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Review

Review on Recent Applications of Cold Plasma for Safe and Sustainable Food Production: Principles, Implementation, and Application Limits

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Abstract: The food and agricultural industries have numerous practical advantages to be gained from the use of cold plasma technology. This paper attempts to showcase the possible uses of cold plasma in the food sector, while also highlighting the most recent developments and market trends. The efficiency of cold plasma in enhancing food products' quality and shelf life has been demonstrated in several investigations. This review has concentrated on current research into how this technology affects various food chain production stages. Cold plasma has become a cutting-edge non-thermal technique that can be used to ensure food safety. The precise mechanism underlying the effectiveness of cold plasma is still unclear. Understanding these mechanisms and potential elements that can restrict or increase their effectiveness and results is crucial to further enhancing and implementing cold plasma treatment in food processing. The main objective of this review is to investigate the use of plasma, its exceptional characteristics, and its advantages in safe, sustainable food production. In particular, this review summarizes recent studies on the use of cold plasma for microorganisms and pesticides treatment, compiling them and discussing their content. As reported in the literature, a critical point has also been reviewed about some diverse plasma configurations. A comparative study of the efficacy of cold plasma in environmental applications (microorganisms/pesticides) has also been reviewed from the literature.

Keywords: cold plasma; food safety; sustainability



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1. Introduction

The science of food preservation has been around for centuries and has permanently changed. Ancient people used physical methods such as sun drying, roasting, smoking, fermenting, and salting to store agricultural products [1]. The food business has seen a demand increase for products over the preceding several decades owing to rising household incomes. Meanwhile, there has been an increasing concern over food safety in the food industry.

Food safety is defined as “The state in which all raw materials of food and feedstuffs entering the human food chain, as well as those destined for animals intended for consumption or production, are fit for human consumption and safe for their intended use” [2]. According to the EU definition, “Food safety is the state of being protected from biological, chemical, and physical hazards during food processing, storage, and distribution to ensure

the durability and preservation of quality of the food for human and/or animal consumption". A balance must be struck between the conservation and preservation of safe food and the protection of public health.

Despite advancements in food safety and processing, foodborne diseases are increasing. Food and agricultural product safety and security have become significant problems and difficulties. Food safety issues and nutritional insecurity arise due to rising demand, food supply shortages, and because food quality issues such as adulteration and other forms of fraud have become widespread in today's world [3]. From farm to fork, the industry should constantly adapt to meet a growing population's nutritional and consumer expectations. This objective can only be accomplished within the constraints of available resources and regulatory requirements [4]. Thermal treatment is the most popular technique for food preservation by managing pathogenic and contaminant microorganisms, despite several drawbacks including overcooking, textural damage, alteration in flavor and organoleptic properties, reduction in nutritional quality due to thermal exposure, etc. [5] Temperature abuse causes the denaturation of proteins, polyunsaturated fats, and carbohydrates, damaging the cellular structure and function of the treated food. Because of increased consumer knowledge and understanding, the food production industry is trying to find ways to meet the growing demand for safe and healthy foods with "fresh-like" qualities.

Scientists have spent decades investigating various processing approaches to produce safe, shelf-stable food with high nutritional value and quality [6–10]. Cold plasma (CP) has been applied to remove microorganisms in a variety of foods such as apples [11], tomatoes [12], and blueberries [13]. This review examines the current state and improvements in CP impact in the food industry to improve food product quality and consumer safety. It also investigates the effects of the technology, which is responsible for delivering an optimized solution, on various food production stages, focusing on the limitations to and future potential for food processing techniques in the industry.

2. Cold Plasma Technology

In 1928, Langmuir invented the term "plasma" to define an ionized gas with a macroscopically neutral electrical charge. Since the 17th and 18th centuries, plasma, a semi-ionized gas composed of excited electrons, ions, and neutrals, has been studied. Plasma is the fourth state of matter and is composed of particles such as positive and negative ions and free radicals [14].

Plasma can be created using many sorts of energy that can ionize gases, including electrical, thermal, optical (UV light), radioactive (gamma radiation), and X-ray electromagnetic radiation. Despite this, CP is frequently generated using electric or electromagnetic fields [15]. To generate CP, a plethora of methods are being developed at a rapid pace. These can operate at normal air pressure or in a partial vacuum. Several gases can technically be applied in CP; the gas about to be ionized could be as simple as either nitrogen or air. Alternatively, it could be a more composed mixture containing components of noble gases such as helium, argon, or neon [7,16]. Electricity, microwaves, or lasers may be used as the driving energy. This diverse set of design aspects demonstrates CP methods' adaptability and the degree to which different types of CP mechanisms are invented and tested. All CP methods for food processing are classified into one of three groups. The position of the food to be treated with the CP being generated specifies these groups: a significant distance from the origin of plasma generation, a reasonable nearness to the generation source, or even within the zone of generation itself that produces plasma. These groups are based chiefly on the half-life and properties of charged, active species inside the plasma and originate almost exclusively from the essence of CP chemistry [14].

2.1. Plasma Production

CP can be generated using various gases and produced by a wide range of methods. Each distinct method has a broad range of uses. Plasmas are formed by providing power to a neutral gas, which induces charge transporters. When high-energy electrons or photons

interact with neutral molecules and atoms in the feed gas, electrons and ions are formed inside the gaseous phase (electron-impact ionization as well as photoionization) [17,18].

Plasma technology is classified into thermal and low-temperature plasma methods on the basis of how the plasma is generated. According to various authors, thermal plasma comprises thermodynamically balanced ions, electrons, and gas molecules. Low-temperature plasma is generally categorized as semi-equilibrium plasma, in which there is a local thermodynamic equilibrium among species such as electrons and gas molecules, and non-equilibrium plasma, in which electrons have higher temperatures and gas molecules have moderate temperatures, with lower temperatures for the whole system [19–21].

The structure of the fed gas implemented for CP influences the generation of reactive species. These substances are primarily in charge of antimicrobial activity. The mechanism of food preservation differs significantly because of the formation of various reactive species by the various gases and generators used [21]. Plasma reactive species can separate covalent bonds and initiate various reactions crucial for numerous technological applications [22].

2.2. Cold Plasma Sources

The plasma-generating technologies most often used in food processing are classified as follows: dielectric barrier discharge (DBD), plasma jet (PJ), corona discharge (CD), radiofrequency (RF), micro-hollow cathode discharge, gliding arc discharge, and microwave (MW) [23]. The kind of plasma source, the structure, and density of the chemical species generated, do then generally influence the method application. The DBD and plasma jet are the two most frequently used forms of CP sources in environmental, biological, and biomedical applications. This aspect is mainly attributable to their simple design and ability to be reconfigured to suit a wide range of objectives and treatment needs [24,25]. Some of the plasma sources are shown in Figure 1.

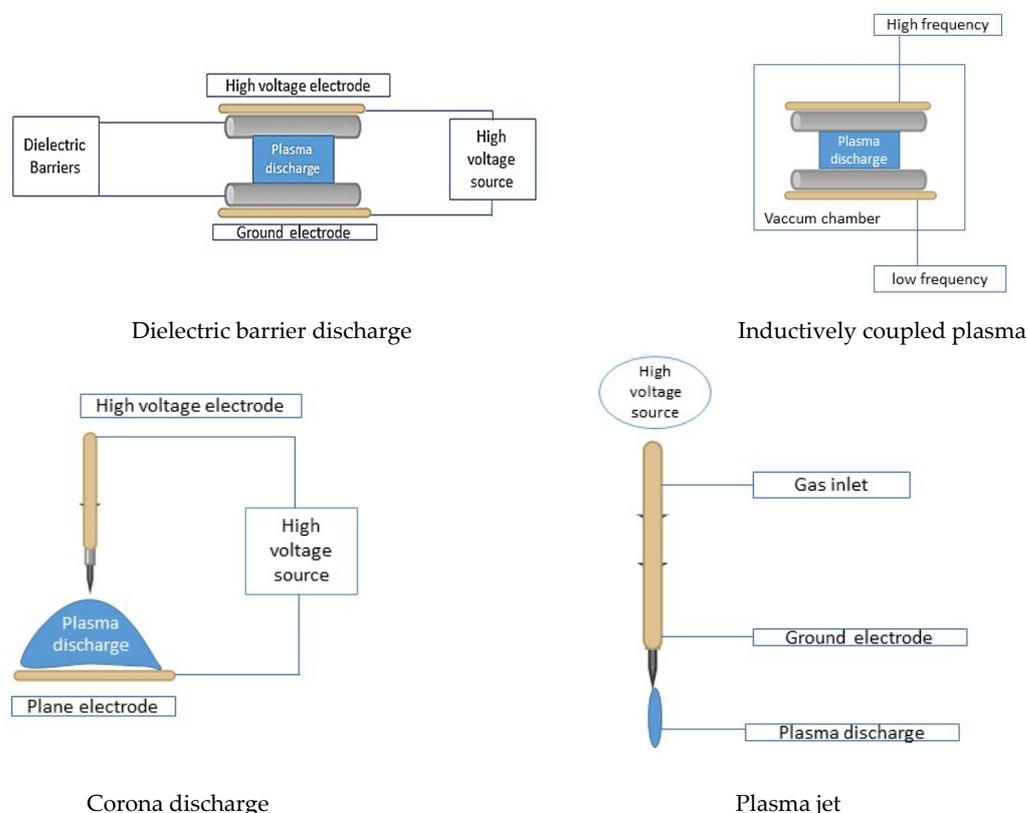


Figure 1. Some configurations of cold plasma systems.

3. Uses of Cold Plasma in Food Industry

A CP system has been investigated for a wide range of purposes at numerous phases of food manufacturing, which include the treatment of ingredients or final products, as well as the treatment of processing equipment, facilities, and the environment, because of its numerous advantages. Among the CP benefits are low-temperature operation, short time frames, power efficiency, and significant antibacterial efficacy with negligible effects on food quality and the environment [26].

Many researchers have discussed the potential uses of CP for different purposes [27–29]. Some of the CP uses related to food production are shown in Figure 2.

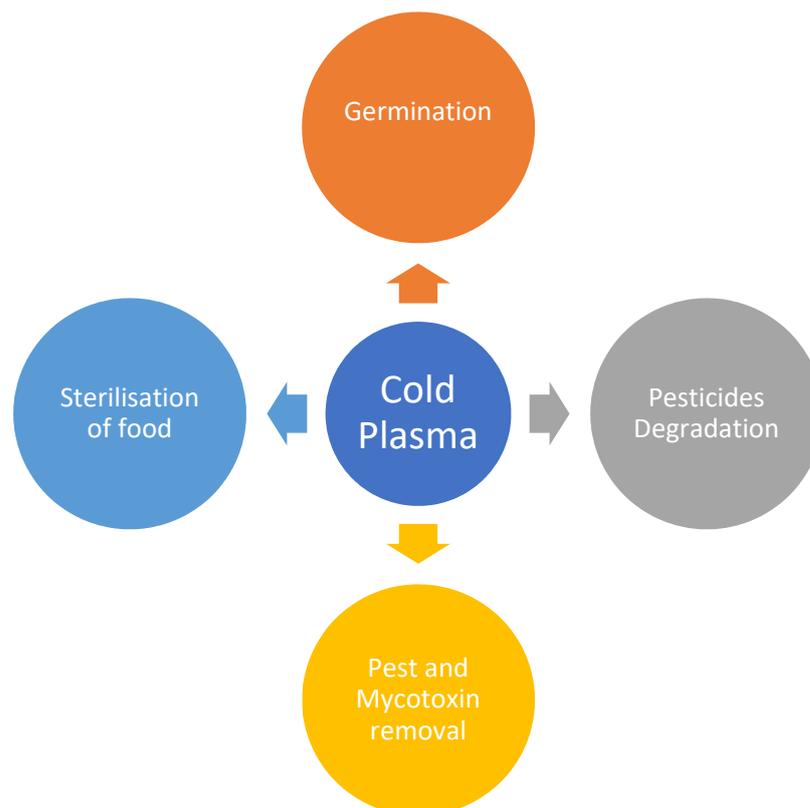


Figure 2. Cold plasma technology is used in various stages of food production.

3.1. Germination

The procedure by which the embryo in the grain evolves to be a plumule and radicle is known as seed germination. Grains take up water, which causes non-active tissues to swell and cell division to begin. The radicle develops from micropylar and begins to move into the growing medium. These eventually develop into the root system, which provides nourishment and water to the plants during their lifetimes [30].

Seed dormancy is a naturally occurring grain feature that allows a species to reproduce in order to survive [31]. Plasma treatment generates a variety of agents capable of breaking dormancy (e.g., UV radiation, radicals, chemical reactions). According to reports, CP has previously been evaluated with different plants:

CP treatments remedy drought stress damage to oilseed rape. The CP method and techniques have remarkably improved seedling growth and germination due to improved seed wettability, antioxidant enzyme activities, soluble sugar and protein contents, and reduced lipid peroxidation-linked membrane deterioration [32]. Therefore, CP treatment can be used to protect seeds from the damage caused by drought stress. The CP treatment can be effective in reducing seedling mortality and improving seed germination rate.

Seed germination rates were found to be faster after plasma treatment. Plasma reactive species have been shown to be capable of penetrating into the seed coat and having

a significant impact on the cells within. Furthermore, plasma exposure causes surface ablation on the seed coat, which actively encourages moisture and oxygen entry into the embryo and stimulates seed germination. Plasma has also been shown to destabilize the cell wall and influence the enzyme activity that brings the seed out of dormancy and encourages germination [33].

Germination and early growth are aided by cold plasma. These effects are linked to decreases in the percentage of fungi-infected seeds, modifications in the physiochemical parameters and biochemical properties of seedcoats (higher hydrophilicity), as well as modifications in antioxidant and phytohormone profiles [34].

Cold helium plasma seed treatment can potentially increase wheat yield by improving germination, promoting wheat development, and raising its physiological quality, resulting in improved grain production and better resistance to pests and mycotoxins [35].

CP treatments have been shown to increase soybean germination and seedling productivity. The improvement in soybean seed germination and seedling growth in response to CP treatment appears to be due to an increase in water absorption, seed supply consumption, and soluble carbohydrate and protein contents [36].

Peanut seed germination and plant growth also improved with CP treatment. CP treatment significantly increased seedling growth parameters, improved plant growth potential, germination percentage, dry mass, enhanced vegetative growth, and dry weight at the fruiting stage. Additionally, it improved plant length, stem dimension, root dry mass at maturity level, and yield in field conditions [37].

Brief plasma procedures (30–60 s) have been shown in studies to significantly improve wheat seeds' germination properties and seedling growth parameters; the mechanism of plasma exposure and spending time in an enclosed reactor after the procedure determined these effects. The most effective treatment was an indirect plasma treatment for 60 s, followed by 24 h of contact time between plasma-produced compounds and grains after treatment. When compared to control samples, this was found to enhance wheat germination by 14.7%. Numerous different growth factors have also been enhanced. CP can be a suitable replacement for pre-sowing grain procedures used in farming to enhance germination [38].

In optimized conditions, plasma treatment causes the functionalization of the wheat seed surface with oxygen functional groups, primarily oxidizing the lipid molecules found naturally on the target surface. Water gets into the seed pericarp smoothly, reducing water contact angle and higher water uptake [39]. The plasma reaction process has the advantages of not being harmful to the seed, applicability to a wide range of crop species, and being environmentally safe [40].

3.2. Pesticide's Degradation

Several studies showed that CP had the potential to degrade pesticide residues in fruits and vegetables. CP's ability to eliminate pesticide residues has been associated with the production of reactive oxygen and nitrogen species. Pesticides are a large variety of chemical substances, widely utilized in agricultural production to protect crops and delay crop deterioration. Nevertheless, pesticide resistance necessitates increased application rates. Pesticide residues are a source of concern in the food business due to their health threats [41,42].

After 5 min of plasma treatment at 80 kV, pesticide residues on blueberries satisfactorily deteriorated with degradation efficiencies of 75% and 80% for boscalid and imidacloprid, respectively. Appropriate modifications in the evaluated quality characteristics were noticed for the treatment conditions. These findings imply that CP treatment at 60 kV 5 min and 60 s at 80 kV can sustain the blueberries' nutritional qualities [43].

Pesticides in water were successfully degraded using atmospheric pressure dielectric barrier discharge plasma in air. The discharge was tested at high voltages in the filamentary regime. It was found to be a quick and effective source of oxygen radicals, excited nitrogen

species, and other plasma species. Degradation products are distinguished by simpler chemical groups [44].

According to studies, CP treatment considerably reduced organophosphorus pesticides without any damaging, hazardous, or undesirable effects on the appearance or texture of many agricultural samples [45,46]. Figure 3 shows the application of cold plasma in food and water.

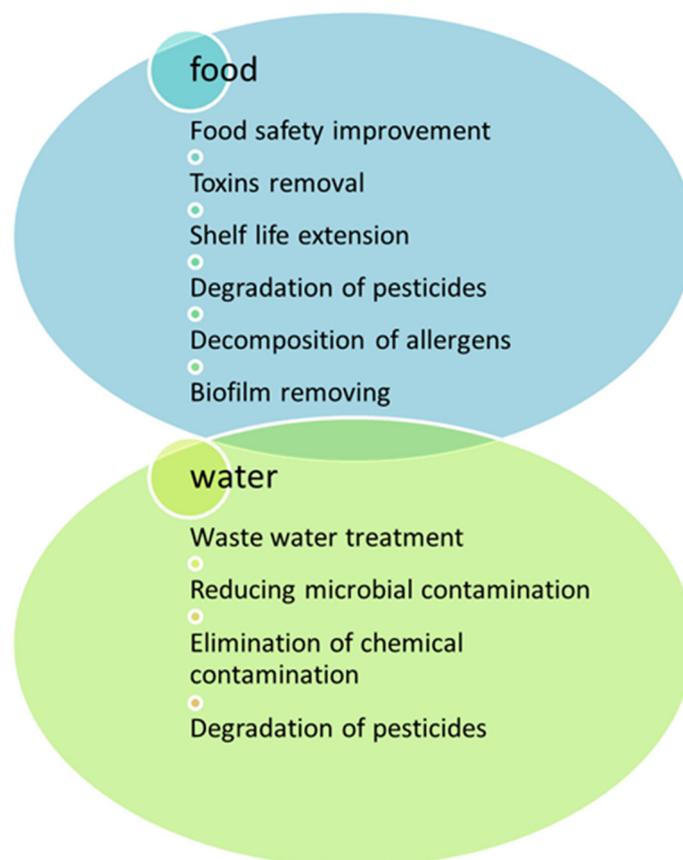


Figure 3. Application of cold plasma in food and water [6].

3.3. Pest and Mycotoxin Removal

Controlled atmosphere storage is an efficient way to keep pests and mycotoxin-producing fungi at bay during storage. However, the use of modified atmosphere storage is hampered by the technology's high cost and the need for a greater understanding of its mechanisms. In recent years, CP has been used to control various pests and mycotoxin-producing fungi. According to [47], Australia's existing postharvest cereal grain management techniques are efficient versus the vast majority of postharvest pathogens and insect pests. Still, they have several drawbacks, including high expenses for maintenance and the development of chemical strength and toughness within insect pests. Innovative postharvest procedures must be sought by Australia's grain sector. Numerous studies have shown CP to be effective against fungal species, mycotoxins, and insect infestation, while having little effect on cereal crops. CP procedures could indeed serve to minimize the presence of pests in stored foods. Sutar et al., have proved that the treatment of wheat flour with 60 W for 30 min prevented the development or appearance of insects (larval stage, pupae, and eggs) [48].

Based on its unique physical and chemical properties, CP is a promising technology for decontaminating surfaces and air in the food industry. CP is a promising technology for pest and mycotoxin removal. The tables below illustrate some findings from studies that examined CP's impact on pests and mycotoxin (Tables 1 and 2).

Table 1. Cold plasma experiments illustrating mycotoxin degradation.

Mycotoxin	Food Matrix	Plasma Type	Results	References
Fumonisin B2 and ochratoxin A	Date palm fruits	atmospheric pressure argon cold plasma jet	Degradation of the two mycotoxins after 6 min and 7.5 min plasma treatments, respectively	[49]
Deoxynivalenol, zearalenone, enniatins, fumonisin B1 and T2, Sterigmatocystin, and AAL toxin	Rice extracts	dielectric barrier discharge	The 60 s treatment extensively degraded pure mycotoxins	[50]
	Corn	high-voltage plasma	90% degradation	[51]
	Hazelnuts	DBD	Mycotoxin reduced by 70%	[52]
Aflatoxin	Nuts	atmospheric pressure plasma	Reduces aflatoxin production (90%) Degradation of mycotoxin up to 72%	[53,54]
	Hazelnuts, peanuts, and pistachio nuts	low-pressure cold plasma	20 min air plasma treatment reduced 50% of total aflatoxins	[55]
AF B1	Glass coverslip	nitrogen gas plasma generated by a static induction thyristor	The concentration reduced to <1/10th after 15 min	[56]
DON, D3G T-2	Barley	low-pressure microwave-generated plasma	50% reduction	[57]

Table 2. Cold plasma experiments illustrating treatments of insect pests.

Insect Pests	Popular Name	The Type of Plasma Method Employed	Greatest Efficient Treatment Time	Outcomes	Source
<i>Plodia interpunctella</i>	Indian meal moth	pulsed plasma jet	20 p/s	larval mortality 86%, 53% pupal mortality and 46% reduction adult development	[58]
<i>Sitophilus granarius</i>	Wheat weevil	vacuum and electromagnetic field plasma system	10 s	100% insect pest elimination	[59]
<i>Tribolium confusum</i> ,	Confused flour beetle,	DBD	20 s	100% elimination achieved	[60]
<i>Ephestia kuehniella</i>	Mediterranean flour moth	DBD	15 min	insect pest elimination at 100% at all stages	[61]
<i>Tribolium castaneum</i>	Red flour beetle	plasma jet	15 min	<i>T. confusum</i> and <i>T. castaneum</i> have an elimination rate of up to 96% and 88%, respectively	[62]
<i>Tribolium confusum</i> ,	Confused flour beetle				
<i>Tribolium castaneum</i>	Red flour beetle				

3.4. Food Sterilization

To ensure optimal food safety, it is critical to use reliable and consistent food sterilization techniques. Due to its capability to inactivate a wide variety of foodborne pathogens without affecting food quality, CP is a promising food sterilization technology. The most researched of the numerous potential mechanisms is the chemical interaction of cell membranes with radicals (O, OH...), excited or reactive molecules (O₂, O₃, NO...), and charged particles [17,63,64]. Reactive species, created by the breakdown of air such as O₃, atomic oxygen, superoxide, peroxides, and hydroxyl radicals, are critical in the destruction of microbes and viruses like Coronavirus SARS-CoV-2 [65,66]. NO and NO₂ play roles in microorganism inactivation by degrading chemical components such as protein molecules, fats, and nucleic acids [67]. Moreover, Hun I. and her collaborators have shown that plasma can also damage the DNA/RNA, restricting the SARS-CoV-2 for viral replication [66].

The reactive species generated in plasma interact with the amino acids in proteins, making structural changes and damaging the microbial cell [20], as shown in Figure 4.



CP is a versatile germicide practice that can be applied to a wide variety of foods. CP has been proven effective in treating biofilms and decontaminating foods such as meats, poultry, fruits, and vegetables. CP systems are being researched and developed worldwide because investigation has demonstrated that they effectively reduce human pathogens [68]. Some of those studies are shown in Table 3.

Table 3. Studies demonstrating decontamination using cold plasma.

Microorganism	Food Matrice	Plasma Type	Results	References
<i>E. coli</i> and <i>Salmonella</i>	Apples surface	Atmospheric cold plasma DBD	Raising the treatment duration enhanced atmospheric cold plasma's antibacterial activities towards the bacteria species.	[69]
<i>S. aureus</i> , <i>E. coli</i> , <i>C. albicans</i>	Orange juice	Dielectric barrier discharge	<i>Staphylococcus aureus</i> , <i>Escherichia coli</i> , and <i>Candida albicans</i> were treated for 12, 8, and 25 s, respectively, and the numbers of each microorganism decreased more than 5 logs.	[70]
<i>Salmonella</i>	Grape tomatoes	Dielectric barrier discharge	Inactivated <i>Salmonella</i> without altering the color or firmness properties of the grape tomatoes.	[12]
<i>Z. rouxii</i>	Apple juice	Dielectric barrier discharge	5-log reduction of viable cells population in 140 s	[71]
<i>Escherichia coli</i>	Raw chicken breasts	Atmospheric pressure plasma jet	20 mm and longer treatment time (10 min) in presence of oxygen to the nitrogen gas.	[72]
<i>S. enterica</i>	Egg	Direct DBD	The composition of carrier gas affected the rate of <i>Salmonella</i> inactivation Plasma treatments did not deteriorate the quality attributes of eggs.	[73]
<i>Escherichia coli</i> O157:H7, <i>Listeria monocytogenes</i> , <i>Salmonella Typhimurium</i> , and <i>Aspergillus</i>	Beef jerky	flexible thin-layer plasma system	Up to 2- to 3-log reduction	[74]
<i>Bacillus atrophaeus</i> , <i>Escherichia coli</i>	Barley and wheat	DBD	reduced by 3.2- and 3.2-log ₁₀ CFU/g for <i>B. atrophaeus</i> cells and <i>E. coli</i> respectively	[75]
<i>Bacillus amyloliquefaciens</i> endospores	Wheat	DBD	3-log CFU reduction in microbial load	[76]
<i>Mesophiles</i>	Chicken breast	DBD-ACP—In package	1.90 log CFU/g reduction in microbial load	[77]
<i>L. monocytogenes</i>	Strawberries	DBD air plasma	4.2 of <i>L. monocytogenes</i>	[78]
<i>Psychrophiles</i>	Raw chicken breast meat	Dielectric discharge	>1.0-log reduction in microbial load	[79]
<i>Bacillus tequilensis</i>	Black peppercorns	Dielectric barrier discharge	3.4-log CFU/g 1.7-log spores/g reduction in microbial load	[80]

Table 3. Cont.

Microorganism	Food Matrice	Plasma Type	Results	References
<i>Salmonella</i>	Korean Rice Cakes	DBD	<i>Salmonella</i> growth is reduced by 3.9 ± 0.3 -log CFU/g.	[81]
<i>Bacillus cereus</i>	Red pepper powder	DBD	≥ 6.0 -log reduction	[82]
<i>Enterococcus faecalis</i>	Fresh pineapple juice	Plasma jet and surface dielectric barrier discharge	8.2-log reduction	[83]
<i>Escherichia coli</i> , <i>Listeria monocytogenes</i> , <i>Staphylococcus aureus</i>	Milk	DBD	98.75–100% fatality rate	[84]

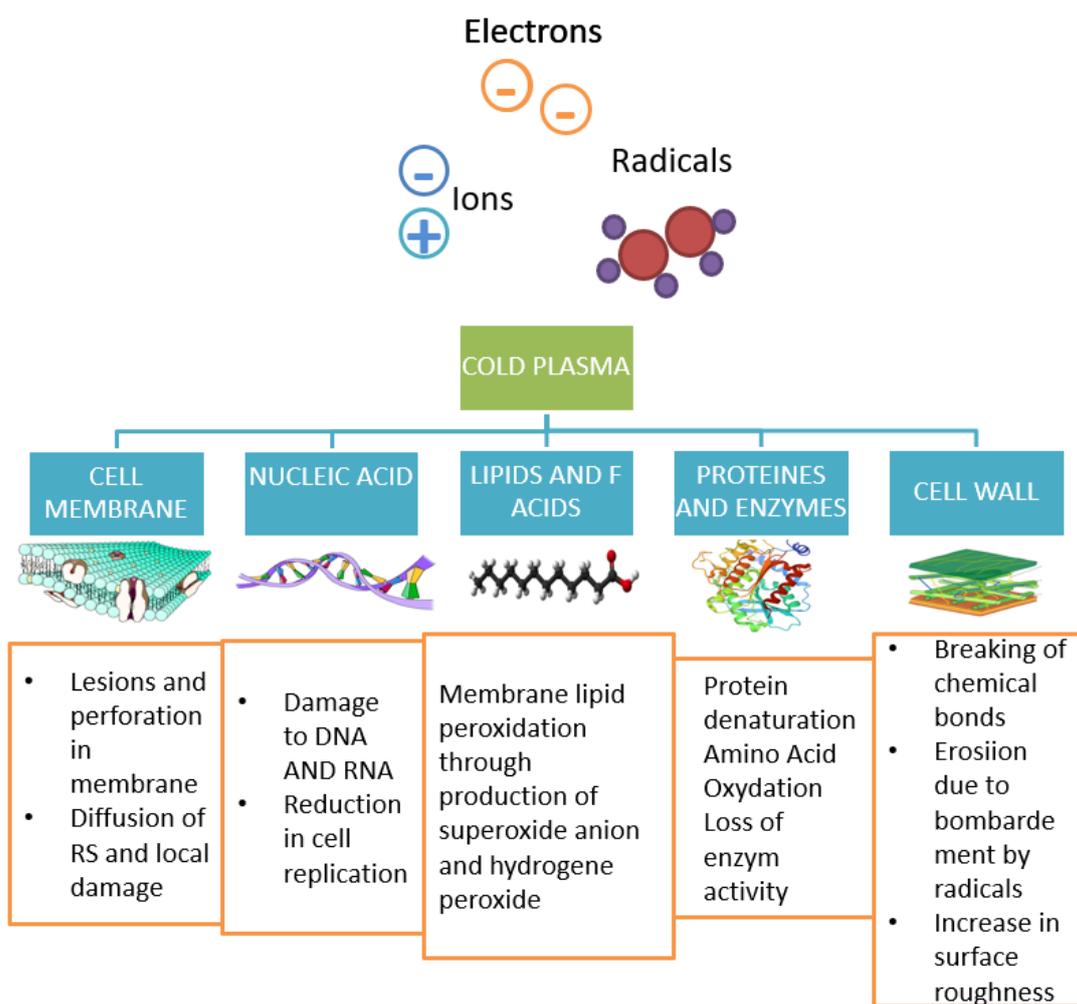


Figure 4. Mechanisms of bacterial inactivation with plasma reactive species [85].

4. Food Quality and Safety Evaluation

Because of its potential to inactivate foodborne pathogens and extend the shelf-life of food products, CP, an exceptional state of matter, has been explored for a broad range of potential uses in the food processing industry. CP has already shown guarantee as an efficient antimicrobial intervention for food contact surfaces. Despite these potential benefits, applying CP to improve and enhance food quality and safety takes time due to food production systems' complex and variable character.

Most research has concentrated on evaluating the overall appearance of CP-treated food products, and their sensory and physicochemical properties. Before drawing definite conclusions about the advantages of plasma technology, more attention must be

paid to the stability of delicate food ingredients such as vitamins and other bioactive constituents [86]. These are important quality characteristics that determine food's nutritional value and safety.

The harmful impacts of the CP procedure on the organoleptic and nutritional characteristics of foods pose significant obstacles to the advancement of the method. The presence of OH radicals in CP causes oxidative damage in meat, which reduces validity and shelf-life due to lipid deterioration and rancidity development [16]. The same type of oxidation has been reported in cereal products [87].

Consequently, any treatment process used on products containing high levels of lipids and fats must always be carefully studied and optimized to minimize the oxidation effect, which can degrade quality aspects [88]. Table 4 summarizes some research findings on the effect of CP on fruit quality.

Table 4. The effect of cold plasma on fruit quality characteristics [89].

Type of Fruit	Plasma Source	Gas Type	Process Parameters	Property	References
Mandarin	Cold plasma	Nitrogen	2.45 GHz, 2, 5, 10 min	Significant increase in total phenolic content and antioxidant activity	[90]
Walnut	Plasma jet	Argon	12 kHz, 15 kV, 3–11 min	No change in total phenolic content with plasma treatment	[91]
Chokeberry juice	Cold atmospheric gas phase plasma jet	Argon	25 kHz, 3 & 5 min	Plasma treated juice showed higher concentrations of hydroxycinnamic acids	[92]
Pomegranate juice	Cold atmospheric plasma jet	Argon	Treatment time, 3, 5, 7 min 25 kHz, 2.5 kV voltage	Plasma treatment increases the total phenolic content	[93]
Fresh-cut kiwifruit	Dielectric barrier discharge	Air	Voltage 2–19 V	Improving color retention and reducing the darkened area formation during storage	[94]
Blueberries	Plasma jet	Air	Feed gas set at 60 psi, frequency of 47 kHz, power consumption of 549 W, CP for 0, 15, 30, 45, 60, 90 and 120 s	Significant reductions in firmness. Surface color significantly impacted after 120 s for the L* and a* values and 45 s for the b* values	[95]
Strawberries	Dielectric barrier discharge	Air	60 kV, 50 Hz	Retaining color and firmness of fruit	[96]
Cherry tomatoes	Dielectric barrier discharge	Air	60 kV, 50 Hz, 30, 60, 180, 300 s	Maintained color, firmness, pH and weight	[97]
Pear	Dielectric barrier discharge		15 kV, 10–20 min	There are no adverse effects on the quality characteristics of the fruits, such as fruit color, mass, fruit firmness, and fruit soluble solids content	[98]
Sour cherry juice	Jet plasma		10, 15, 20 kV 1–9 min	Insignificant change in color and pH increase in the level of total phenols	[99]
Tender coconut water	DBD		18–28 kV 1–3 min	Increase in the level of total fatty acids decrease in the level of total phenols and ascorbic acid	[100]
Kiwi turbid juice			13, 22, 31 W15, 25, 35 Kv 1–5 min	Increase in the level of flavor and texture decrease in the level of total phenols	[101]

5. Advantages and Disadvantages of Cold Plasma

Despite numerous studies, several aspects of the CP technique in the food industry remain unknown. For example, there are still some research gaps regarding the effects of CP on allergens and antioxidants. Furthermore, studies on the safety, toxicity, and/or

health effects of CP-treated food products on humans are required. Because different plasma components have different effects on different food products, optimization studies for the type, intensity, and duration of plasma treatments, as well as the food type, are required [102].

The growing use of green preservation techniques has led to the development of diverse technologies, each pursuing application in the food industry worldwide. Regrettably, most suggested green technologies are either limited due to the high cost of equipment, have an impact on product quality, are not suitable for all food types, or are insufficient for maximum food product protection [1]. On the one hand, most literature only described CP application at pilot-scale levels with limited surface coverage. As a result, increasing the plasma-generating electrode size may increase the plasma's quantity and coverage. Regrettably, this whole progress is time-consuming and expensive [28]. On the other hand, CP enhances the nutritional quality of some food products by increasing total phenolic compounds, amino acids, and sugars. Such improvements, however, are dependent on the gas mixture used to generate plasma and the mode of exposure/penetration over the food material [28]. Table 5 summarizes some of the advantages of CP technology in the food industry.

Table 5. Advantages of cold plasma in food industry.

Field	Cold Plasma Activity	References
Safety	Microbial inactivation	[103–105]
	Spore inactivation	[106]
	Toxin and allergens Inactivation	[10,107]
	Enzyme inactivation	[29]
Quality	Preserve nutritional content	[108]
	No sensory alteration	[9]
	Physical and structural integrity	[109]
	Compositional integrity	[110]
Shelf life	Reduce protein oxidation	[111]
	Reduce lipid oxidation	[112,113]
	Inhibits microorganisms	[114]

6. Conclusions

Non-thermal processing techniques have drawn a lot of interest over the past 20 years from the food sector, which is looking for gentle and efficient processes. Alternative technologies have the potential to improve functioning and shelf life while decreasing damaging effects on food nutrients and natural flavor. High-pressure processing, ultrasound, pulsed electric field, ultraviolet light, high-intensity pulsed light, gamma irradiation, and, most recently, non-thermal plasma, a food technology category using physical and chemical effects to modify foods without overheating or altering them, are the most effective non-thermal techniques. Non-thermal treatments offer the possibility to control the treatment of specific molecules within foods. In addition, they may be gentler on the cellular structure of some sensitive products. The consumer demand for product safety requires the food research community to improve food quality and shelf life through various novel technologies. People expect the food they consume to be safe, and technological advances have made this a reality for many food products. However, as we have seen in numerous outbreaks and large-scale recalls involving everything from leafy greens to meat to berries, this is not always the case. The food research community must continue to work to improve food safety and quality to meet the ever-growing demand from consumers. Applications of CP technology are reportedly being utilized nowadays to decontaminate various food goods. However, CP treatment is rarely employed on a commercial scale in the food sector

because current research focuses mainly on the processing and characteristics of plasma in various food products. Although more research is needed to characterize further these technologies' effects on food products and human health, they are generally considered safe when properly applied. Currently, a great deal of research is being conducted on the effects of plasma on various food products.

To this end, it is necessary to overcome the barriers to adopting and utilizing CP technology in the food industry effectively. Most of the CP systems discussed in this review paper are lab-scale configurations, which presents a significant challenge in terms of commercialization. Additional research studies are required to develop prototypes and scale up for commercial production. With the right tools and resources, CP technology could revolutionize the food industry and provide a more efficient, safe, and cost-effective way of producing food products. With the increasing demand for safe and efficient food processing methods, CP technology is well-positioned to impact the food industry significantly.

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