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Plasma Applications in the Food Industry

Aplicaciones del Plasma en la Industria Alimentaria

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Resumen

Debido al crecimiento poblacional desmedido, se busca el constante mejoramiento de la calidad de los alimentos, por tal motivo nos encontramos inmersos en una constante búsqueda de alternativas que ayuden al mejoramiento de los alimentos desde el cultivo (semilla, suelo, entre otro), hasta un alimento procesado y listo para el consumo. Adicionalmente, con la finalidad de encontrar alternativas sustentables y ecológicas se está estudiando el uso del plasma, ya que ofrece una ruta única para la modificación de superficies del alimento de forma controlada, además de que es respetuoso con el medio ambiente, y en la mayoría de los casos, ofrece soluciones rentables que pueden sustituir o complementar tratamientos clásicos. La elección del tipo de plasma depende del tipo de muestra y del efecto que se quiera dar, se puede modificar rugosidad, hidrofobicidad, recubrimientos, nanoestructuración, mejorar absorción, dispersión, entre otros. Por ese motivo en este trabajo se estará abordando el cómo ha contribuido la tecnología del plasma frio en los diferentes tipos de alimentos de la industria de alimentos, desde alimentos sin procesar (desde la semilla), hasta alimentos procesados (enlatados, embutidos).

Palabras Clave: Alimento, Mejoramiento, Plasma.

Abstract

Excessive population growth has led to a constant improvement in the quality of food. For this reason, we are constantly searching for alternatives that help improve food, from cultivation (seed, soil, among others) to processed food ready for consumption. Additionally, in order to find sustainable and ecological options, the use of plasma has been studied, because it offers a unique route for the controlled modification of food surfaces as well as being environmentally friendly, and in most cases, it offers cost-effective solutions that can replace or complement traditional treatments. The selection of the type of plasma depends on the application and the desired effect. It can modify roughness, hydrophobicity, coatings, and nanostructuring and improve absorption and dispersion, among others. For this reason, this work will address how cold plasma technology has contributed to the different types of food in the food industry, from unprocessed foods (from seed) to processed foods (canned sausages).

Key Words: Food, Food enhancement, Plasma.

Introduction

Plasma is the fourth state of matter, solid, liquid, gas, and plasma, at higher temperatures (1). Plasma can be defined as an ionized gas, composed of ions, electrons, atoms, molecules, and electromagnetic radiation (1, 2), meaning that this gas has positively and negatively charged molecules and depending on the density of the charged particles, it will define the properties of this gas providing it with characteristics of a weak or strongly ionized gas (3). The requirement for the gas to be "plasma" is that it must be electrically neutral, which means that it has a concentration of positive charge almost equal to its negative charge (2); for this reason, the plasma is considered as a quasineutral gas (1).

The main parameters to classify plasma are electron density and temperature, where electron density refers to the degree of ionization, plasma can be divided into two categories: high-temperature plasma and low-temperature plasma (4). When an electrical discharge passes through a gas or is exposed to extreme heat, atoms within the gas gain or lose electrons, generating ions and free electrons. High-temperature plasma (hot plasma) generates a very high ionization percentage; low-temperature plasma (cold plasma) is a partially ionized gas. Cold plasmas are generated close to room temperature (25 °C – 100 °C) and are usually made at low pressure ($p < 133$ mbar) in reactors with very different geometries. Such reactors generate plasmas through radio frequency, microwave, or pulsed discharge systems (5).

Plasma treatment is an established industrial method suitable for reacting with the surface to improve the properties of substrates. Plasma technology is a treatment that occurs in a short time. It can generate a great variety of effects on surfaces, depending on the gas; the process is clean since it does not affect the environment and works with complicated surface geometries (6, 7). The plasma creates by means of electric fields and at low pressures a working gas as shown in Figure 3, the surface of the sample is placed so that the ions, electrons, neutral species (reactive or non-reactive) and photons that are generated by cold plasma bombard the surface.

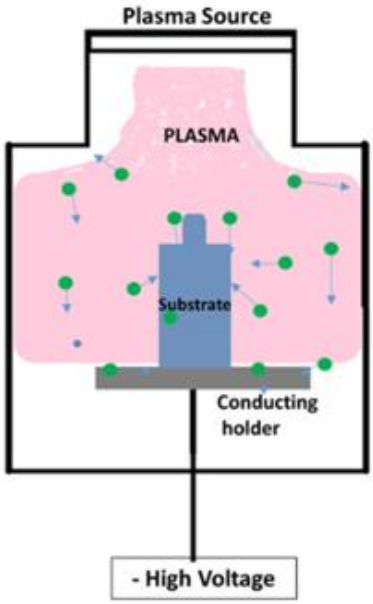


Figure 1. Schematic diagram of a glow discharge. Reprinted from Ref (8)

The effects of plasma technology are activation, erosion, surface cleaning, and crosslinking. Activation alters surface characteristics by substituting or adding new functional groups (5). Erosion generates highly adherent polymer surfaces, removes the last superficial layers of the substrate, and can produce a surface with rough topography employing air gas such as nitrogen or oxygen, increasing the time and power. Surface cleaning, widely used in industrial processes, can remove unwanted materials from the surface using ion bombardment and ultraviolet radiation (7). Crosslinking increases the density on the surface of the polymers and some surface properties, such as chemical resistance and gas or liquid monomers; free macro-radicals are formed in the polymer chain if the macro-radicals react with each other, then the process is beneficial (9).

Plasma has been used mainly in lighting sources, current switches, thermonuclear fusion, and plasma accelerators. However, it has been expanded to areas such as aeronautics, nanotechnology, medicine, agriculture, and food. Thanks to plasma, ferrous, non-ferrous materials, ceramics, textiles, glass, gases, liquids, and foods such as meat, seeds, fruits, and vegetables, among others, can be modified (9). Cold plasma offers a unique way for modifying surfaces without affecting their overall properties. In food, the application of radio frequency plasma consists of modifying the food surface in a controlled manner (7). Plasma has the advantage of being environmentally friendly and, in most cases, it provides cost-effective solutions that can replace or complement classical treatments. The selection of plasma depends on the type of sample and the desired effect; it can modify roughness, hydrophobicity, coatings, and nanostructuring and improve absorption and dispersion, among others (11, 12, 13, 14, 15, 16)

Plasma treatment in agriculture arises from the need to improve the quality of current food production, including increasing germination rate, uniformity, yield, and plant resistance. In addition, companies are looking to operate in a sustainable and environmentally friendly manner. Among the applications of plasma in agriculture and in different aspects of the food industry are increasing germination percentage, decontamination, breaking dormancy, or increasing the length of seed sprouts, and the list of applications is now much longer (17).

The seed treatment can occur directly with irradiation, where the seed undergoes various changes that give it an active surface to where other functional groups can adhere. The seed is etched, and at the same time, it is decontaminated from different microbes (13).

Cold plasma can interact with food components, including food proteins. Interaction of cold plasma with protein leads to dimerization, oxidation, deamidation,

nitration, sulfoxidation, dehydrogenation, and hydroxylation of amino acids (19).

Puač evaluated two treatments; the first one used plasma directly on the seed, and the second one used plasma at atmospheric pressure to obtain plasma-activated water; these treatments were compared with the control group to correlate their enzyme activity and protein content in the initial germination phase, obtained with the result that the difference between the enzyme activity (CAT), observed three days after the inductive light pulse strongly suggest that approximately 48 h after the pulse *Paulownia tomentosa* seeds enter the 3rd phase of the germination process-radicle protrusion and elongation phase, i.e., germination sensu stricto is ended. Post-germinative processes then take place (20).

Table 1. Studies where cold plasma has been used in agriculture.

Food	Conditions	Result	Reference
Seeds	Pretreatment (CPt: 0, 15, and 30 s), ultrasound power (P: 0, 60, 120, and 180 W), and air temperature (T: 30, 35, and 40 °C).	The maximum germination percentage (92%), germination index (14.91), and germination rate (21.33%), as well as the highest values of seedling vigor index I (178.67 mm) and vigor index II (420.72 mg), had pretreatment with CPt: 15 s before ultrasound-assisted drying at T ≤ 35 °C and P ≤ 120 W.	(21)
	Seeds were treated for 5 and 7 min with cold plasma (CP5 and CP7 groups) and 10 min with electromagnetic field (EMF10 group) six days before sowing	All treatments increased RebA (Rebaudioside A) concentration approximately 1.6-fold.	(22)
	Under a working pressure of 50 Pa at a forward power of 200 W	CP treatment slowed the germination of seedlings and caused the lower activity of α-amylase enzyme in seeds after imbibition, indicating CP interruption of the signaling pathway that activated α-amylase enzyme production.	(23)
Fruit	21 kV for 5 min	Cold plasma implementation on the enhancement of bioactive compounds, antioxidant activity, cytotoxicity, antiproliferative activity, and antimigratory activity of RTR microgreens against MCF7 and HepG2 by inducing apoptosis through Bax, Bcl-2, and Caspase-3 expressions.	(24)
	Atmospheric cold plasma (ACP) treatment of 10, 15, and 30 min was studied on strawberry fruit using a dielectric barrier discharge (DBD) at 60 kV with an input voltage of 260 V at 50 Hz	ACP treatment (* 60 kV for 15 min) was found to be an efficient post-harvest treatment for preserving strawberries at 25 °C. Treatment efficaciously extended the shelf-life of strawberries for three days at 25 °C. Significant reduction of 2-log was found in the microbial count of strawberry.	(25)

Meat

Different factors affect the quality of meat during processing and storage, and controlling these factors is important in the meat industry to guarantee good quality and customer satisfaction. Meat has a high moisture content and essential nutrients such as proteins, lipids, vitamins, and minerals (14). For this reason, meat safety, especially contamination by microorganisms, is one of the main concerns. Among the different ways of decontamination, is pasteurization; however, high temperature causes undesirable changes in meat quality in appearance, texture, and nutritional content (26, 27).

Abdel-Naeem *et al*, 2022 explored the decontamination efficacy of cold dielectric barrier discharge (DBD) plasma using different gases and exposure times at low voltage (20 kV) on chicken breast fillets, the treatment used exposed to oxygen or argon (for 3 and 5 min each), in addition to the control group, additionally determined microbial quality, physicochemical properties, topographical structure, and sensory attributes. The results showed that all plasma-treated samples revealed a significant reduction in bacterial counts, shear strength, and pH values, with no significant changes in thiobarbituric acid, total volatile base nitrogen, and percent cooking loss. Sensory attributes were significantly improved in all plasma-treated samples, except the appearance and color of oxygen-treated samples; finally, it concluded that DBD plasma treatment with argon gas could be safely applied to successfully decontaminate poultry meats in poultry processing plants without any negative impact on their appearance and quality (28).

With advances in recent years, in addition to the use of plasma for the decontamination of microorganisms, it can also modify the color, texture, and flavor of meat. Meng *et al*., 2022 added a cold plasma-treated phosphate solution to smoked sausages as a new ingredient to evaluate the color, texture, and flavor of the samples as an alternative to the use of nitrite in meat, which is directly associated with gastrointestinal tumors, stomach cancer, and other diseases. The results showed that, compared to nitrite (0.075 g/kg nitrite added to sausage), the addition of 30~90% nitrite and cold plasma-treated phosphate solution had no significant effect on the relative content of oxygenated myoglobin ($p > 0.05$). The amount of residual nitrite in the smoked sausage prepared with 30~70% nitrite and cold plasma-treated phosphate solution was significantly lower than that in the nitrite-treated group. Adding nitrite combined with cold plasma-treated phosphate solution had no significant effect on the texture (hardness, elasticity, cohesiveness, and resilience) and sensory evaluation of smoked sausage. Sixty-nine volatile compounds were detected, and 20 had VIP (Variable Importance Plot) scores higher than one. In conclusion, cold plasma treatment represents a potential technology to partially replace nitrite with a plasma-treated phosphate solution (29).

Furthermore, some studies seek to modify the properties of meat indirectly, such as with additives; however, this usually does not give a good result; for example, Maciej *et al*., 2014 sterilized black pepper because it is the most widely used by butchers to produce meat products and is also known as the "king of spices" or "black gold." Black pepper is among the most widely used spices in the United States and Europe. It is essential to have sterile black pepper when it comes to maturing products, for example, sausages or some types of cheese. In addition, black pepper has been found to have antimicrobial properties, antioxidant effects, and antipyretic and analgesic properties. As a result, it was obtained that sterilized black

pepper did not reveal the same organoleptic characteristics as the spice not treated with plasma sterilization. In general, it can be concluded that plasma sterilization offers new opportunities for microbial decontamination of food products since it reduces the number of microorganisms without the application of heat; for this reason, it did not reveal the same organoleptic characteristics as the spice not treated with plasma sterilization. Overall, it can be concluded that plasma sterilization offers new opportunities for microbial decontamination of food products, as it reduces the number of microorganisms without the application of heat (30).

Table 2. Studies where plasma has been used in meat products.

Food	Conditions	Result	Reference
Chicken	Different exposure times (seconds) [0 (T0), 10 (T10), 20 (T20), and 30 (T30)], Fertilized eggs were subjected to analyses at designated time points (0, 15, and 30 s).	Cold plasma treatment did not significantly affect the hardness, gumminess, and chewiness, which are prominent characteristics of native chickens; the results demonstrated that the weights of slaughtered males and females were similar among treatments and related to customer requirements.	(31)
	35.6 ± 4 W for 60-kV treatments, 52.1 ± 0.1 W for 70-kV treatments, and 71.8 ± 10.3 W for 80-kV treatments	The modified atmosphere with 35% O2 and 60 % CO2 and IPCP treatment at 60 kV for 60 s to extend quality or shelf life and improve food safety of raw chicken breast meat sealed in a barrier package and stored at refrigerated temperature.	(32)
	The microsecond-pulsed DBD discharge was created by applying alternating current and pulsed high voltage of 0 to 30 kV with 0- to 2-mA current output and 3.5-kHz frequency between the electrodes at a duty cycle of 70%.	This study demonstrates that the combined application of ACP with PAA provides an effective hurdle and a synergetic approach for reducing *Salmonella typhimurium* on the surface of poultry meat, with the highest reduction in Salmonella population by 5.3 log CFU/cm^2.	(33)
Poultry products	Plasma treatment voltage was fixed at 50 kV, 5 min	240 s and 90% RH showed a 3.0-log reduction of LI (*Listeria innocua*). While rotating, these conditions were then replicated using a "dirty" stainless steel knife. The results showed only a 0.5-log LI reduction.	(34)

Different types of meat (beef, pork, lamb, and chicken breast)	10 min, 80 kV RMS (root mean square)	Results show that the induced reactive species can degrade cholesterol in its pure form. However, the treatment did not affect the cholesterol content in meat samples.	(35)

Other food products

Plasma has also come to be used in other types of food, such as canned foods; for example, Capelli *et al*. 2021, used plasma to inactivate viruses, especially SARS-CoV-2, since its contamination in food is of concern to the scientific community and consumers. This research aimed to evaluate the ability of a cold plasma sanitation system to inactivate SARS-CoV-2 RNA in packaged foods by evaluating two different plastic materials that were subjected to 5 and 10-minute exposure to plasma after experimental RNA injection and, in addition to viral degradation, possible changes in the performance of the materials were studied. As a result, 10 min of exposure was almost completely sufficient to remove viral RNA from the surfaces of the containers; furthermore, the treatment did not produce any significant variation in the performance of the packaging material nor in the shelf life of the tested packaged products, so that plasma treatment for the removal of viruses from the surface of food has great potential (36).

Table 3 describes other studies where the plasma has been used for different purposes, from the most common microbial decontamination to its application to improve nutrient adsorption and physical properties.

Table 3. The table shows the use of cold plasma in different types of food.

Food	Conditions	Result	Reference
Milk	40 ± 0,25 W for 30, 180, and 300 s (CSM30, CSM180, and CSM300)	The microbial inactivation rate of the CSM300 sample was like that of the pasteurized sample.	(37)
	1, 2, 3, 4, and 5 min were evaluated; the jet generated cold plasma at 20 kV and had an arc drop voltage of 2 kV with a frequency ranging from 15 to 25 Hz	This study demonstrated that using 0.9 mol N2 & 0.1 mol O2 per mol as feed gas had a more detrimental effect on skim milk than N2. Therefore, nitrogen appeared to be a better choice of feed gas for modification of milk properties without damaging the structure of proteins.	(38)
Packaging of Apples	The high-voltage source was AC, and a frequency of 60 Hz was used. The reactor vessel was made from Pyrex, and the electrodes were copper. The reactor volume was about 1.88 L	The results of this paper have demonstrated the presence of plasma-processed film. A plasma-processed vanillin film was obtained. By ESEM and FTIR analyses, it was shown that some molecules of the vanillin precursor were affected by the corona activation.	(39)

Ready-to-eat ham packaging	A dielectric barrier discharge (DBD) plasma system (PG 100–3D, Advanced Plasma Solutions, Malvern, PA, USA) with a voltage output of 0 to 30 kV at 3.5 kHz was used.	Post-treatment storage is required to inactivate L. monocytogenes completely after ACP treatment. However, selecting a specific gas composition inside the package is crucial to achieving the required level of microbial inactivation. This study will help select optimized process and storage conditions for in-package ACP treatment to reduce L. monocytogenes while maintaining the ham quality.	(40)
Unpeeled almonds	20 kV peak to peak and a frequency of 15 kHz	This study suggests cold atmospheric pressure plasma (CAPP) as a promising technology for inactivating pathogens such as *Salmonella Enteritidis* PT30 on almonds. Air plasma treatments achieved more than a 5 log10 reduction. However, color changes were observed.	(41)

Conclusion

Cold plasma in the food industry can still be considered a recent technology; in this analysis, we show other uses of plasma in the food industry in addition to decontamination; it is important to remember that plasma is a technology that has the advantage of being much more environmentally friendly than traditional processes, which makes it of great interest due to the need to implement green technologies. Thanks to the different applications that are taking place with this technology, which is expanding rapidly, it can be considered a technology with great potential to improve food. For this reason, this type of research is of great importance.

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