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Cold Plasma: A Sustainable Innovation for Enhancing Polyphenol Levels

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ABSTRACT

Cold plasma treatment, an eco-friendly and non-thermal technology that utilizes electricity and reactive gases such as oxygen, nitrogen, and helium, has emerged as a promising innovation in food processing. Unlike conventional heat treatments, which often degrade heat-sensitive bioactive compounds and essential nutrients, cold plasma offers a non-destructive approach to preserving and enhancing the functional properties of food components. This technology effectively inactivates enzymes, eliminates microorganisms, extends shelf life, and maintains food quality while mitigating the nutrient loss commonly associated with thermal processing. More importantly, recent studies indicate that cold plasma treatment enhances the extraction and bioavailability of bioactive compounds, including flavonoids, polyphenols, and antioxidants, thereby improving the nutritional and functional properties of functional foods. However, despite its potential, a comprehensive understanding of the specific mechanisms underlying these improvements remains an area for further research. Addressing this knowledge gap is essential for optimizing cold plasma applications in food processing and maximizing its benefits for functional food development.

Keywords: Cold plasma, Bioactive Compound, Green Extraction, Polyphenols

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1. Introduction

As the global population is expected to reach 10 billion by 2050, there is an increasing demand for innovative food production and processing methods to meet the rising need for food. Ensuring a safe global food supply that meets nutritional needs and addresses environmental concerns is a significant challenge. It is crucial to implement environmentally friendly strategies to protect food from decay and pests, thereby extending its shelf life and enhancing global food security. Recent years have seen notable advancements in food processing, particularly in the development of minimally processed foods and non-thermal processing technologies. These innovations have resulted in products with fresh-like characteristics, minimized nutrient degradation, and an overall perception of high quality. By adopting these approaches, we can meet the growing food demands of the future and contribute to a more sustainable and secure food supply chain (Araújo Bezerra et al., 2023; Silveira et al., 2019).

Thermal processes can compromise the quality of foods. To address this, non-thermal technologies have been developed to minimize the negative effects of heat on food, as well as to enhance processing speed and efficiency. One such innovative technology is cold plasma, which holds promise in various food processing applications. Cold plasma can preserve and clean food items, serving as a precursor to activities such as drying, extracting, cooking, curing, and hydrogenation. Additionally, the reactive plasma species generated during cold plasma treatment can improve the sensory and nutritional properties of foods (Elenilson et al., 2020, Jiajie et al., 2023).

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2.What Is Cold Plasma?

Plasma, often referred to as the "fourth state of matter," is an ionized gas containing free electrons, positive ions, excited neutral atoms, free radicals, and photons. It is the most abundant state of matter in the universe, comprising over 99.9% of observable matter, excluding dark matter. Unlike solids, liquids, and gases, plasma exhibits unique properties such as electrical conductivity, sensitivity to electromagnetic fields, and the ability to generate reactive chemical species. These characteristics make it highly valuable in various applications, including industrial processing, medical treatments, and food preservation (Burducea et al., 2023; Muhammad et al., 2018). Plasma can be broadly categorized into thermal (hot) plasma and non-thermal (cold) plasma. Thermal plasma exists in a state of thermodynamic equilibrium, where both electrons and heavy particles (ions and neutral molecules) have nearly the same high temperature, often reaching thousands of degrees Kelvin. This type of plasma is commonly used in welding, plasma torches, and nuclear fusion. Cold plasma, on the other hand, operates under non-equilibrium conditions, meaning that while electrons attain high energy levels, the overall gas temperature remains low, often near room temperature. This characteristic makes cold plasma particularly suitable for applications where excessive heat could damage materials, such as in food processing, medical sterilization, and biological treatments. In the food industry, cold plasma technology involves two key components: inputs and outputs. The inputs consist of energy sources such as electricity or microwaves, as well as carrier gases like air, helium, argon, oxygen, or nitrogen. The outputs include highly reactive species such as ultraviolet (UV) light, ozone, and other reactive compounds that contribute to microbial inactivation and surface modifications. Unlike conventional chemical treatments, cold plasma typically leaves no harmful residues, making it an environmentally friendly alternative. The presence of reactive oxygen species (ROS), reactive nitrogen species (RNS), charged particles, and excited molecules enhances its effectiveness in microbial decontamination, enzyme inactivation, and food quality preservation (Albertos et al., 2017; Koddy et al., 2021). Understanding the fundamental differences between thermal and cold plasma, along with their unique properties, allows for their targeted application in various fields, particularly in food safety and quality enhancement.

2.1. Types of Plasma

Plasmas can be distinguished into two main types: equilibrium (thermal) plasma and nonequilibrium (low temperature) plasma, also known as non-thermal or cold atmospheric plasma. In thermal plasma, all the various chemical components, electrons, and ions are in a state of thermodynamic temperature equilibrium. Conversely, cold plasma can be generated at either atmospheric or reduced pressures with minimal power input. This type of plasma is often produced by electric discharge in a gas at lower pressure or by using microwaves, resulting in temperatures ranging from 30-60 °C. In contrast, thermal plasmas are typically formed at higher pressures (around 100 kPa) and require a substantial amount of power input (up to 50 MV), usually achieved through the use of radio frequency or microwaves (Olatunde et al., 2021; Liu et al., 2024).

2.2. Natural phenomena based on plasma

We categorize many natural phenomena as potentially paranormal, but they actually demonstrate how limited our understanding is of the uneven distribution of electric charges, ions, electric fields, and their effects on our planet. The natural rotating plasmid, such as ball lightning and similar forms, and the non-rotating plasma, like atmospheric lightnings, Aurora Borealis, the solar corona, firestorms, burning fuels, and plasma in atomic and hydrogen bomb explosions, as well as experimental plasma discharges known as "cords," reveal the complexity of these phenomena. Notably, the Sun and all stars are examples of natural rotating plasmids. (Patúc 2020)

The term "plasma" was coined by American chemist and physicist Irving Langmuir in 1928 during his experiments on electrical discharges in gas at the General Electric Research and Development Center in upstate New York. There does not seem to be any documentation explaining the rationale behind this suggestion, making it challenging to provide a definitive answer. Langmuir's concept proposed that the electrons, ions, and neutrals in an ionized gas could be viewed as corpuscular material moving within a fluid-like medium. This innovative idea led to the introduction of the term "plasma" to describe ionized gas, a term that had already been in use in medicine and biology for some time (Franklin and Braithwaite, 2009)

3. The effect of Cold Plasma on polyphenol compound Extraction

This review offers an overview of the fundamentals of cold plasma technology and the detailed mechanism of interaction between reactive plasma species and polyphenol compounds found in food, such as simple phenolic acid, individual phenolic compounds, flavonoids, and anthocyanins.

3.1. Polyphenols

Polyphenolic compounds are plant-based chemical compounds that contain at least one aromatic ring with a reactive hydroxyl group. These compounds are classified into various groups based on the number of phenolic rings and related structural elements, such as flavonoids and phenolic acids. Natural polyphenols are a diverse group of plant compounds, with over 8,000 known compounds. Found in fruits and vegetables, polyphenolic compounds are essential components contributing to the antioxidant properties of these foods. They encompass flavonols, flavones, isoflavones, flavan-3-ols, lignans, and anthocyanidins. These compounds safeguard food from free radical activity and help preserve its quality. Upon ingestion, they deliver cumulative effects of antioxidant, anti-inflammatory, and antimicrobial properties within the body (Sruthi et al, 2022).

The impact of cold plasma on polyphenol compounds largely depends on the food matrix and plasma process parameters, including voltage, feed gas, and treatment time (Kumar et al., 2023; Panpipat et al., 2020). Flavonoids degrade faster than other polyphenols due to their high ability to scavenge plasma-generated free radicals. The reactive species cause oxidative degradation, double bond cleavage of polyphenol compounds, and assist in the extraction of phenolic compounds. It is noteworthy that cold plasma technology has both positive and negative impacts on polyphenol concentration (Sharma et al., 2020).

Cold plasma is a promising technology that has the potential to be integrated into extraction processes adhering to green chemistry principles, as well as to reduce the resources required in traditional solvent-based extraction methods. Several studies in the food industry have investigated the effects of cold plasma on bioactive compounds like vitamin C, carotenoids, and phenolic compounds (Paixão et al., 2019). A recent study found that using cold plasma technology during the processing of guava-flavored whey beverages resulted in enhanced properties, including increased concentrations of bioactive and volatile compounds. Additionally, the study noted that the fatty acid profile of the beverage was influenced by various process parameters, such as processing time and flow rate (Silveira, et al.,2019).

This study investigated the influence of glow discharge plasma on the quality of siriguela (purple mombin) juice by adjusting the processing time (5–15 minutes) and nitrogen gas flow rate (10–30 mL/min). Pre-processing and post-processing evaluations were conducted to analyze physicochemical properties and bioactive compounds. Noteworthy findings include the preservation of vitamin C levels and product color following processing. Conversely, the plasma treatment resulted in increased levels of pigments, total phenolics, antioxidant activity, and B vitamins within the juice. Notably, the antioxidant activity exhibited an increase, while polyphenol oxidase activity decreased by approximately 20% (at a nitrogen gas flow rate of 20 mL/min for 15 minutes). Moreover, under specific processing conditions, peroxidase exhibited a slight activation of 6%. The study emphasizes the necessity of optimizing cold plasma food processing to achieve the desired impact on bioactive compounds in siriguela juice. The variability in treatment effectiveness is linked to processing times and intensities, impacting the extraction and degradation of bioactive compounds (Paixão et al., 2019).

The study investigated the effects of cold plasma on the enzymatic activity, color, bioactive compounds, and antioxidant activity of avocado pulp with lime extract (PL) and without extract (PW). Various experimental conditions were tested, including different durations (10, 20, and 30 minutes) and gas flow rates (10, 20, and 30 ml). The results showed that a gas flow rate of 20 ml/20 min in PL effectively reduced POD and PPO activities, minimized browning, and preserved the color. Cold plasma treatment increased the levels of phenolic and carotenoid compounds in PW under specific conditions, as well as in PL, leading to enhanced antioxidant activity. Strong correlations were found between phenolic content and ORAC-H in both PL (0.85) and PW (0.75). Furthermore, levels of myristic and palmitic acids decreased after cold plasma treatment, while oleic, linoleic, and linolenic acid levels increased. The study concluded that the combination of lime extract in avocado pulp with cold plasma technology is effective in maintaining quality characteristics and improving bioactive content (Batista et al., 2021).

A recent study investigated the impact of an 8-minute cold plasma pre-treatment (20 kHz) on the content of antioxidants, antioxidant activity, volatile compounds profile, microbial count, pH, and color in herb extracts. The study encompassed 12 herbs: Echinacea purpurea, Salvia officinalis, Urtica dioica, Polygonum aviculare, Vaccinium myrtillus, Taraxacum officinale, Hypericum perforatum, Achillea millefolium, Sanguisorba officinalis, Leonurus cardiaca, Ballota nigra, and Andrographis paniculata. Before the cold plasma treatment, the herbs were ground and suspended in water, representing a novel approach that had not been previously studied. The findings revealed that most plasma-treated extracts exhibited a higher content of polyphenols (11 out of 12). Moreover, the content of flavonoids and anthocyanins increased in four extracts, with the anthocyanin content showing a marked increase compared to the control (up to 77%). The antioxidant activity, assessed through different methods (ABTS, DPPH, FRAP), was also higher in nine plasma-treated solutions. Additionally, the cold plasma treatment reduced the total aerobic bacteria count, influenced the color, and raised the pH of the extracts. The surface structure of the plant material post-extraction was significantly damaged, likely leading to a higher extraction yield of bioactive compounds and consequently resulting in greater antioxidant activity in the cold plasma-treated extracts (Pogorzelska-Nowicka et al., 2021).

In a study conducted by Loureiro et al., the impact of various excitation frequencies (200, 500, and 800 Hz) of cold plasma technique as a pretreatment for drying tucumã was investigated. The SEM images depicted alterations on the pretreated tucumã's surface, resulting in improved drying rate and water diffusivity, thereby reducing the drying time. Samples treated with 200 and 800 Hz exhibited minimal color variation and reduced drying time. Furthermore, the pretreatment led to an increase in the concentration of phenolic compounds (45.3 mg GAE g^{-1}) and antioxidant compounds (799.8 µM ET) ($p < 0.05$). Notably, carotenoids were observed to be more susceptible to degradation at 500 Hz. The findings suggest that the proposed pretreatment involving the application of the cold plasma technique for drying foods has the potential to preserve and enhance their nutritional quality.(Loureiro et al., 2021).

In a recent study, researchers investigated the use of atmospheric pressure non-thermal plasma for decontaminating medicinal plants. Nigella sativa seeds were treated with atmospheric pressure floating-electrode dielectric-barrier discharge (FE-DBD) plasma for 15, 30, and 40 minutes, and the total microbial count of the seeds was analyzed. The results demonstrated a significant reduction in microorganism density at all three exposure times compared to the control, with complete elimination of microorganisms observed after 40 minutes of exposure. No significant changes were observed in the levels of total phenolic compounds and antioxidant activity before and after plasma exposure. However, the levels of linoleic acid and oleic acid decreased after 40 minutes of FE-DBD plasma exposure, indicating the potential oxidation of unsaturated fatty acids. Additionally, the ratio of unsaturated fatty acids to saturated fatty acids significantly decreased under these conditions (Abdi et al., 2020).

In a recent study, researchers explored the use of high-voltage atmospheric cold plasma (HVACP) as a pretreatment for grape pomace to facilitate the extraction of phenolic compounds. The study involved applying HVACP at 60 kV for varying periods (5, 10, and 15 minutes). The results revealed that HVACP treatment disrupted the epidermal cell structures of the grape pomace, reduced the water contact angle of grape peels, and accelerated grape drying. These effects became more pronounced with longer treatment periods. Furthermore, HVACP treatment led to a 10.9–22.8% increase in the yield of phenolic extracts, which exhibited a higher concentration of anthocyanins and demonstrated improved antioxidant capacity (16.7–34.7%) (Bao et al., 2020).

The study monitored the changes in bioactive phytochemicals of six varieties of Thai germinated brown rice (GBR) alongside cold plasma-treated GBR (PGBR). Following treatment with optimal plasma conditions, the germination percentage, root length, and seedling height of the most responsive rice cultivar increased by 84%, 57%, and 69% respectively. Notably, there were no significant differences in the antioxidant activities of the GBRs and PGBRs for all rice cultivars. However, the PGBR group exhibited higher levels of γ-oryzanols during the 2-day germination period compared to the GBR group. Certain PGBR cultivars reached their peak values for total phenolic compounds, total vitamin E, simple phenolics, phytosterols, triterpenoids, and anthocyanins one day earlier than the corresponding values for GBR. Conversely, the concentrations of 2-acetyl-1-pyrroline reduced significantly with prolonged germination time in both GBR and PGBR samples (Yodpitak et al., 2019).

The study investigated the effects of using indirect cold plasma treatment on the levels of vitamin C, polyphenols, and flavonoids, as well as the antioxidant activity (FRAP, DPPH, ABTS), and sucrose, fructose, and glucose contents in cashew apple juice (Anacardium occidentale L). The treatments were conducted using a benchtop plasma system, considering two operational variables: N2 plasma flow rate (10, 30, and 50 mL/min) and treatment time (5, 10, and 15 min). The plasma treatment resulted in increased levels of vitamin C, flavonoids, and polyphenols, as well as enhanced antioxidant activity. However, prolonged exposure to plasma led to a decrease in most bioactive compounds, underscoring the importance of optimizing the process conditions (Rodríguez et al., 2017)

Another study showed the impact of cold plasma on microorganisms in Echium and Mint, in comparison to a heat treatment method. One gram of powdered Echium and Mint leaves was evenly spread on a glass slide and subjected to plasma exposure for 30 minutes. The study measured the phenolic compounds and color changes in Mint and Echium as a result of both plasma and heat treatments. The findings indicated that plasma did not significantly affect the phenolic compounds or color changes, whereas the heat method had a notable impact. Consequently, cold plasma could serve as an effective alternative to heat treatment for decontaminating spices without compromising their quality
(Jazayeri and Abdi 2024).

5. Advantages and Disadvantages

Cold plasma technology has emerged as a promising non-thermal processing method with a wide range of applications in the food and biological industries. One of its primary advantages lies in its cost-effectiveness and operational efficiency, as it functions under ambient temperature and atmospheric pressure conditions. Unlike conventional thermal and chemical treatments, cold plasma enables rapid processing while preserving the structural and nutritional integrity of heat-sensitive materials. Moreover, it exhibits antimicrobial efficacy by generating reactive species such as ozone, hydroxyl radicals, and nitric oxides, which effectively inactivate pathogenic and spoilage microorganisms (Misra et al., 2016). This property makes cold plasma particularly valuable for enhancing food safety without the need for excessive chemical additives or high-temperature processing. Additionally, the reduced energy consumption compared to traditional sterilization and decontamination techniques further underscores its sustainability and economic feasibility. Despite these advantages, several limitations must be considered. One notable challenge is the uneven treatment of large or irregularly shaped food matrices, which may result in inconsistent microbial inactivation and variable physicochemical modifications (Pankaj et al., 2017). Additionally, the exposure of food products to reactive plasma species can accelerate lipid oxidation, potentially leading to undesirable changes in sensory attributes such as flavor and aroma. The impact of cold plasma on the color and texture of fruits and vegetables has also been documented, with some studies indicating alterations in pigment stability and surface microstructure due to oxidative stress and dehydration effects (Jiang et al., 2020). Furthermore, the use of noble gases, particularly helium, in plasma generation can substantially elevate operational costs, posing an economic barrier to large-scale industrial implementation. These challenges highlight the need for further research to optimize process parameters, mitigate adverse effects, and enhance the overall efficiency of cold plasma applications in food processing.

Table 1. Influence of plasma treatments on phenolic compounds

Food	Treatment Conditions	Point(s) of Assay	Effect of Plasma Treatment on Phenolic Compounds	Reference
Strawberries (fresh cut)	Air (dielectric barrier discharge, electric source) Voltage (45 kV) and time (1 min)	7 days at 4 ˚C	Increase TPC, flavonoid, and anthocyanin contents up to day 5	Li et al., 2019
Blueberries (uncut)	Air (capillary tube, electric source) frequency (47 kHz), gas flow (4 ft3 /m), and time (15–120 s)	After treatment	Reduction of anthocyanin content as treatment time increased	Lacombe et al., 2015
Apples (fresh cut)	Air (dielectric barrier discharge, electric source) Power (150 W), frequency (12.7 kHz), gas flow (1.5 L/min), and time (30 and 120 min)	After treatment	Reduced TPC; reduction of some procyanidin dimers and trimers (120 min)	Ramazzina et al., 2015
Onion powder	He (chamber, MW source) MW intensity (400 W), frequency (2.45 GHz), gas flow (1 L/min), pressure (0.7 kPa), and time (40 min)	28 days at 4 and 25 ˚C	No effect on quercetin content	Kim et al., 2017
White grape juice	Air (dielectric barrier discharge, electric source) Voltage (80 kV) and time (1–4 min)		Reduced TPC and flavonoid contents; increased flavonol	Pankaj et al., 2017
Chokeberry juice	Plasma jet power: 4 W Feed gas: Argon gas Frequency: 25 kHz Time: 3 and 5 min	After treatment	Increase by 20% in Amazonian juice at 10 min and 10 ml/min	Gan et al., 2021(~~1~~)
Blueberries	DBD plasma Voltage: 60 and 80 kVTime: 2 and 5 min	5 days at 4 ˚C	Decrease by 40% at 80 kV and 5 min	Sarangapani et al., 2017
Fresh lettuce	RF glow discharge Power: 75 and 150 W Feed gas: Oxygen Time: 20–300 s	After treatment	Increase by 250% at 150 W and 2 min	Song et al., 2015
Banana slices	DBD plasma Voltage: 4.8–6.9 kV Frequency: 12–22 kHz Time: 35–155 s	16 days at 4 and 25 ˚C	Increase by 30% at 6.9 kV and 155 s	Pour et al., 2022
Sour cherry marasca juice	Gas phase plasma Power: 4 W Voltage: 2.5 kV Frequency: 25 kHz Feed gas: Argon gas Time: 3, 4, and 5 min Flow rate: .75, 1, 1.25 L/min	10 days at 4 ˚C	Increase by 37% at 1.0 L/min and 3 min	Artés-Hernández et al., 2021
Acai pulp	DBD plasmaVoltage: 20 kV Frequency: 50, 500, and 750 Hz Time: 5, 10, and 15 min	After treatment	Decrease by 37% at 20 kV, 50 Hz, and 10 min	Dantas et al., 2021
Lamb's lettuce	Plasma jet Power: 35 W Feed gas: Argon gas Frequency: 27.12 MHz Flow rate: 20 SCCM Time: 1–2 min	7days at 25 and 4 ˚C	No significant change	Grzegorzewski et al., 2011
Amazonian juice	Glow plasma Frequency: 80 kHz Time: 10, 20, and 30 min Flow rate: 10, 20, and 30 ml/	After treatment	Increase by 57% at 2.0 L/min and 5 min	Castro et al., 2020

	min			
Kiwi fruit	DBD plasma Feed gas: Air relative humidity: 60% Time: 10 + 10 and 20 + 20 min	3 days at 28 ˚C	increase by 5% at 15 kV and 40 min	Ramazzina et al., 2015
Fresh cut pitaya	Glow plasma Power: 80 W Feed gas: Nitrogen gas Frequency: 50 kHz Flow rate: 10, 20, and 30 ml/min Time: 5, 10, and 15 min	After treatment	Decrease by 49% at 1 L/min and 5 min	Li et al., 2019
Sriguela juice	Gas phase plasma Power: 4 W Voltage: 2.5 kV Frequency: 25 kHz Feed gas: Argon gas Time: 3, 4, and 5 min Flow rate: .75, 1, 1.25 L/min	7 days at 25 ˚C	Increase by 134% at 5.87kV and 180 s	Kumar et al., 2023

6. Conclusion and Future Prospects

Thermal processing may engender adverse effects such as a cooked flavor, texture modifications, and changes in sensory attributes, which have prompted the exploration of non-thermal food processing technologies within the food industry. Cold plasma, encompassing antimicrobial processes, poses untapped potential, particularly in its impact on allergens and anti-nutritional factors a field ripe for further investigation. Demonstrating promise as a non-thermal food processing method, cold plasma utilizes charged, highly reactive gaseous molecules and species to deactivate contaminating microorganisms in food, garnering considerable attention from the global scientific community. Plasma pretreatment offers the potential to optimize the extraction of bioactive compounds, elevating both yield and nutritional quality, thus emerging as a technology with potential utility in the valorization of grape processing byproducts for functional food and nutraceutical applications within the winemaking industry. Despite its proven efficacy across various food sectors, including cereals, fruits, vegetables, dairy, and meat processing, cold plasma technology faces substantial challenges, like scaling up productivity and treating large-format foods. This technology underscores potential for reduced drying time, enhanced extraction efficiency, and the production of meats devoid of trans isomers thus offering healthier food alternatives. However, notwithstanding the multitude of advantages derived from cold plasma applications, there remain several challenges, necessitating further inquiry to optimize and regulate the effects of plasma on the nutritional and sensory quality of food. Moreover, a deeper understanding of plasma's role across different chemical groups present in food, and the development of larger or more potent plasma systems, warrant extensive scientific inquiry. Promoting a richer comprehension of cold plasma technology and its future prospects necessitates meticulous scientific inquiry to comprehensively ascertain its potential.

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