



A Review on Cold Plasma Technology for Pesticide-Free Food Safety: Mechanisms, Efficiency, and Future Perspectives

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Abstract

Pesticides are essential in modern agriculture but often leave harmful residues on food, raising considerable health and environmental concerns. Cold plasma technology, initially developed for applications in the polymer and electronics industries, has emerged as an innovative non-thermal method with promising implications for enhancing food safety. Cold plasma, a quasi-neutral ionized gas, is generated under low-pressure conditions, creating a range of reactive species capable of degrading pesticide residues. Recent advancements now allow cold plasma to be produced at atmospheric pressure, expanding its potential applications and spurring extensive research into its efficacy. This technology offers a pesticide-free approach that not only prioritizes human health but also supports eco-friendly practices in line with sustainable agriculture principles. Cold plasma stands to significantly impact food safety by fostering healthier ecosystems and promoting a more balanced relationship between agriculture and nature. This review examines the effectiveness of cold plasma technology as a transformative tool for achieving pesticide-free food safety, detailing its mechanisms, efficacy, and future potential in reducing pesticide residues in agricultural products.



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Introduction

Pesticides, while vital for modern agriculture, can leave behind harmful residues in food products, posing significant health risks. These risks encompass acute poisoning, chronic damage to the nervous system, and the potential development of serious diseases like Parkinson's and cancer.¹ By prioritizing pesticide-free solutions, mitigates these health threats and ensure the safety of our food supply. Furthermore, pesticide-free practices extend their benefits to the environment.² They help reduce soil degradation, prevent water pollution, and protect non-target species such as pollinators. This eco-friendly approach aligns with the principles of sustainable agriculture, promoting healthier ecosystems and contributing to a more balanced coexistence between farming and nature.³ Cold plasma technology represents a cutting-edge, non-thermal innovation that has garnered significant attention for its potential applications within the food industry. Historically, cold plasma found its primary utility in the polymer and electronics sectors, where it was employed for modifying and functionalizing various polymer surfaces. However, in recent years, this technology's scope has dramatically expanded, encompassing fields such as biomedical devices and biological materials, including food products. Plasma refers to a quasi-neutral ionized gas composed predominantly of photons, ions, free electrons, and atoms in various charge states, either fundamental or excited.⁴ Plasma can be categorized as 'thermal' when its electrons and gas species are in thermodynamic equilibrium and 'non-thermal' when they exist in a state of non-equilibrium. Initially, cold plasma was generated under low-pressure conditions, which limited its range of applications. However, recent advancements in plasma engineering have enabled cold plasma generation at atmospheric pressure, driving extensive research into its potential across various life sciences interfaces. Within the industry, different systems are used for generating cold plasma, each tailored to specific applications. These systems encompass a range of methods, including corona discharges, microwave plasma, radio frequency plasma, inductively coupled plasma, capacity coupled plasma, electron cyclotron resonance plasma, and dielectric barrier discharge plasma. Among these, dielectric barrier discharge and jet plasma have gained prominence in food research due to their straightforward, versatile, and

adaptable designs and operations.⁵ Generating plasma in a neutral gas involves providing sufficient energy for ionization, resulting in a complex chemistry characterized by numerous reactive species. Ongoing research in plasma chemistry aims to identify the reactive species generated in plasma and elucidate their interactions with the biological and chemical components of food products.

This necessitates substantial research efforts to comprehend the mechanisms underlying microbial inactivation, toxin degradation, or other beneficial effects, ultimately leveraging this knowledge to enhance food products and processing techniques. Pesticide degradation by cold plasma treatments has emerged as a highly effective and safe method for reducing pesticide residues in agricultural products. Research findings indicate that cold plasma treatments significantly diminish pesticide levels without detrimental effects on the color and texture of the treated samples.⁶ This approach offers several advantages, including the ability to detoxify food products at relatively low temperatures and in a short timeframe. Importantly, it is a non-toxic and safe process for human consumption. The cold plasma used in these detoxification processes operates at lower temperatures than traditional plasmas, which allows electrons to efficiently break down pesticide molecules and ionize gases without relying on heavy particles with high energy.⁷ The aim of this review is to explore the potential of cold plasma technology as an innovative and effective approach for achieving pesticide-free food safety. It seeks to provide a comprehensive understanding of the mechanisms, efficiency, and future perspectives of cold plasma technology in the context of pesticide elimination from agricultural products.

Cold Plasma Technology: Overview and Application

The term "cold plasma" refers to a partially ionized gas that is not in thermal equilibrium with its surroundings. It is called "cold" because the temperature of the gas is much lower than that of a typical thermal plasma, which is in thermal equilibrium with its surroundings.⁸ Cold plasma is generated by applying an electric field to a gas, which ionizes the gas and creates a plasma. The plasma can be used for a variety of applications, including surface treatment, sterilization, and medical treatment. Cold plasma is also sometimes

called non-equilibrium plasma or low-temperature plasma.

It was initially discovered by Sir William Crookes in 1879 and later named by Irving Langmuir in 1927. Plasma, the fourth state of matter, can exist as either thermal plasma or non-thermal (cold) plasma. Thermal plasma operates under thermodynamic equilibrium and is applied in various industrial contexts, where particles such as electrons, ions, and neutral molecules act uniformly. In contrast,

cold plasma operates on electrodynamic principles at normal atmospheric pressure, producing electrons and heavier species in thermal non-equilibrium.

Cold plasma technology has been extensively studied for sterilization, microbial inactivation, and mycotoxin degradation. It presents a promising solution for food preservation that meets consumer demands for both safety and nutritional quality without compromising sensory attributes.

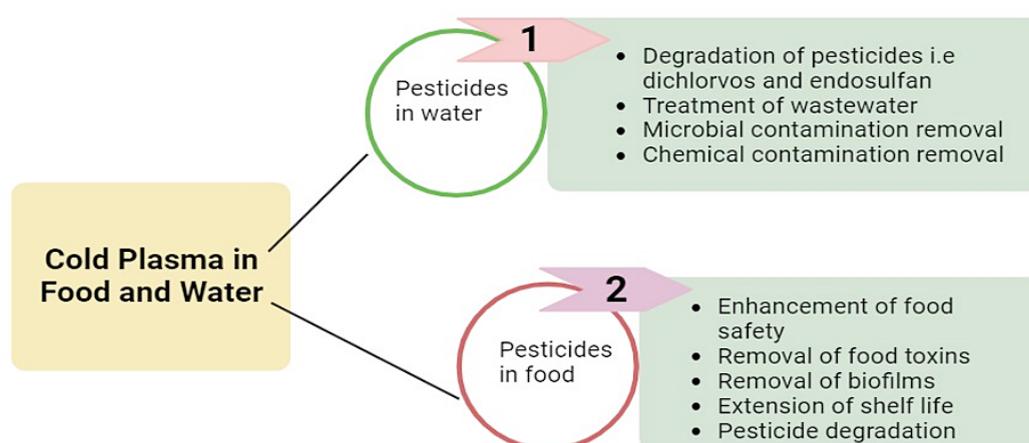


Fig. 1. Cold plasma technique in water and food

Corona discharge is one of the methods used to generate cold plasma. When a high voltage is applied to a small diameter wire or electrode, it creates a strong electric field that ionizes the gas around it, creating a corona discharge.⁹ Corona discharge is a low power electrical discharge that occurs at or near atmospheric pressure. Corona discharge processes have a wide range of applications, including electrostatic precipitation, *Shigella flexneri*.¹⁰

Glow discharge is a plasma treatment that can be used to reduce contamination of foods and food contact surfaces with pathogenic bacteria.¹¹ It involves exposing the bacteria to a one atmosphere uniform glow discharge plasma, which can inactivate the bacteria and reduce their population. The effectiveness of the treatment can be influenced by factors such as the duration of exposure, pH of the culture media, incubation temperature, and culture age. Both gram-positive and gram-negative pathogens can be susceptible to glow discharge

plasma treatment, although spore-forming bacteria like *Bacillus cereus* may be more resistant. A study found that a one atmosphere uniform glow discharge plasma (OAUGDP) was effective in inactivating various foodborne pathogens, including *Escherichia coli* O157:H7, *Listeria monocytogenes*, *Staphylococcus aureus*, *Bacillus cereus*, *Salmonella Enteritidis*, *Vibrio parahaemolyticus*, *Yersinia enterocolitica*, and *Shigella flexneri*.¹² Plasma treatment generates active species such as ultra-violet photons, atomic oxygen, ozone, and free radicals,¹³ which have antimicrobial effects. These active species can cause alterations in lipids, proteins, and nucleic acids, leading to the inactivation of pathogens.

A plasma jet is a type of atmospheric-pressure plasma source that generates a high-temperature and high-density plasma stream. It consists of two concentric electrodes through which a mixture of gases, such as helium and oxygen, flows. The plasma jet can be used for various applications,

such as etching and deposition of materials, due to its ability to generate high concentrations of reactive species and its scalability to treat large areas.¹⁴ The plasma jet technology has the potential to contribute to pesticide reduction through its ability to generate reactive species that can degrade or neutralize pesticides. The plasma jet can be used for the treatment of contaminated surfaces, such as fruits and vegetables, by directly exposing them to the plasma jet¹⁵ figure 1.

The reactive species produced by the plasma can interact with the pesticides on the surface, breaking down their chemical structure and reducing their toxicity.¹⁶ This can effectively reduce the amount of pesticide residues on the surface of agricultural products. Furthermore, the plasma jet can also be used for the treatment of water contaminated with pesticides.¹⁷ By introducing the plasma jet into the water, the reactive species can react with the pesticides, leading to their degradation and removal from the water. This can be particularly useful in agricultural settings where pesticide runoff can contaminate water sources.

Dielectric barrier discharge (DBD) has been shown to contribute to the reduction of pesticides. DBD is an atmospheric pressure plasma discharge that can be generated using a dielectric barrier between two electrodes. This discharge creates a non-equilibrium plasma environment that can interact with various

substances, including pesticides. One way in which DBD contributes to pesticide reduction is through the generation of reactive species such as reactive oxygen species (ROS) and reactive nitrogen species (RNS). These species have strong oxidative and nitrosative properties, which can degrade and break down the chemical structure of pesticides.¹⁸ Another mechanism by which DBD contributes to pesticide reduction is through the generation of UV radiation. DBD can produce UV radiation in the range of 200-300 nm, which is known to have germicidal and photochemical effects.¹⁹ However, further research is needed to fully understand the mechanisms and optimize the DBD technology for specific pesticide reduction applications.

Mechanisms of Cold Plasma Technology

Inactivation of Spores

Cold plasma generates reactive species, such as reactive oxygen species (ROS), which induce oxidative stress in spores.²⁰ The oxidative stress leads to damage to the spore membrane, including electroporation and etching, causing structural and functional alterations. Cold plasma species act on multiple sites within the spore, resulting in further damage and ultimately cell death.²¹ Electron microscopic studies have shown complete disintegration of fungal spore membranes due to electroporation and etching caused by the reactive plasma species Figure 2.

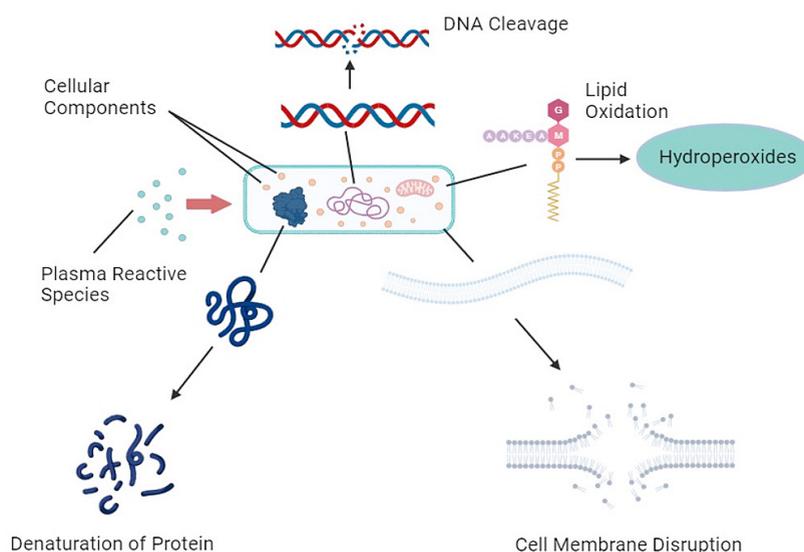


Fig. 2: Mechanism of microbial inactivation by cold plasma

Deactivation of Enzymes and Toxins

Cold plasma treatment has been shown to neutralize microbial toxins and inhibit the synthesis of toxins.²² The reactive species generated by cold plasma can break down toxins, such as aflatoxin, into degradation products that are less toxic.²³ High-performance liquid chromatography revealed the inactivation of aflatoxin production by certain fungi following plasma treatment. Cold plasma treatment has also been shown to reduce the content of ochratoxin A in food samples artificially inoculated with mycotoxigenic fungi.²⁴

Impact of Pesticides on Health and Environment

Organophosphate pesticides are widely used in agriculture to control insects and pests. Some common examples include chlorpyrifos and malathion. These pesticides work by disrupting the nervous systems of insects. They have been associated with health concerns, including neurotoxicity in humans.²⁵ Neonicotinoid pesticides, such as imidacloprid and clothianidin, are used to protect crops from a variety of pests, particularly in seed treatments. These pesticides have faced scrutiny due to their potential harm to pollinators like bees. Glyphosate is a widely used herbicide known by brand names like Roundup. It is used to control weeds in agriculture.²⁶ Glyphosate has been a subject of controversy and regulatory review regarding its potential health and environmental impacts.²⁷ Atrazine is another herbicide used to control broadleaf weeds and grasses in crops like corn and sugarcane. It has been a subject of concern due to its potential to contaminate water sources. Dichlorodiphenyltrichloroethane (DDT) has been banned in many countries, it is still used in some regions to control disease-carrying mosquitoes.²⁸ DDT is known for its environmental persistence and bioaccumulation in food chains. Carbamate pesticides, such as carbaryl, are used to control a wide range of insects, including beetles and ants. They work by inhibiting acetylcholinesterase, similar to organophosphates, and can have neurotoxic effects.²⁹ Fungicides are used to control fungal diseases in crops. Common examples include captan, mancozeb, and chlorothalonil. While primarily targeting fungi, some fungicides may also have effects on non-target organisms.³⁰ Herbicides are used to control weeds in crop fields. In addition to glyphosate and atrazine, other herbicides like 2,4-D and paraquat are also used for weed control.³¹

The use of synthetic pesticides can have negative effects on both the environment and human health. In terms of human health, exposure to pesticides has been linked to serious ailments such as cancer, endocrine disorders, neurological problems, and reproductive issues. Sabarwal *et al.*³² reviewed the hazardous effects of chemical pesticides on human health, including cancer and other associated disorders. In terms of environmental effects, studies have shown that pesticides can lead to a decline in soil and water quality, as well as a decline in biodiversity and species richness. A study by Potts *et al.*³³ found that the use of neonicotinoid pesticides was linked to a decline in bee populations, which can have negative effects on pollination and food production. Synthetic pesticides can have negative effects on both the environment and human health.

Exploring Pathways for Pesticide Degradation with Cold Plasma

Plasma sterilization is an innovative method for sterilizing surfaces, widely applied in the food processing industry. It uses plasma a highly energetic state of matter composed of ionized gases as a non-thermal sterilization technique. This method effectively removes microorganisms such as bacteria, viruses, and fungi from surfaces.³⁴ One of the primary benefits of plasma sterilization in food processing is its non-thermal nature, meaning high temperatures aren't needed for sterilization. This quality is especially advantageous for heat-sensitive food products, as it maintains quality that could be compromised by traditional thermal methods like pasteurization. Plasma sterilization is also known for its short treatment durations.³⁵ Unlike chemical disinfectants, which may leave residues on food surfaces, plasma sterilization avoids leaving chemical residues and prevents the formation of persistent toxic compounds.³⁶ It has broad-spectrum antimicrobial effects with minimal environmental impact and can be safely applied to various packaging materials without causing damage. Plasma treatment also has the added benefit of extending shelf life by inactivating spoilage enzymes, making it an effective choice for ensuring food safety and quality in food processing.³⁷ Overall, plasma sterilization represents a promising advancement, providing efficient and environmentally friendly solutions. It operates effectively at room temperature and pressure, leaving no chemical residues and

having a minimal environmental impact. Cold plasma is highly versatile, applicable to a wide range of foods and packaging materials, and is gaining regulatory approval. Compared to other non-thermal Technologies cold plasma stands out for its balanced

blend of efficiency, safety, and eco-friendliness. While each method offers unique benefits, cold plasma's advantages position it as a promising technology for the future of food processing.

Table 1. Pesticide Residue Degradation and Contaminant Control by Cold Plasma Treatment

Application	Cold Plasma Treatment	Benefits and Findings
Food Surface Decontamination	Generation of reactive species (H ₂ O ₂ , O ₃ , radicals, etc.)	Effective degradation of pesticide residues on food surfaces
	Advanced oxidation processes	Production of simpler, less toxic degradation products
	In-package Dielectric Barrier Discharge (DBD)	Significant reduction in pesticide residues (e.g., on strawberries) after short treatment times (5-8 minutes)
Air Disinfection	Continuous Direct-Current Corona Discharge Plasma	Successful in disinfecting air contaminated with postharvest mold (<i>Penicillium</i>)
Controlled Growth Environments	Prevention of contamination	Potential to reduce the need for traditional pesticides
Soil Remediation	Removal of Non-Aqueous Phase Organic Liquids (NAPLs)	Rapid removal of high concentrations of NAPLs
	Degradation of Persistent Organic Pollutants (POPs)	Effective degradation of soil pollutants such as PCBs, acid scarlet GR, and DDT
Sustainability and Safety	Safe and sustainable food production	Reduction of pesticide residues and contaminants without traditional chemicals
	Reduced consumer risk	Possibility of zero-residue clean labels
	Soil remediation	Remediation of contaminated soils

Interactions between Cold Plasma Radical Species and Pesticides

The interactions between cold plasma radical species and pesticides have been studied in various research studies. Cold plasma treatment has been shown to degrade pesticides in water, leading to their removal or transformation into less harmful compounds.³⁸ This degradation process can result in the loss of pesticide activity and reduce their toxicity. Cold plasma can degrade pesticide residues by generating reactive species such as H₂O₂, O₃, O,

H, and OH radicals.³⁹ Overall, cold plasma has the potential to safely and sustainably degrade pesticide residues and control contaminants in the agricultural and food sectors.

Chemical Transformations of Pesticides During Cold Plasma Treatment

Cold plasma treatment has been shown to effectively degrade pesticide residues on various substrates, including water and food surfaces. In the case of pesticide residues on strawberries, high voltage

in-package dielectric barrier discharge (DBD) discharge reduced the residues significantly after 5-8 minutes of treatment. Similarly, continuous direct-current corona discharge plasma was successful in disinfecting air contaminated with *Penicillium*, a common postharvest mold rot. This technology shows promise in preventing contamination in controlled growth environments and reducing the need for pesticides. Cold plasma technology has also been explored for soil remediation contaminated with organic compounds, including non-aqueous phase organic liquids (NAPLs). Additionally, persistent organic pollutants (POPs) in soil, such as polychlorinated biphenyls (PCBs), acid scarlet GR, and dichlorodiphenyltrichloroethane (DDT), can be degraded using cold plasma. Overall, cold plasma treatment offers the potential for safe and sustainable food production by degrading pesticide residues and controlling contaminants without the use of traditional pesticides and fertilizers. It provides a viable approach for reducing consumer risk, achieving zero-residue clean labels, and remediation of contaminated soils Table 1.

Effect of Cold Plasma on Nutritional Value of Food

Foods are rich in nutrients that promote microbial growth, leading to spoilage over time, especially during storage. Traditionally, food preservation relied on high-temperature methods such as pasteurization, canning, drying, and smoking. While these thermal treatments effectively inactivate microbes, they often degrade the nutritional and sensory qualities of food, causing the breakdown of bioactive compounds, off-flavor development, undesirable color and texture changes, and nutrient loss. This has driven researchers to explore non-thermal preservation methods.⁴⁰ Non-thermal techniques, including cold plasma, high-pressure processing (HPP), irradiation, ozone, pulsed light, and ultrasound, offer potential advantages in preserving food without compromising its nutritional value.⁴¹ Studies indicate that these methods achieve effective microbial inactivation, extended shelf life, and higher-quality products compared to conventional methods.⁴² The impact of each non-thermal technique on food quality and structure depends on its distinct mechanism of action.

Experimental Studies Investigating Pesticide Degradation

Plasma technology has emerged as a promising solution for pest control in stored cereal crops. The potential of cold plasma in pesticide removal degraded pesticide residues on blueberries, with removal efficiencies of 75% and 80% for boscalid and imidacloprid respectively, after 80kV for 5 min of plasma treatment. The degradation of both pesticides followed first-order kinetic reactions. Plasma technology has emerged as a promising solution for pest control in stored cereal crops. One of the early findings on the insecticidal properties of atmospheric-pressure plasma was reported by a study by Abd El-Aziz *et al.*⁴³ demonstrated a significant increase in the mortality of *Plodia interpunctella* and *Tribolium castaneum* when treated with cold plasma. These results suggest that *P. interpunctella* larvae are particularly sensitive to plasma treatment, as indicated by elevated levels of lipid peroxides and reduced levels of glutathione and protein, which are indicative of the oxidative effects of such treatment. Donohue *et al.*⁴⁴ also developed an ozone-mist sterilization technique for insects using a dielectric discharge system. With this method, aphids were eliminated within 30 seconds without causing noticeable damage to the plant leaves. The susceptibility of different insects to nonthermal plasma treatment varied considerably due to variations in plasma generation methods and organism structures. Similarly, studies by Abd El-Aziz *et al.*⁴³ demonstrated that *P. interpunctella* larvae were more sensitive to plasma than pupae, possibly due to the protective effect of the pupal sclerotized cuticle. Cold plasma technology, with its short treatment times, process flexibility, and absence of residues, appears to be an attractive option for pest control during food storage. However, further research is needed to assess process efficacy, elucidate the mechanisms of action, and understand the effects on the target product.

Factors Influencing Cold Plasma Efficiency in Pesticide Degradation

The efficiency of cold plasma treatment is influenced by a multitude of factors, encompassing microbial characteristics, food attributes, and the operational parameters of the plasma system. Notably, adjusting

instrument settings, including voltage, frequency, treatment duration, and gas composition, can yield varying treatment outcomes. For instance, a study investigating the impact of various dielectric barrier discharge high voltage atmospheric cold plasma parameters on *Bacillus atrophaeus* spore inactivation observed significant effects of these parameters.⁴⁵ Direct plasma exposure for 60 seconds led to a reduction of spores by at least 6

log₁₀ cycles across different gas types. Conversely, indirect exposure for the same duration resulted in either a 2.1 or 6.3 log₁₀ cycle reduction in spore count, depending on the gas used. Notably, relative humidity played a crucial role in bacterial spore inactivation during high-voltage atmospheric cold plasma treatment. Several factors come into play in regulating the antimicrobial effects of cold plasma treatments, as depicted in Figure 3.

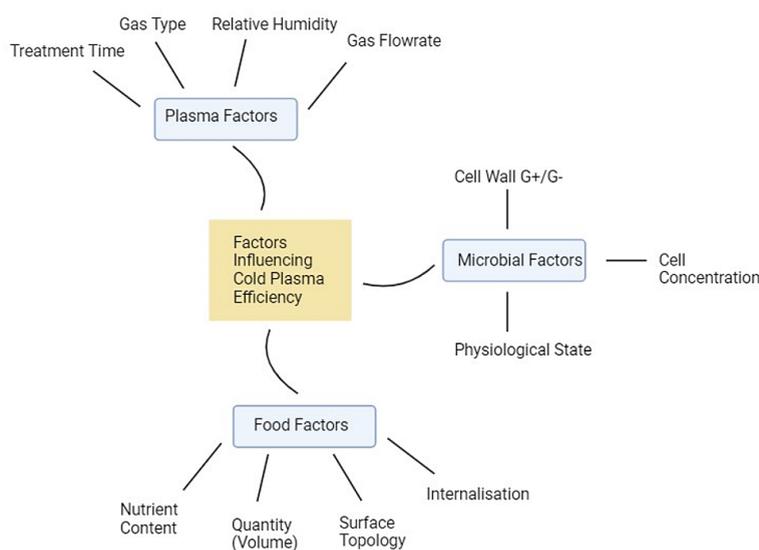


Fig. 3: Factors Influencing Cold Plasma Efficiency

Furthermore, the characteristics of the working gas utilized for plasma generation significantly impact its effectiveness. Oxygen's presence in plasma generation is particularly crucial for enhanced microbial inactivation, as it leads to the production of ozone (O₃), a potent oxidizing agent employed in water treatment as a disinfectant. The dissociation of oxygen molecules at high voltages results in ozone production. Additionally, the treatment duration plays a pivotal role in cold plasma-mediated microbial inhibition. Food intrinsic and extrinsic factors also exert a substantial influence on product shelf-life and microbial composition. Factors like food composition, nature, moisture content, and overall composition are pivotal in determining the effectiveness of a food preservation strategy. It is noteworthy that the water content of food products affects the efficacy of cold plasma treatment, with higher hydroxyl radical generation during treatment in liquid water phases promoting more effective microbial inactivation.⁴⁶

Microbial characteristics, including type, strain, physiological state, growth phase, and mode of existence (planktonic or sessile), are equally critical factors. Spore-forming microorganisms like *Clostridium* and *Bacillus* species, known for their resistance to various food preservation treatments, are more resistant to preservation methods, including cold plasma, due to factors such as spore structure, DNA saturation by acid-soluble proteins, and low inner spore membrane permeability to hydrophilic molecules.³⁵ Furthermore, the presence of biofilms on food contact surfaces poses significant challenges in terms of food safety. Cold plasma treatment has demonstrated effectiveness in disrupting and inactivating microbial biofilms, making it a valuable tool in food safety protocols. In summary, cold plasma treatment's efficacy is influenced by a complex interplay of factors, and understanding these variables is essential for optimizing its application in food safety and preservation.

Cold Plasma vs. Conventional Pesticide Removal Techniques

Comparative Analysis of Cold Plasma with Traditional Methods and other Technologies

Cold Plasma vs. Traditional Thermal Processes

Traditional thermal processes, while effective in reducing and eliminating microbe contamination, may not be suitable for temperature-sensitive foods. In contrast, cold plasma technology offers a non-thermal alternative that can inactivate microbial spores without denaturing proteins or affecting organoleptic properties. Cold plasma can be a valuable tool for food safety, especially for temperature-sensitive products.⁴⁷ According to a preliminary cold plasma study, plasma may enhance food shelf life and quality. The antifungal and antimycotoxin properties of cold plasma benefit fresh produce, agricultural commodities, nuts, peppers, herbs, dried meat, and fish.⁴⁸

Cold Plasma vs. Hurdle Technology

Hurdle technology, which combines multiple preservation techniques, has been recommended as an effective approach for achieving better germicidal results. Cold plasma can be integrated into hurdle technology to enhance food safety by providing an additive effect in combination with other preservation methods.⁴⁹ This integration can help achieve improved microbial inactivation and extend the shelf-life of food products. A recent investigation shows that HCP effectively inactivated natural microbes and foodborne pathogens in packaged vegetables, demonstrating strong microbial suppression in mixed vegetables stored at 4°C. Importantly, HCP maintained the vegetables' color, respiration rate, and antioxidant activity, showing no negative impact on these quality attributes.⁵⁰

Safety and Regulatory Considerations

Assessing the Safety of Cold Plasma-Treatment on Pesticide Removal

The safety of cold plasma treatment on pesticide removal is an important consideration. While cold plasma technology has shown potential for food decontamination, including pesticide residue removal, it is necessary to assess its safety in this context. Research has demonstrated the effectiveness of cold plasma in reducing pesticide residues on various food products. For instance, research by Sarangapani *et al.*⁵¹ demonstrated

that atmospheric cold plasma significantly reduced pesticide levels on the surface of blueberries. However, the formation of by-products or residues due to plasma-generated reactive species could present safety concerns, depending on the pesticide, food product, and specific treatment conditions.⁵² Some studies have indicated limitations and potential negative effects of HCP, such as lipid oxidation in fish and the degradation of oligosaccharides in juice.⁵³ These changes suggest that cold plasma treatment may sometimes alter food quality and necessitate further research to thoroughly assess the potential for toxic residues on treated foods. Nonetheless, while cold plasma is a promising approach for pesticide reduction, understanding its full safety profile, including the risk of toxic by-products, is crucial.

Future Perspectives and Challenges

Scaling up and Potential Integration Cold Plasma Technology in Food Industries

Plasma technology holds numerous potential applications in the food industry, each with its own set of advantages and challenges. Applications that do not involve direct contact with food, such as food packaging and surfaces in contact with food, typically feature smooth and uniform surfaces. This makes the treatment process more straightforward and simplifies the regulatory approval process. On the other hand, when cold plasma comes into direct contact with food intended for human or animal consumption, the interaction becomes more complex, leading to greater regulatory challenges.⁵⁴

Packaging and Contact Surfaces

Plasma discharges have proven successful for modifying the surfaces of food packaging materials and for sterilizing them.⁵⁵ Recent designs of plasma systems also show promise for sanitizing surfaces used in food processing, such as conveyor belts, through intermittent disinfection cycles. Similarly, this technology can be employed to disinfect food containers before they are filled with products. Furthermore, recent advancements have led to the development of active packaging through the surface coating of antimicrobials onto polymer packaging using a plasma discharge process. This has resulted in reduced microbial loads in products like beef, leading to extended shelf life.

Food Decontamination

The multi-species nature of plasma technology offers an advantage because it makes it difficult for bacteria to develop resistance.⁵⁶ Consequently, extensive research has been conducted on using cold plasma for food decontamination. However, the effectiveness of this method varies widely depending on the specific food product. Various studies have explored plasma disinfection of fresh fruits, vegetables, dry fruits, nuts, seeds, protein

foods, spices, liquids, and eggshells. Factors such as surface roughness, moisture content, and chemical composition play a significant role in determining the efficacy of the process and its suitability for specific foods. The regulatory definitions and metrics for food decontamination, such as pasteurization, sterilization, and disinfection, can vary significantly between different agencies, countries, and food products as given in table 2.

Table 2. Food Decontamination Using Cold Plasma

Food sample	Microorganism	Plasma Type	References
Egg	<i>S. enterica</i>	Direct DBD	57
Barley and wheat	<i>Bacillus atrophaeus</i> , <i>Escherichia coli</i>	DBD	58
Strawberries	<i>L. monocytogenes</i>	DBD air plasma	59
Apple surface	<i>E. coli</i> and <i>Salmonella</i>	Atmospheric cold plasma DBD	60
Lettuce	<i>Malathion Chlorpyrifos</i>	DBD	61
Blueberries	<i>Aerobic microbes</i>	Atmospheric cold plasma	62
Almond	<i>E.coli</i>	Atmospheric pressure plasma jet	63
Pistachio	<i>Natural fungi</i>	Low pressure cold plasma	64
Mandarin	<i>Penicillium italicum</i>	Cold plasma	65

Addressing Technical and Economic Challenges

Cold plasma technology has garnered considerable attention for its potential applications across various industries, including healthcare, electronics, and food processing. While its promise is evident, there are significant technical and economic challenges that must be addressed to fully realize its potential. One of the primary technical challenges in adopting cold plasma technology is the scalability of the equipment.⁶⁶ Many laboratory-scale cold plasma systems are available, but scaling up for industrial use can be complex and costly. Manufacturers need to develop large-scale, cost-effective systems that can be integrated into existing production processes. This requires advancements in reactor design, power sources, and process control systems to make the technology economically viable. Cold plasma systems can consume a significant amount of energy, which can be a barrier to widespread adoption.⁵⁴ Developing more energy-efficient plasma sources and optimizing operating parameters is essential to reduce energy consumption. Additionally, integrating cold plasma technology with renewable energy sources, such as solar or wind power, could enhance

its sustainability and economic viability. Cold plasma technology often encounters regulatory hurdles, particularly in industries like food processing and healthcare. Establishing standardized safety and efficacy protocols and collaborating with regulatory agencies can expedite the approval process. Investing in education and training programs for technicians and operators is critical to ensure safe and efficient operation. Convincing industries to embrace a relatively new technology like cold plasma can be challenging.⁶⁷ As advancements continue, cold plasma has the potential to revolutionize various industries and offer sustainable and cost-effective solutions to complex problems.

Conclusion

In conclusion, cold plasma technology presents a promising array of applications, ranging from spore inactivation and enzyme/toxin deactivation to efficient pesticide degradation. Its advantages, including efficiency, eco-friendliness, versatility, rapidity, and scalability, have positioned it as an attractive solution in various industries. However, several challenges and considerations must be addressed to fully

harness its potential. Cold plasma technology holds the promise of revolutionizing various industries by offering sustainable and cost-effective solutions to complex challenges. Addressing these technical and economic challenges, along with safety and regulatory considerations, will be essential to fully unlock its potential in pest control, food safety, and other applications. Continued research, innovation, and collaboration will play a pivotal role in advancing this promising technology.

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The authors declare that there is no potential conflict of interest associated with this manuscript.

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Even though adequate data has been given in the form of tables and figures, however, all authors declare that if more data is required then the data will be provided on request basis.

Ethics Statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement

This study did not involve human participants, and therefore, informed consent was not required.

Clinical Trial Registration

This research does not involve any clinical trials.

Permission to Reproduce Material from Other Sources

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