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COLD PLASMA TECHNOLOGY - A REVIEW OF THE BASICS AND IT'S EMERGING APPLICATIONS IN THE FOOD AND AGRICULTURE SECTOR

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ABSTRACT

Cold plasma is an emerging non-thermal method of food processing and preservation. Over the past five years, there has been a huge increase in the number of research works on cold plasma applications. Cold plasma is the best alternative to traditional sanitizers in the food industry without leaving any harmful residues. Applications in the food sector include food decontamination, enzyme inactivation, reduction of food safety hazards, and enhancing efficiency of unit operations such as drying and extraction. In the agriculture sector, cold plasma has proved its potential for seed decontamination, enhancement of seed germination and plant growth, soil and water remediation etc. This paper aims to give an insight into the fundamentals of cold plasma and its promising applications in the food and agriculture sector along with the underlying mechanisms.

Keywords: Cold plasma, applications, food, agriculture, processing

1. INTRODUCTION

The world's food and agriculture sector is under tremendous pressure to increase output because of the population's fast rise. The strain on the environment and natural resources is increased by the overuse of fumigants, pesticides, and food preservatives. Sustainable methods that can guarantee food safety and pest control without endangering the environment are becoming more and more necessary (Ohta, 2016). Thus, there is a great demand for technology that may successfully lower the levels of plastic residue in soil, mycotoxins in food, and pesticide residues in fresh produce. One such effective technology that is still in demand in research is cold plasma, and scientists are constantly finding new uses for it. This study primarily reports on the principles of cold plasma and its developing applicability in the food industry.

2. COLD PLASMA TECHNOLOGY BASICS

Plasma was discovered as the “fourth state of matter “by Sir William Crookes in 1879. Later the term “plasma” was coined by Irving Langmuir in 1927. Plasma is the most abundant matter (more than 99%) in the universe (Domonkos *et al*., 2021). Plasma is an ionized gas that contains charged particles, free radicals, ultraviolet radiation (UV), reactive oxygen species (ROS: O, O_2, ozone (O_3), and OH), and reactive nitrogen species (RNS: NO, NO_2) (Laroque *et al*., 2022).

Plasma is classified into thermal and non-thermal plasma based on the relative temperature of electrons and heavy species (ions and neutrals). Thermal plasma is also known as equilibrium plasma since the temperature of the electrons is equal to the temperature of heavy species. Thermal plasma is completely ionized and has a high temperature above 10,000 K. On the overuse of fumigants, pesticides, and food preservatives increases the strain on the environment and natural resources other hand, cold plasma is known as non-equilibrium plasma since the temperature of electrons is higher (5000°C - 10^5°C) than that of heavy species (25°C–100°C). The net temperature of cold plasma is near to room temperature or slightly above it. It is worth noting that thermal plasma is completely ionized gas while cold plasma is partially ionized gas. Cold plasma can be generated in a vacuum and at atmospheric pressure. The discharge volume, reaction conversion, and input flow rate are low for cold plasma compared to thermal plasma. Cold plasma is relatively safe and easy to handle. The Installation cost of cold plasma is less while thermal plasma is expensive (Indarto *et al*., 2008).

2.1. Principles of cold plasma

The basic mechanisms behind the formation of cold plasma are gas breakdown and the formation of electron avalanches. These mechanisms are better explained by Townsend theory, Streamer theory, and Paschen’s law (Laroque *et al*., 2022).

Townsend theory: When an external electrical potential is applied, electrons liberated from the cathode surface migrate toward the anode. These accelerated electrons undergo collisions with atoms and molecules within the gaseous medium, leading to the ionization of these entities and the production of numerous positive ions and electrons, initiating an electron avalanche. The electron avalanche is a phenomenon wherein electrons, propelled by the electric field, interact with atoms and molecules, liberating electrons through ionization. The liberated electrons undergo subsequent acceleration and collisions, perpetuating a chain reaction that results in the successive release of additional electrons. The extensive ionization process disrupts the gas, rendering it fully conductive.

Streamer theory: Instantaneous recombination between positive ions and electrons releases photons which produce secondary electrons by photo-ionization. Secondary avalanches join the main avalanche and highly conductive channel formation occurs.

Paschen's law: The product of electrode gap distance and gas pressure determines the gas breakdown voltage.

2.2. Generation of Cold Plasma

Electrical discharges such as direct current (DC) or alternating current (AC) at frequencies up to 100 kHz, radio frequency discharges between 100 kHz and 100 MHz, and microwave discharges above 100 MHz can all result in the production of cold plasma (Mravlje *et al*., 2021). Dielectric barrier discharge, plasma jet, corona discharge, and gliding arc discharge are examples of electrical discharge techniques. Working gases that are frequently utilized include nitrogen, argon, helium, oxygen, and their mixes (Domonkos *et al*., 2021).

2.2.1. Dielectric barrier discharges (DBD)

The generation of Dielectric Barrier Discharge (DBD) plasma involves the application of high voltage across two metal electrodes, namely a powered electrode and a ground electrode. One or both of these electrodes are coated with a dielectric material, such as polymer, glass, quartz, or ceramic, and are positioned at a variable gap ranging from 0.1 mm to several centimeters. The dielectric material serves to restrict current flow, prevent electric arc formation, and facilitate the ionization of the surrounding gas (Misra *et al.*, 2019). Operating within this configuration, the typical parameters for DBD plasma encompass (i) gas pressures ranging between 1 × 10^4 and 1 × 10^6 Pa, (ii) a frequency band between 10 and 50 MHz, and (iii) the utilization of alternating current (AC) or pulsed direct current (DC) with voltage amplitudes oscillating within the range of 1 to 100 kV (Laroque *et al*., 2022).

2.2.2. Atmospheric pressure plasma jet (APPJ)

Atmospheric pressure cold plasma jet consists of two coaxial electrodes between which feed gas flows at a high flow rate. It produces stable, homogeneous, and uniform discharge at atmospheric pressure. Plasma jets can't be applied to a larger area but an arrangement of several jets can overcome this limitation (Laroque *et al*., 2022).

2.2.3. Corona discharge (CD)

Corona discharge is generated by the application of high voltage to sharp electrode tips, edges or thin wires. It is commonly used in ozone generators (Laroque *et al*., 2022).

2.2.4. Gliding Arc Discharge (GAD)

The gliding arc (GA) represents an electrical discharge configuration characterized by its formation between two or more divergent electrodes linked to a high-voltage power supply, accompanied by a high-velocity gas flow interposed between these electrodes. The dynamic behavior of the arc involves its movement from the initial ignition zone along the electrodes until the power system reaches a point where it can no longer adequately compensate for the losses incurred due to the expanding volume of plasma. Subsequently, the arc undergoes extinguishment and is subsequently re-established in the ignition zone (Pawlat *et al.*, 2019).

2.3. Exposure methods

Plasma treatment can be performed as direct or indirect exposure (Nisha and Rita, 2019; Mravlje *et al*., 2021).

2.3.1 Direct exposure

In this approach, the sample is directly subjected to plasma, coming into close contact with both UV radiation and other species generated by the plasma (Mravlje *et al.,* 2021).

2.3.2. Indirect or remote exposure

In the case of indirect exposure, the sample is positioned at a distance from the plasma source to minimize damage from excessive heat and reactive species produced by the plasma. This method ensures that the product is only exposed to lower concentrations of long-lived species, such as reactive oxygen species (ROS) and reactive nitrogen species (RNS). Additionally, indirect treatment can be achieved by employing plasma-activated liquids like plasma-activated water (PAW) or plasma-activated sodium chloride (Mravlje *et al*., 2021).

Plasma-activated water is an effective alternative to traditional sanitizers in the fresh produce industry. With the increase in exposure time and power level, a reduced pH and an increased concentration of reactive nitrogen species such as nitrates and nitrites were achieved. Irrespective of the power levels, 20 min Plasma-activated water was found stable for two weeks of refrigerated storage at 4^0C. (Risa Vaka *et al*., 2019).

2.4. Factors affecting the effectiveness of cold plasma

2.4.1. Process factors

Gas composition and flow rate, variations in voltage, frequency, and power, treatment time, electrode material, geometry, and shape, dielectric material, exposure distance, etc. are the process factors that affect the effectiveness of the treatment. With increase in power level and exposure time, higher effectiveness is obtained.

2.4.2. Product factors

Product factors include composition, moisture content, pH, surface properties, surface area/volume ratio

2.4.3. Environmental factors

Relative humidity, and temperature are the environmental factors that affect treatment efficiency. An increase in relative humidity results in higher inactivation due to the formation of more hydroxyl radicals (Lazra *et al.*, 2020).

2.4.4. Microbiological factors

Microbiological factors include type of microorganisms, growth phase, and concentration.

2.5. Applications in the food sector

2.5.1. Decontamination of foods

Heat and chemicals are two common conventional sterilization techniques that are harmful, time-consuming, and leave poisonous residues. Research shows that cold plasma has a greater effect on bacterial spores than traditional techniques such as heat, chemical treatments, and UV irradiation (Thirumdas *et al*., 2015). Microbial inactivation is primarily caused by reactive oxygen species (ROS) and reactive nitrogen species (RON). These reactive substances trigger cell rupture by oxidizing the carbohydrates and lipids on the cell membrane. Additionally, reactive species damage cells internally by oxidizing lipids, denaturing proteins, and damaging DNA (Laroque *et al*., 2022).

It has been demonstrated that cold plasma treatment can reduce *Salmonella*, *Escherichia coli*, *Listeria monocytogenes*, and *Staphylococcus aureus* by more than 5 logs (Rao *et al*., 2023). According to Niemira (2012), the efficacy of this treatment varies depending on the particular food type and processing conditions. Treatment times might be as short as 3 seconds or as long as 120 seconds.

The effectiveness of a large gap atmospheric cold plasma produced by an open-air high-voltage dielectric barrier discharge (DBD) pilot-scale reactor was examined in a study by Ziuzina *et al.* (2020). The reactor was designed to clean and maintain the quality of spinach and strawberries, and it could operate in both static (batch) and continuous modes. *E. coli* in strawberries and spinach was reduced by 2.0 and 2.2 logs, respectively, and *L. innocua* by 1.3 and 1.7 logs, respectively, under static application of atmospheric cold plasma. A 3.8-log reduction was attained by continuous mode against the *L. innocua* inoculation on strawberries. Notably, there were no appreciable variations in color, hardness, pH, or total soluble solids (TSS) between samples treated with atmospheric cold plasma and control samples. The treatment's benefits persisted throughout the shelf life, demonstrating the pilot-scale plasma reactor's excellent antibacterial efficacy while also maintaining the strawberries' quality.

According to Lee *et al*. (2021), chicken salad packaged in a commercial polyethylene terephthalate container underwent an in-package atmospheric dielectric barrier discharge treatment (ADCP) at 24 kV for two minutes. According to the study, treating chicken salad with ADCP reduced the amount of native mesophilic bacteria by 1.2 log, Salmonella by 1.0–1.5 log, and the Tulane virus by 1.0 log.

Research on the decontamination of pathogenic and spoilage bacteria in pork and chicken meat through liquid plasma immersion indicated that a liquid plasma containing 60 ppm H_2O_2 can effectively reduce the presence of *S. Enteritidis*, *S. Typhimurium*, *E. coli*, and *C. jejuni* on the surfaces of pork and chicken meat (Sammani et al., 2022).

Crocus sativus L. stigmas treated with radiofrequency low-pressure cold plasma resulted in a considerable reduction of total microorganisms, coliforms, *E. coli*, molds, and yeasts, respectively, 5.75, 6.71, 6.07, and 4 log $CFUg^{-1}$ (Khodabandeh *et al*., 2023).

2.5.2. Enzyme inactivation and blanching

It has been shown that cold plasma is useful in deactivating spoilage enzymes, such as PPO, POD, LOX, and lipase. Since enzymes are essentially proteins, they are inactivated by the chemical species found in cold plasma. These chemical species either break down certain bonds or chemically modify the side chains, causing the alteration of the secondary structure of proteins (Misra *et al*., 2016).

Research conducted on wheat germs revealed that, at optimal conditions of 25 minutes at 24 kV, lipase and lipoxygenase activity dropped to 25.03% and 49.98%, respectively. Longer treatment periods and greater voltage were found to promote inactivation (Tolouie *et al*., 2018).

A decrease in PPO and POD activity was observed during the cold plasma processing of acai pulp. The oxidation of side chains of amino acids, the disruption of peptide bonds, and the creation of protein-protein cross-links were among the hypothesized processes for enzyme deactivation (Dantas *et al*., 2021).

Additionally, slices of banana showed a significant reduction of 70% and 100% in PPO and POD activity after being treated with cold plasma. A voltage of 6.9 kV for 46 seconds was found to be the optimal condition for this reduction (Khoshkalam Pour *et al.*, 2022).

2.5.3. Reduction of mycotoxins

Cold plasma has proven effective in breaking down mycotoxins, including aflatoxins, deoxynivalenol, enniatins, zearalenone, and fumonisin. Additionally, it has demonstrated the ability to deactivate fungi that produce these mycotoxins, such as Aspergillus, Alternaria, Penicillium, and Fusarium, in various food commodities (Gavahian and Cullen, 2019).

Investigation on hazelnuts intentionally contaminated with aflatoxin indicated that aflatoxin B1 and G1 exhibited greater sensitivity to plasma compared to aflatoxin B2 and G2. Ozone directly targeted the C8-C9 double bond of AFB1 and AFG1. Conversely, AFB2 and AFG2, lacking this double bond, were less responsive to reactive oxygen species (Siciliano et al., 2016)

In the context of roasted coffee, cold plasma treatment emerges as a potential method for breaking down and mitigating toxins produced by mycotoxin-producing fungi. The plasma treatment involved roasted coffee subjected to an input power of 30 W, an output voltage of 850 V, and a helium flow rate of 1.5 L/min. After a 6-minute treatment, fungal activity was entirely inhibited, resulting in a substantial 4-log reduction. Furthermore, a 50% reduction in ochratoxin A (OTA) content was achieved after 30 minutes of plasma treatment (Casas-Junco *et al.*, 2019).

The impact of cold plasma on diminishing the population of *Aspergillus flavus* and the overall levels of aflatoxins was studied by Esmaeili *et al*. (2022). Three critical process variables were taken into account: exposure time (5–10–15 min), power supply voltage (10–15–20 kV), and the composition of argon to air (0–50–100%). The most notable reductions in aflatoxins (B1, 83.70%; B2, 74.36%; G1, 41.39%, and G2, 50.74%) were observed when exposed to conditions of 20 kV, 15 minutes of exposure, and a 62.23% argon-air gas mixture.

In a study conducted on rice grains intentionally contaminated with molds or mycotoxins, the microbial activities of *Aspergillus niger*, *Rhizopus oryzae*, *Penicillium verrucosum*, and *Fusarium graminearum* were significantly inhibited by the cold plasma treatment. The maximum reductions in deoxynivalenol (DON) and ochratoxin A (OTA) were 61.25% and 55.64%, respectively (Guo *et al.*, 2023).

2.5.4. Reduction of pesticides

In a study by Anbarasan *et al.* (2022), the reduction of Chlorpyrifos pesticide in soybeans was investigated through cold plasma and ozone treatments. The findings indicated that cold plasma exhibited greater efficacy against chlorpyrifos compared to ozone treatment, causing minimal changes in soybean quality. Ozone treatment achieved only a 50% reduction in pesticide after 30 minutes of exposure, whereas cold plasma treatment achieved the same reduction in just 6 minutes.

In another study conducted by Wang *et al*. (2023), dielectric barrier discharge (DBD) plasma was employed to degrade carbendazim (MBC) in an aqueous solution. Under optimal conditions (160 kV, 50 Hz), plasma treatment for 10 minutes resulted in an 89.04% degradation of the MBC solution (initial concentration: 0.5 μg/mL). The plasma degradation products exhibited a low toxicity level.

2.5.5. Reduction of food allergens

The application of cold plasma treatment to peanuts led to a noteworthy reduction in the antigenicity of key peanut allergens, specifically Ara h 1 and Ara h 2. The treatment resulted in a decrease in protein solubility, accompanied by the potential formation of insoluble aggregates. Prolonged exposure to plasma induced alterations in the secondary structure of proteins, particularly impacting the α-helix and β-sheets structures. These modifications had implications for epitope binding capacity, consequently influencing the overall antigenicity of the treated peanuts (Venkataratnam *et al.*, 2020).

2.5.6. Reduction of anti-nutritional factors

Kheto *et al.* (2023) treated Guar seed flour with cold plasma for 5 to 20 min at different power levels (10 and 20 kV). Cold plasma treatment at 10 kV for 15 min significantly reduced the antinutritional factors while maintaining the nutritional value. However a high-intensity cold plasma treatment (20 kV-20 min) was more effective in reducing the tryps in inhibition activity. An increase in treatment time reduced the carbohydrate, and protein content and crystallinity. Cold plasma treatment of pearl millet flour resulted in a decrease in antinutritional factors such as tannin and phytic acid. Maximum reduction was observed at 30 kV for 20 min-treated Pearl Millet Flour. The possible mechanisms of reduction are the breakdown of glycosidic bonds in tannins, splitting of phytic acid into phytate rings, and increased phytase enzyme activity (Sarkar *et al.*, 2023).

2.5.7. Increase of bioactive compounds and antioxidant activity

Acai pulp underwent cold plasma treatment across various excitation frequencies (50, 500, 750 Hz) and processing durations (5, 10, 15 min). The application of cold plasma resulted in an enhancement of total phenolic content and antioxidant activity in the acai pulp, except samples treated at 500 and 750 Hz for 15 min. The observed increase in total phenolic content was likely attributed to membrane rupture, leading to the release of phenolic compounds previously bonded to cell walls. The generation of chemically reactive species, charged particles, and UV during plasma treatment was hypothesized to break covalent bonds and cell membranes, facilitating the release of certain bioactive compounds (Dantas *et al.*, 2021)

2.5.8. Food packaging

The conventional sterilization methods of food packaging include dry heat, wet heat or steam, UV radiation, and the use of chemicals (ethylene oxide and hydrogen peroxide). The use of heat is not appropriate for all types of packaging materials. PET is a heat-sensitive material and hence heat sterilization is not preferred. Chemical sterilization may cause health risks due to toxicity, mishandling, residue, and environmental hazards. CP is emerging as an alternative method for packaging sterilization to overcome the limitations of traditional methodsCold plasma (CP) can alter the surface properties of packaging materials, influencing factors such as roughness, functionality, wettability, barrier function, antimicrobial properties, and biodegradability. This technology proves particularly advantageous in overcoming limitations associated with biodegradable packaging materials. The induced roughness can be attributed to the plasma etching effect, wherein the film's surface undergoes modifications due to processes such as the cleavage of chemical bonds, scission of polymer chains, or chemical degradation of film components facilitated by free radicals. This increase in roughness contributes to a decrease in thickness and improved diffusion properties. Cold plasma treatment exposes polar functional groups on the surface, thereby enhancing printability, increasing adhesion, and improving wettability (Perera *et al.*, 2022).

Moreover, CP can be used as an in-package treatment. The location of the gaseous disinfectants inside a package where they come into touch with the food product that has to be disinfected is the fundamental concept of in-package plasma therapy. The product is initially sealed and packaged in plastic (or rarely glass) packaging for in-package plasma treatment. The gas within the package may be a modified gas mixture or the surrounding air. A breakdown of the gas happens when this package or the gas inside is subjected to a strong electric field for a brief amount of time. The gas's ionized state, or plasma, serves as a sterilizing agent and inactivates microorganisms without compromising the integrity of the packing materials (Misra *et al.*, 2019).

The effects of dielectric barrier discharge atmospheric cold plasma (DACP) treatment on the storability of grape tomatoes and the inactivation of Salmonella were investigated by Min *et al*. (2018). Grape tomatoes were inoculated with or without Salmonella, packed in a commercial clamshell container made of polyethylene terephthalate (PET), and cold plasma-treated for three minutes at 35 kV and 1.1 A using a DACP system that included a pin-type high-voltage electrode. Salmonella was rendered inactive by the DACP treatment without affecting the grape tomatoes' firmness or color.

2.5.9. Drying

Several studies have demonstrated the efficacy of cold plasma (CP) pretreatment in enhancing the drying process, improving the quality of dried products, and reducing energy consumption. CP has been found to augment moisture diffusion and enhance drying efficiency by modifying the surface characteristics and impacting the internal microstructure of materials (Du et al., 2022).

In a study by Ranjbar Nedamani *et al*. (2022), apple slices underwent treatment with dielectric barrier discharge (DBD) plasma at 100W and 60 Hz, followed by traditional air drying at 60°C with 0.5 m/s airflow. The cold plasma pretreatment remarkably reduced the drying time from 9,600 seconds to 3,600 seconds, while the energy consumption during drying was 85 times lower compared to the traditional air-drying method. Additionally, the shrinkage of plasma-treated samples was minimal, with total shrinkage closely resembling that of undried samples.

Examining the impact of cold plasma on tucuma fruits, Loureiro *et al*. (2021) treated the fruits with dielectric barrier discharge plasma at 20 KV for 10 minutes, varying the frequencies at 200, 500, or 800 Hz, followed by drying in an oven with forced air circulation (60 °C; 0.5 m/s). Cold plasma treatment, particularly at 200 and 800 Hz, induced structural changes in the plant tissue of tucuma, facilitating the drying process, as evidenced by alterations in drying rate and water diffusion.

In the case of saffron stigmas, Tabibian *et al*. (2020) employed glow arc discharge treatment followed by hot air oven drying. This treatment approach not only reduced drying time but also enhanced effective moisture diffusivity in the saffron stigmas. These findings collectively underscore the potential of cold plasma in improving various aspects of the drying process and product quality across different agricultural and food materials.

2.5.10. Extraction

The vacuum-cold plasma pretreatment of *Berberis vulgaris L* was conducted at power levels of 60, 70, and 80 W, with varying durations (1, 3, and 5 minutes) aimed at enhancing the extraction of anthocyanins. Optimal conditions were determined to be 80 W for 5 minutes, resulting in an extraction yield of 256.32 mg/L anthocyanins and 433.71 mg/L polyphenols (Dara et al., 2023).

Li *et al*. (2023) delved into the application of cold plasma pretreatment (CPP) for extracting anthocyanins from Haskap. The treatment prompted the degradation of cell wall components, an increase in surface roughness, heightened hydrophilicity, improved hydration properties, and altered enzymatic activity. These observed impacts collectively led to an intensified binding of Haskap to the solvent, facilitating the solubilization of anthocyanins. The use of CPP notably heightened the extraction rate of anthocyanins (13.35-20.47%), increased the count of anthocyanin monomers, and bolstered the antioxidant activity of the extracts

2.6. Applications in the agriculture sector

2.6.1. Pest control during storage

The substitution of conventional chemical fumigation with cold plasma treatment represents a discerned approach to integrated pest management. In a comprehensive study conducted by Pathan *et al.* (2021), the efficacy of cold plasma treatment in addressing pulse beetle infestation in stored chickpeas over an extended four-year duration was investigated. Given the prevalent issue of resistance observed in *Callosobruchus chinensis L*. towards synthetic pesticides, the exploration of alternative pest control strategies becomes imperative. Four distinct cultivars of chickpea underwent cold plasma treatment at varying power intensities (40, 50, and 60 W) and durations (10, 15, and 20 minutes). Subsequently, both plasma-treated and untreated chickpeas were sealed in airtight ziplock pouches for storage. Periodic observations were conducted to monitor the extent of infestation. The study findings indicate that cold plasma treatment demonstrated heightened efficacy in mitigating pulse beetle infestation in the treated chickpea samples. Conversely, the untreated chickpeas experienced notable infestation and damage, predominantly occurring within the initial quarter of the storage period. These results underscore the potential of cold plasma as an effective method for pest management in chickpea storage facilities

Kirk-Bradley *et al*. (2023) conducted a study investigating the insecticidal efficacy and mechanism of high-voltage atmospheric cold plasma using a dielectric barrier discharge reactor against *Callosobruchus maculatus*, a significant pest affecting stored grain quality. The research revealed that a mortality rate exceeding 90.0% for both egg and larval stages could be achieved with an extended treatment time of 3 minutes and a higher voltage setting of 70 kV. However, to attain a 95% mortality rate in adult insects, it was necessary to apply this treatment condition along with a post-treatment retention time of 4 days. Effective management of plasma processes was demonstrated by employing modified atmospheric pressure with a working gas composition of 65% oxygen, 30% carbon dioxide, and 5% nitrogen. This gas composition targeted specific phases of the insect lifecycle known for transmitting pathogens, thereby addressing concerns related to increased mycotoxin contamination and degradation of grain quality. The study thus highlights the potential of high-voltage atmospheric cold plasma as a strategic tool in pest control, particularly for mitigating the impact of *Callosobruchus maculatus* on stored grains.

2.6.2. Seed decontamination, germination and plant growth

Cold atmospheric pressure plasma (CAPP) has demonstrated its efficacy in seed decontamination without compromising germination capacity. In a study conducted by Safari *et al.* (2017), the potential impacts of cold plasma on the structure and growth patterns of *Capsicum annuum* were investigated. Seeds were subjected to argon-derived dielectric barrier discharge (DBD) plasma for durations of 0, 1, or 2 minutes. The findings revealed that a 1-minute plasma treatment positively influenced shoot and root lengths, as well as the total leaf area. Conversely, a 2-minute plasma treatment exhibited adverse effects on these growth parameters. This highlights the influence of cold atmospheric pressure plasma on plant morphology and suggests the importance of optimizing exposure durations for beneficial outcomes in agricultural applications.

The synergistic impact of non-thermal plasma treatment on both water and seeds concerning the germination rate and plant growth of radish (*Raphanus sativus*), tomato (*Solanum lycopersicum*), and sweet pepper (*Capsicum annuum)* was systematically investigated. Dielectric barrier discharges in air, conducted under atmospheric pressure and room temperature, were employed for this study. The results elucidated a positive correlation between plasma treatment duration and both germination rate and seedling growth across the evaluated plant species. Notably, seeds treated with plasma for 10 minutes (P-10), when subsequently irrigated with plasma-activated water for 30 minutes (PAW-30), exhibited heightened plant growth. The observed increase in germination rate is attributed to augmented surface wettability and the elimination of bacteria and pathogens on the seed surface. Moreover, the localized heating effect likely facilitates the opening of the seed coating, enhancing water absorption. The plasma discharge generated reactive oxygen and nitrogen species (RONS) such as O3, N2O, and electrons, which have been shown to modify the water uptake rate and augment germination metabolisms, as discussed by Sivachandiran and Khacef (2017). These findings underscore the multifaceted influence of non-thermal plasma treatment on seed and water interactions, providing insights into potential applications for optimizing plant growth in agricultural contexts.

The application of a dielectric barrier discharge cold plasma (CP) device on common sunflower seeds resulted in a notable enhancement of sunflower lateral organs and roots, exhibiting a growth increase ranging from 9% to 14% when compared to the control group. Metagenomic analysis uncovered significant alterations in the structure of the bacterial assembly associated with the plant after CP treatment. This modification was attributed to the antimicrobial impact of reactive species generated by CP. The treatment led to a prevalence of spore-forming Mycobacterium sp. in the above-ground tissues of the seedlings. Although the overall bacterial diversity in the roots experienced minimal changes, the shift induced by CP treatment in microbial composition is believed to underlie the observed stimulation in seedling root growth. This effect, in turn, has enduring implications on lateral organ growth, possibly mediated by an increase in water uptake and/or direct root signaling. Additionally, a discernible but low-amplitude difference in protein abundance was identified in the roots of emerging seedlings, aligning with the characteristic response to low-intensity stress stimuli. These protein abundance differences may be linked to changes in the plant-associated microbiome following CP treatment, as reported by Tamosiune *et al.* (2020).

2.6.3. Control of plant diseases

Cold plasma is a powerful tool for the control of post-harvest diseases caused by bacterial and fungal pathogens in fruits and vegetables. Yagul *et al.* (2023) investigated the efficacy of both direct and indirect cold plasma treatments in addressing banana crown rot, concurrently examining their impact on the physicochemical attributes of the fruit. The experimental protocol involved the inoculation of bananas with a spore suspension containing the three most pertinent fungi associated with crown rot, with an initial concentration of 10^5 spores/mL. Subsequently, the samples were subjected to storage conditions simulating those of an export container, specifically at 13 °C, and were observed at intervals of 0, 14, 28, and 42 days. Quantitative assessments of rotting and ripening indices were undertaken utilizing standardized scales. Furthermore, an analysis of key physicochemical parameters, including pH, soluble solids, color, hardness, and firmness, was performed on the samples. To gain insights into the underlying mechanisms, optical emission spectroscopy (OES) measurements were employed to scrutinize the generation of reactive species resulting from both direct and indirect cold plasma methods. The outcomes of the study revealed that the rot indices following direct and indirect treatments paralleled the efficacy of fungicide application in preserving the fruit throughout the experimental duration. Noteworthy was the absence of significant alterations in pH, firmness, and °Brix levels in the treated samples over the course of the storage period.

2.6.4. Soil remediation

Treatment of soil with cold plasma has proven to be successful in soil bacteria eradication and reduction of microplastics in land. Dielectric barrier discharge plasma was applied for the remediation of microplastic-contaminated soil from landfills (Jingyuan *et al.*, 2023). The study found that reactive oxygen species (ROS) produced by DBD plasma rapidly removed microplastic pollutants in the soil. A 96.5% remediation efficiency was achieved after 30 minutes of treatment at an airflow rate of 1500 mL min^{-1}. A higher remediation efficiency was achieved with air than nitrogen.

Lazra *et al.* (2020) examined the impact of plasma exposure on soil bacteria, testing durations of 15-60 seconds and a more prolonged exposure of 10 minutes. The findings indicated that a 60-second treatment was notably more effective in reducing the number of organisms compared to shorter treatment periods. Surprisingly, a longer exposure time of 10 minutes did not result in a decrease in the number of bacteria.

2.6.5. Agricultural wastewater treatment

Cold plasma, identified as an advanced oxidation process (AOP), demonstrates notable efficacy in the rapid dissipation of agro pollutants within water and wastewater. The findings of Patange *et al*. (2018) underscored the considerable potential of ACP technology in diminishing and fully inactivating key indicator microorganisms present in model dairy and meat wastewater effluent. Specifically, treatment at 80 kV for 5 minutes, followed by a 10-minute post-treatment retention time (PTRT), resulted in the effective reduction of microorganisms to undetectable levels. It was observed that untreated effluents exhibited toxicity towards aquatic models, whereas plasma treatment mitigated these toxic effects.

Furthermore, the impact of plasma on the degradation of carbamates, a broad-spectrum insecticide widely employed in agriculture, was investigated by Moutiq *et al.* (2020). The study revealed significant reductions of three carbamates, namely carbaryl, methiocarb, and aminocarb, by 50.5%, 99.6%, and 99.3%, respectively, following a 5-minute treatment at an applied voltage of 90 kV. These results emphasize the potential of cold plasma technology in addressing environmental pollution concerns associated with agrochemicals, thereby contributing to sustainable water treatment practices.

2.7. Advantages and limitations of cold plasma

Cold plasma can generate stable plasma at atmospheric pressure and it is easy to handle. It can be used for treating thermally labile samples and has excellent scalability and industrial applicability. Short treatment times (from seconds to minutes), low electrical requirements and low operating costs are other advantages (Domonkos *et al*., 2021). Cold plasma doesn’t leave any toxic residues on treated material. Cold plasma sanitation doesn’t require water and hence reduces water usage as compared to traditional sanitizers such as chlorine. Cold plasma pretreatment enhances the efficiency of drying and extraction and hence reduces the energy required for these unit operations. Due to the waterless and energy-saving behavior of cold plasma, it is considered as an environmentally sustainable technology.

However, the initial investment cost of cold plasma system is high. Cold plasma treatment at high power and longer exposure time causes an increase in the oxidation of lipids in meat and fish products. Extreme polymerization of oligosaccharides in juices are also reported. The treatment has resulted in a reduction in color in walnuts, strawberries and spinach. Other limitations include a decrease in firmness of fruits, an increase in acidity or a decrease in pH in the case of milk (Thirumdas *et al*., 2015).

3. CONCLUSION

Cold plasma is a powerful tool in food and agriculture sector as it is an environmental friendly and economically feasible technique which can replace the use of chemical pesticides, fumigation, and additives. A significant number of research works are being reported in the past five years on cold plasma applications in the food and agriculture sector. It can be used for food decontamination, enzyme inactivation, and reduction of myctoxins, pesticides, allergens and antinutritional factors. Other promising applications include seed germination and plant growth, control of plant diseases, pest control during storage, soil remediation and wastewater treatment. Cold plasma is an interesting area of research among scientists and its new applications in food process unit operations are yet to be discovered. There is a need for optimization of cold plasma process parameters for each application to ensure that the concentration of reactive species would not cause harm to food quality and the safety of consumers. The scale-up of lab-scale reactors to large-scale systems has to be achieved with better performance along with operational safety. There is a need for regulatory approval for cold plasma treatment to make full use of this technology.

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