment of 80 kV for 5 min could effectively decrease the fludioxonil, azoxystrobin, pyriproxyfen, and cyprodinil by 71%, 69%, 56%, and 45% respectively [118]. Sarangapani et al. [117] achieved an 80.18% and 75.62% decomposition of boscalid and imidacloprid, respectively, in blueberries upon DBD plasma treatment without any changes in their color or other physical attributes. Similarly, the efficacy of CP in degradation of several pesticides, including 17β-Estradiol, endosulfan, organophosphate, and dichlorvos/omethoate, has been revealed [131, 132].

All these reports have suggested that plasma-triggered pesticide degradation is mainly affected by gas composition, input voltage, treatment duration, and plasma power. Some of the studies reporting the effects of CP on different pesticides are listed in Table 4.

Food Allergen Degradation

After pesticides, food allergens are considered the most hazardous contaminants of food products. Food allergens are the compounds that are naturally present in food products but induce the allergic reactions in certain individuals [16]. Some of the most commonly consumed food products that have been reported to elicit allergic reactions include milk, egg, soybean, nuts, and fish. However, the tricky part of the management of food allergens is that the food products

Table 4 Effect of CP on pesticides

S. no	Target sample	Pesticide	Plasma source	Observation	Reference
1	Tangerine	Cypermethrin	PAW	Significantly reduce from 1 to 0.25 ppm	Sawangrat et al. [119]
2	Grapes	Phoxim	PAW	Reduction of pesticide by 73.60%	Zheng et al. [126]
3	Tomatoes	**Chlorpyrifos**	DBD	Reduction of 89.18% in the pesticide concentration was observed	Ranjitha Gracy et al. [128]
4	Maize	**Chlorpyrifos and carbaryl**	DBD	Degradation of chlorpyrifos and carbaryl, up to 91.5% and 73.1%, respectively	Feng et al. [127]
5	Wolfberry	Omethoate and dichlorvos	DBD plasma	Time- and voltage-dependent pesticide degradation	Zhou et al. [120]
6	Mango	Chlorpyrifos and cypermethrin	GAD plasma	74% and 63% degradation of chlorpyrifos and cypermethrin, respectively	Phan et al. [71]
7	Blueberries	Boscalid and imidacloprid	DBD	Degradation achieved was 80% for boscalid and 76% for imidacloprid	Sarangapani et al. [117]
8	Apple	Paraoxon	DBD RF plasma	84–100% pesticide degradation depending on initial pesticide concentration	Heo et al. [130]
9	Water	Endosulfan	DBD	Degradation was reported	Reddy et al. [132]
10	Strawberry	Pyriproxyfen, fluidoxonil, and cyprodinil	DBD in-package plasma	Time- and voltage-dependent pesticide degradation	Misra et al. [118]

APRF atmospheric pressure radiofrequency, *DBD* dielectric barrier discharge, *GAD* gliding arc discharge, *RF* radiofrequency, *PAW* plasma-activated water

inducing allergic reactions in some individuals may be highly beneficial in some other aspects like soybean is rich in protein. However, such allergens are difficult to be eliminated using conventional techniques. In addition, the use of conventional treatments often leads to undesirable changes in the food product itself. Similar to the microbial decontamination and pesticide degradation, the composition of gas used to produce plasma is the key factor that determines the efficacy of plasma in allergen removal [133, 134]. Changes in the linear and the conformational epitopes of the allergen and their reactivity have been proposed to be the major mechanisms of plasma-induced allergen inactivation. The reactive species in the CP degrade the linear epitopes and trigger the structural changes in the proteinaceous conformational epitopes that cause the deactivation of allergens [135]. Furthermore, various oxygen, nitrogen, and hydroxyl radicals have been shown to adversely affect the protein structure that renders the allergen molecules ineffective [1, 136].

Recently, effects of CP have been studied against several allergens, such as glycinin, conglycinin, β-conglycinin, α-lactalbumin, and β-lactoglobulin [51, 136, 137]. Degradation of food allergens by cold plasma like tropomyosin in prawns and anacardic acids in cashew nuts has been documented [51, 138]. Moreover, Venkataratnam et al. [139] reported the decrease in allergenicity of peanut after cold plasma treatment. CP exposure has completely eliminated the primary allergenic components of soy protein, glycinin, and β-conglycinin by converting them into insoluble aggregates [136, 140]. In soymilk, the CP-triggered oxidative reactions and conformational changes led to an 86% decrease in the activity of soybean trypsin inhibitor [137]. Similarly, CP effect has also been studied on allergenic compounds present in milk, such as α-lactalbumin, α-casein, and β-lactoglobulin [141]. Table 5 presents the effect of CP on food allergens.

Food Packaging

Packaging of food materials has always been an important part of food industries. Efficient food packaging is crucial to enhance the shelf life, while maintaining physical and chemical attributes and preventing microbial contamination of food products. In the past few decades, the conventional packing materials have been replaced by polymeric materials that offer more advantages in terms of functionality and stability of food stuffs. However, the polymeric materials are often hydrophobic in nature and have low surface energies [24]. Plasma-induced changes in packaging films are classified in two mechanisms: surface activation and surface deposition [142].

Table 5 Effect of CP on food allergens

Sr. no	Food product	Food allergen	Plasma source	Observation	Reference
1	King prawn	Tropomyosin	Plasma jet	Level of α-helix structures declined while levels of β-sheets and random coils increased	Ekezie et al. [51]
2	Cashew nuts	Anacardic acids and other allergens	Glow plasma discharge	Did not affect allergenicity	Alves Filho et al. [138]
3	Peanut	Ara h 1	DBD	Decreased antigenicity	Venkataratnam et al. [139]
4	Soymilk and soybean	Trypsin inhibitor and Kunitz-type trypsin	DBD	Decreased activity of soybean trypsin and Kunitz-type trypsin inhibitors	Li et al. [137]
5	Pure Aflatoxin B_1	Aflatoxin	DBD	76% degradation	Shi et al. [189]
6	Soy protein isolate	β-conglycinin and glycinin	DBD, MCPT	Reduced immunoreactivity by 89 to 100%	Meinlschmidt et al. [136]
7	**Milk**	α-casein and whey proteins	RF	25% allergenicity reduction for α-casein and 27.7% allergenicity reduction for whey fractions	Tammineedi et al. [141]

DBD dielectric barrier discharge, *MCPT* microwave-combined plasma treatment, *RF* radio-frequency

During surface activation, plasma modifies the barrier properties of the polymeric film that essentially reduces the hydrophobicity and permeability of the film. This, in turn, increases the shelf-life of the food product while decreasing the chances of contamination during storage and transport. In this direction, the plasma exposure causes the formation of cross-linked or polar groups on the film surface. During surface deposition, the packing film is coated with desired elements that alter its thickness as well as affect its properties. As with other substances, the plasma-induced changes in the film properties are largely dependent on the type of plasma, gas source, gas composition, plasma power, and treatment duration. On the contrary, a study has reported no effect of plasma-induced changes in the packaging films on shelf-life improvement upon extended periods of storage [143].

Recently, CP technique is gaining immense interest in the sterilization and enhancement of the functionality of food packaging materials. The main advantage of CP is its effect on the entire surface of the packing material and, therefore, reduces the chance of the shadow effect or non-exposure of parts of material to sterilizing agent [53]. CP has also reported changes in crystal structure, improvement in barrier properties, and mechanical strength in casein- or protein-based edible films [43, 144]. Also, enhancement in surface roughness and microorganism inhibition properties in new kind of antimicrobial active packaging has been observed after application of capacitively coupled plasma treatment [76]. Plasma treatment is found to be partially cleaved acyloamino groups of zein film, making it more tensile and robust film [145]. Application of CP on fish protein films has improved their color, mechanical, and barrier properties [146, 147]. CP has also decreased the sensitivity of films to water and decreased water vapor permeability and their solubility. Furthermore, surface activation has been defined as the formation of polar groups or cross-linked molecules that enhance the properties of the packaging film's surface, such as hydrophobicity and oxygen and moisture permeability [148]. An increase in surface hydrophobicity and antimicrobial characteristics of films has been reported following treatment with DBD plasma in the presence of ZnO. This could be due to incorporation of oxygen-containing functional groups on the surface [149]. Some of the studies focused on effects of CP of most commonly used food packaging films are tabulated (Table 6).

Effect of CP on Starch, Vitamins, and Lipids

Carbohydrates and lipids are among the most important biomolecules present in food products. Ozonolysis caused by the plasma species has been considered as the major pathway of breakdown of the glycosidic bonds that led to the depolymerization of the carbohydrate molecules and subsequent oxidation of its breakdown products to form CO_2, carboxyl and carbonyl compounds, lactones, and hydroperoxides [113]. Plasma-induced structural modifications in starch molecules have altered their properties, such as pasting characteristics, swelling power, water absorption, solubility, and enzyme susceptibility [48, 150, 151]. These changes have been attributed to cross linking, increase in surface energy, depolymerization, change in hydrophilic nature, and incorporation of functional groups [48, 150, 152].

Nowadays, modified starch is used as a prominent food additive and CP is being employed to modify starch. Starch is usually modified via cross-linking and depolymerization.

Table 6 Effect of CP on food packaging material

S. no	Packaging material	Plasma source	Observation	Reference
1	Casein edible films	DBD	Little change in crystal structure, tensile strength, elongation, thermo stabilization, and barrier property were improved	Wu et al. [43]
2	Protein-based films	Glow plasma	The mechanical properties of protein films improved, also affected surface roughness of the protein films	Moosavi et al. [144]
3	Antimicrobial active packaging film	CCP	The surface roughness of films increased; growth of microorganisms is inhibited when the concentration is 1% or above	Wong et al. [76]
4	Zein films	Airglow discharge plasma	Plasma treatment partly destroyed the acylamino groups of film, a more robust surface, and increased tensile strength	Li et al. [145]
5	Zeinfims (via composting with chitosan and plasma treatment)	DBD	Enhances flexibility and barrier properties	Chen et al. [41]
6	Fish protein films	Glow plasma	Improved mechanical, barrier, and color properties of films	Romani et al. [146]
7	Cassava + PLA + PCL	DBD	Increase of the surface roughness and decrease of the water contact angle. Also, water vapor barrier was also improved	Heidemann et al. [190]
8	Fish protein films	Glow plasma	Decreased the sensitivity to water of fish protein films. Also, decrease in water vapor permeability and solubility in water	Romani et al. [147]
9	Zein films	DBD	Decreased water contact angles, improvement in surface-free energy, modified surface roughness, and improved cytocompatibility	Dong et al. [191]
10	PVA thin films	DBD	Contact angle decreased, increase in the surface roughness, exhibited excellent antifogging and highly transparent features	Paneru et al. [192]
11	Zein films	DBD	Surface hydrophilicity and mechanical strength were significantly increased	Dong et al. [193]
12	**Carboxymethyl cellulose-coated polypropylene films**	APP	Films had improved mechanical and water vapor permeability properties	Honarvar et al. [194]
13	**Chitosan films**	DBD	Significant increase in the surface roughness and in the thymol diffusion after plasma treatment	Pankaj et al. [54]
14	**Defatted soybean meal-based edible film**	MCPT	Tensile and moisture barrier properties increased, film roughness improved printability and biodegradability	Oh et al. [81]
15	**PLA film**	MCPT	Surface roughness, printability and water contact angle of PLA films increased. Also, photodegradation, thermal, and microbial biodegradable properties of the films were remarkably improved	Song et al. [82]
16	**High amylose corn starch film**	DBD	Enhanced surface roughness, oxygenated compounds and hydrophilicity	Pankaj et al. [195]
17	PLA film	RFP	Reduced water permeability	Tenn et al. [148]
18	PP and PE films	APP jet	Enhanced hydrophobicity	Kostov et al. [196]
19	Chitosan film	Low-pressure plasma	Enhanced anti-bacterial efficiency	Ulbin-Figlewicz et al. [197]
20	PP film	DBD	Enhanced hydrophilicity	Paisoonsin et al. [149]

APP atmospheric pressure plasma, *DBD* dielectric barrier discharge, *MP* microwave plasma, *MCPT* microwave-combined plasma treatment, *RFP* radiofrequency plasma, *PLA* polylactic acid, *PCL* polycaprolactone, *PET* polyethylene terephthalate, *PE* polyethylene, *PP* polypropylene, *CCP* capacitively coupled plasma

Changes in gelatinization and crystallinity of starch have been reported upon CP treatment [48]. Moreover, improvement in paste-cooling stability and reduced retrogradation in corn starch has also been reported on cold plasma treatment [153]. CP treatment enhanced the water uptake rate in black gram. It has been suggested that CP treatment increased the number of water binding sites and surface etching because of protein and starch fragmentation [47].

CP treatment has also been reported to reduce the cooking time of brown rice due to inclusion of polar groups between starch molecules [154]. In rice, CP treatment modified the starch that led to decrease in gelatinization and pasting temperatures, degree of hydrolysis, amylose content, and retrogradation tendency [155].

In lipids, the major effect of plasma has been observed for their oxidation. However, plasma effects on lipid oxidation are variable and inconclusive. Few studies have observed no effect of plasma on oxidation of lipid molecules [156, 157]. Nevertheless, CP has been employed for the production of partially hydrogenated oils or trans-free oils. Hence, more studies are needed to further elucidate the exact mechanism of CP on lipids and the utility of plasma-generated partially hydrogenated oils. With respect to food products, lipid oxidation poses a major problem as it leads to changes in the shelf-life, odor, and taste. Hence, it is important to elucidate the effects of oxidizing elements of CP with respect to lipids present in the food items. Previous studies have reported no marked changes in the lipid oxidation status of CP-treated food items, including sushi, raw pork, fresh pork, and beef jerky [73, 158]. On the contrary, a significant lipid oxidation has been reported in CP-treated mackerel fillets [159]. Also, lipid oxidation has been documented in several CP-treated dairy and meat fats [160]. A new technique of producing partially hydrogenated soybean oil has been devised using hydrogen plasma [50]. This study has opened up a new domain of CP application in hydrogenation of oils and considered to be a desirable characteristic as performed at atmospheric pressure in the absence of a catalyst. Hence, more experimental evidences are required for a conclusive effect of CP on lipids of food stuffs. Some of the effects of CP on food characteristics are tabulated (Table 7).

Among vitamins, the effect of CP has been evaluated on the stability and levels of vitamin C in food products. Analysis on whole vegetables and fruits, such as radish sprout, lettuce, and kiwifruit, has shown no significant impact of CP on their vitamin C content [97, 98]. On the contrary, Hosseini et al. [161] reported reduction in the level of vitamin C in sour cherry juice after treatment with plasma. A few other studies also reported the reduction in vitamin C content of cashew apple juice and orange juice upon CP treatment [94, 116]. Decrease in vitamin C content is attributed to the interaction with oxidizing species of plasma. In addition, few studies have shown enhancement in other vitamins after cold plasma treatment [86, 162].

Seed Germination

An enhanced rate of seed germination has been observed following plasma treatment. The reactive species of plasma are known to be able to penetrate the seed coat and directly influence the cells inside. In addition, exposure to plasma leads to surface ablation on the seed coat that promotes the penetration of moisture and oxygen to the embryo and enhances seed germination [53, 163]. Exposure to plasma has also been observed for the disruption of the cell wall, and affects on the enzyme activity that brings the seed out of the dormant phase and promotes germination.

Plasma treatment has generally been associated with a more rapid germination of seeds owing to several factors. Recently, Dawood [164] and Billah et al. [165] have reported enhanced seed germination in moringa seeds and black gram seeds, respectively, after cold plasma treatment. Moreover, plasma-activated water (PAW) also showed positive effect on seed germination in black gram, radish, tomato, and sweet pepper [46, 166]. Fenugreek seeds and wheat seeds have been observed for enhanced germination rate upon argon plasma jet [167, 168]. Also, CP treatment has increased the germination rate (102%), seed conductivity (20%), and radical root (36.2%) of mung bean seeds [169]. These findings have suggested that CP treatment enhances the water inhibition capacity of seeds, which not only enhances the germination rate but also inhibits the growth of microbes and enhances other growth aspects. An increase in the demethylation levels of ATP, growth regulators, and rapamycin has been observed in argon plasma-treated soybean sprouts [170]. Also, an 80% increase in germination rate of radish and enhancement in stem elongation by 60% in tomatoes have been reported after treatment with DBD PAW [46]. Few studies have also observed negligible effect of cold plasma on seed germination of mung beans [44] and grain seeds [171]. Some studies reporting the effect of cold plasma on seed germination are tabulated for reference (Table 8).

Limitations and Future of Non-thermal Plasma

From the discussion, cold plasma has been observed as a disruptive technology for the many food processes. However, adoption of cold plasma for food-manufacturing and food-processing might face one of more of the followings major challenges like design and source of plasma, control of cold plasma process, and regulatory aspects. Though the conditions of cold plasma process can be tuned to maximize the production of desired component from the agricultural or food commodities, focus is required to design the cold plasma for scale-up as well as on commercialization of the in-package plasma technology.

Even with a plethora of studies, several aspects of the CP technique with respect to food industry are still not known. For instance, there are still some gaps in the research concerning the effects of CP on allergens and antioxidants. Moreover, studies need to be conducted on the safety, toxicity, and/or health effects of CP-treated food products in

Table 7 Effect of CP on food components like starch, lipids, and vitamins

S. no	Food product	Plasma source	Observation	Reference
1	Waxy and normal maize starch	PAW	Crystallinity of starches got increased; changes in gelatinization temperatures and resistant starch content got increased	Yan et al. [48]
2	Sour cherry juice	Plasma jet	Vitamin C got decreased but less than thermal processing	Hosseini et al. [161]
3	Camu-camu juice	DBD	Vitamin C bioavailability got increased	de Castro et al. [110]
4	Vegetable oil	Plasma jet	Significant changes in content of conjugated dienoic acid and moisture content got decreased	Na et al. [49]
5	Strawberry juice	DBD	Vitamin C retention was maximum in comparison with other techniques used	Mehta and Yadav [69]
6	Tomato-based beverage	DBD	Vitamin C retention was maximum in comparison with other techniques used	Mehta et al. [62]
7	Corn starch	Plasma jet	Improved paste-cooling stability and reduced retrogradation of corn starch	Wu et al. [153]
8	Siriguela juice	Glow discharge plasma	Vitamin B got increased	Paixão et al. [86]
9	Acerola juice	Glow discharge plasma	Increased vitamin A content, maximum retention of vitamin C, and carotenoid content got improved	Fernandes et al. [162]
10	Corn and tapioca starch	RFP	Water binding capacity, swelling power, and viscosities of both starches got increased	Banura et al. [152]
11	Sushi	DBD	No changes in fatty acid composition of sushi	Kulawik et al. [158]
12	Fresh mackerel fillets	DBD	Increased lipid oxidation	Albertos et al. [159]
13	Rice starch	DBD	Increase in pasting and final viscosities	Thirumdas et al. [150]
14	Banana starch	Corona discharge plasma	Increase in pasting temperature	Wu et al. [151]
15	Orange juice	DBD	Reduced vitamin C content	Xu et al. [94]
16	Cashew apple juice	Indirect plasma mode	Increased vitamin C content	Rodríguez et al. [116]
17	Radish sprouts	MP	No change in ascorbic acid	Oh et al. [98]
18	Beef and dairy lipids	DBD	Oxidation of lipids and formation of typical oxidation products like ozonides, aldehydes, and carboxylic acids along with hydroperoxides	Sarangapani et al. [160]
19	Pork	Plasma jet	No significant change in lipids	Choi et al. [198]
20	Soyabean oil	HVACP	Changes in the fatty acid composition. Reflected iodine value similar to a commercial hydrogenated oil	Yepez and Keener [50]
21	Zein	DBD	Decrease of surface hydrophobicity; increase in tensile strength and solubility	Dong et al. [108]
22	Rice flour	RFP	Enhanced hydration	Thirumdas et al. [199]
23	Brown rice	RFP	Increase in amylase activity	Lee et al. [200]
24	Brown rice	DBD	Decrease in cooking time; increase in water uptake	Thirumdas et al. [154]
25	Pea protein	DBD	Increase in water-binding capacity	Bußler et al. [140]
26	Fish oil	DBD-plasma jet	Accelerated lipid oxidation	Vandamme et al. [157]
27	Parboiled rice	RFP	Reduced cooking time; enhanced water absorption	Sarangapani et al. [201]
28	Milk	DBD	Lipid oxidation of milk was slightly changed	Kim et al. [156]
29	Basmati rice	RFP	Reduced cooking time; enhanced water absorption	Thirumdas et al. [202]
30	Lettuce	MP	No change in vitamin C content	Song et al. [97]

DBD dielectric barrier discharge, *RFP* radiofrequency plasma, *PAW* plasma-activated water, *HVACP* high-voltage atmospheric cold plasma, *MP* microwave plasma

humans. Furthermore, the applicability of CP technique on fatty products is still unresolved, owing to the possibility of increased oxidation in such products and subsequent decrease of their nutritional value.

Due to variable effects of different plasma components on different food products, optimization studies are needed with respect to the type, intensity, and duration of plasma treatments as well as the food types. Recent few studies have reported the

Table 8 Effect of CP on seed germination

S. No	Target product	Plasma source	Observation	Reference
1	Moringa seeds	RFP	Improvement in germination potential	Dawood [164]
2	Mung bean seeds	Plasma jet	No change is observed w.r.t. germination	Darmanin et al. [44]
3	Black gram seed	DBD	Enhanced seed germination rate	Billah et al. [165]
4	Black gram	PAW	Increased germination, growth, and development	Sajib et al. [166]
5	Grain seed	Glow discharge plasma	No change in seed germination rate	Baldanov et al. [171]
6	Wild asparagus	RFP	Increase in germination percentage	Porto et al. [203]
7	Sweet basil	RFP	Enhanced stimulatory effect on germination	Singh et al. [163]
8	Fenugreek seeds	Ar-plasma jet	Helps in stimulation of seed germination	Boutraa et al. [167]
9	Wheat seed	Ar-plasma	Enhanced germination rate	Iqbal et al. [168]
10	Okra seeds	Glow discharge plasma	Enhanced germination rate	Kumar et al. [204]
11	Brown rice	DBD	Increased germination rate, reduced germination time	Yodpitak et al. [205]
12	Wheat seed	APP	Enhanced germination rate	Los et al. [206]
13	Oilseed rape	RFP	Increased germination rate and plant growth	Ling et al. [45]
14	Cotton seed	Plasma jet	Improved germination rate	de Groot et al. [207]
15	Mung beans	DBD	Increased germination rate, enhanced enzyme activity	Sadhu et al. [169]
16	Radish, tomato, and sweet pepper	PAW	Positive effect on seed germination and seedling growth	Sivachandiran and Khacef [46]
17	Soyabean sprouts	DBD	Enhanced germination and seedling growth of soybean, increased the concentrations of soluble protein, antioxidant enzymes, and ATP	Zhang et al. [170]
18	Peanut	DBD	Improved germination and seedling growth	Ling et al. [208]

APP atmospheric pressure plasma, *DBD* dielectric barrier discharge, *RFP* radiofrequency plasma, *PAW* plasma-activated water

effect of CP on firmness, discoloration, and pH of vegetables and fruits.

One of the major limitations of CP efficiency is its dependency on the surface topography of the target. At present, the cold plasma technology has limited penetration depth, and in order to maintain the product quality, interactions between product and processes should be minimum. Cold plasma technology has recently gained the pace in the improvement of food processing and food quality. Cold plasma has already crossed the technology readiness level (TRL5). Also, present scale of operation is at gram or kilogram scale. However, further work is essential to design systems that are scalable to industrial requirements. Hence, efforts need to be initiated for the scale-up of CP techniques for larger food commodity at industrial scale. For this, more intensive and focused efforts are required to exploit the use of plasma technique at commercial level.

Conclusions

Cold plasma (CP) technique is a non-conventional, non-thermal technique that has been demonstrated to exhibit high potential in enhancing food quality, ensuring better food safety, and facilitating better packaging of food products. CP technique has been shown to be extremely beneficial in the areas where the applications of conventional techniques are not feasible. Since CP technique can be implemented at atmospheric pressure and ambient temperature, its use could be safe on food products without or minimal loss of their nutritional and sensory characteristics. Food processing sector and agricultural industries need to understand the importance of CP and make sincere efforts for its applicability at commercial level for the benefit of society in large.

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Declarations

Conflict of Interest The authors declare no competing interests.

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