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Application of Cold Plasma in Foods

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Abstract

Nowadays, the food industry, according to the needs of the growing population in the world, must align itself with the existing nutritional standards on the one hand and the increasing expectations of consumers on the other hand. Of course, the limitation of available resources and monitoring requirements during the process should be added to these items. For this reason, in order to overcome the upcoming challenges, the need for new technologies has been felt. The application of cold plasma in food and agriculture industries is one of these cases, which in this article tried to examine the different aspects of their use. It is worth mentioning that the use of cold plasma in the food industry is a new technology and extensive research is still being done in this regard.

Introduction

"Plasma" is called the fourth state of matter. In fact, plasma is a neutral ionized gas composed of excited and non-excited atoms, free radicals, ions and molecules with almost zero net electric charge. Crookes first discovered plasma in 1879, but almost 50 years later, in 1929, Tonks and Langmuir developed plasma generators.

Plasma is classified based on thermodynamic equilibrium, degree of ionization and density. In thermodynamic equilibrium in thermal plasma, electrons, ions and neutral species can be found. In a non-thermal equilibrium plasma, the temperatures of the plasma species are not in the same range. Unlike thermal plasma, the electron temperature in non-thermal equilibrium plasma is higher than the temperature of the gas composed of heavy particles such as molecules, atoms and ions [1]. The temperature of positive and neutral electrons and ions in the local regions in the local equilibrium plasma are in the same range. In addition, the temperature of ions in local equilibrium plasma is much higher than the temperature of ions in non-thermal plasma. Usually, plasmas with low non-thermal equilibrium are known as cold plasmas [2].

Plasma can be classified into two categories, low pressure plasma and atmospheric plasma, depending on the pressure conditions in it. Atmospheric plasma is produced under standard environmental conditions without the need for a high-cost reaction chamber and without the need for a pump to maintain the required pressure [38]. In the food industry, plasma equipment under atmospheric pressure is used due to the lack of need to adjust pressure and high temperature [3].

Generally, different technologies are used to produce plasma with atmospheric pressure in the food industry. Among these technologies, we can mention Glow Discharge (GDP), Corona Discharge (CD), Direct Barrier Discharge (DBD), Resistive Barrier Discharge (RBD), Atmospheric Pressure Plasma Jet (APPJ) and Microwave (MW) technology [4]. In all types of plasma, electron collisions under certain conditions such as gas discharge, radio frequency and reverse ionization are used to generate plasma [1].

Among the different types of plasma sources, APPJ and DBD plasmas have the highest disinfection properties for food. In addition, these sources are easily available, and their construction is simple, and they are also commercially available. DBD plasma consists of two electrodes, at least one of which is covered with a dielectric barrier material. By avoiding any transfer of the arc from the processing environment, this barrier creates many small discharges, which causes uniformity and stability in the decontamination of samples [5]. The APPJ consists of two concentric electrodes inside a nozzle through which the carrier gas passes. The internal electrode applies a high voltage between 100 and 250 V at a high frequency (13.56 MHz) to ionize carrier gases such as oxygen, helium or a mixture of gases [6]. These gases detonate the active zone of the jet plasma and help expel the stream of active particles from the electrodes [7].

Application of Cold plasma in agriculture

The use of cold plasma has many advantages in agriculture due to its use at low temperatures and short processing times, as well as the lack of damage to food products, seeds, humans and the environment. Plasma discharges produce ultraviolet radiation, charged particles such as electrons and ions, active neutral particles, and electric fields. These factors cause changes in pH, redox potential, concentrations of reactive oxygen species (ROS), reactive nitrogen species (RNS), and electrical conductivity, and affect seed germination, plant growth, and crop quality. Today, however, the contribution of plasma technology in agricultural operations includes soil amendment, increased seed germination or growth, production of nitrogen-based fertilizers, disinfection of seeds or crops intended for planting or storage, removal of ethylene to slow aging, disinfection of surfaces or Processing tools and reducing pathogen invasion are limited [8].

Selcuk et al. [9] investigated the effectiveness of low-pressure cold plasma inactivation using air or SF6 for two pathogenic fungi Aspergillus and Penicillium on the seed surface. This study included the examination of a wide range of seeds, including tomato, wheat, bean, pea, soybean, barley, rye, lentil and corn seeds. The plasma decontamination process was carried out by a batch process in a vacuum chamber, using gas injection and then plasma discharge for 5 to 20 minutes. Finally, plasma treatment was found to reduce fungal counts in seeds to levels below 1% of initial counts, depending on initial contamination, without affecting seed germination quality. SF6 plasma treatment for 15 minutes reduced the number of both species by 3 logarithms. Therefore, this study showed that plasma treatment is a quick and practical disinfection method that allows the removal of aflatoxin-producing fungus from the surface of seeds and kernels.

Today, cold plasma technology has attracted the attention of scientists due to the increase of seed germination capabilities. In particular, it has been proven that using plasma treatments increases the germination speed and germination performance of seeds [10].

Park et al. [11], the effect of water treated with different atmospheric plasmas, i.e., thermal spark discharge, transfer arc discharge and sliding arc discharge on germination, growth rate and overall nutrition of several plants have been reported. They stated that non-thermal sliding arc discharge leads to acidic pH and production of significant amount of oxidizing species (e.g., H_2O_2), while sliding arc discharge due to the presence of RNS (No, No2 No3) causes significant acidification of water, due to RNS (No, No2, No3), thermal spark discharge treatment depends on the initial composition of water and the production of RNS, leads to a neutral pH or higher than the basic state.

Application of Cold Plasma for Food Quality

In most cases, plant foods are subjected to a minimal or thermal processing before consumption. The ultimate goal of any processing is to increase the useful life of the food, to create edibility, to create a suitable taste, while maintaining the nutritional quality and organoleptic characteristics of the food [12].

Apart from food quality, some physicochemical parameters such as pH, acidity, texture, color, respiration rate and weight loss rate are among the things that are taken into consideration to judge the quality of fresh fruits and vegetables and their products. Regarding the application of cold plasma in food, it is stated that the chemical species of plasma that are responsible for microbiological inactivation are mainly active radicals that tend to react with food components. For this reason, optimizing plasma processes for food decontamination without losing quality can be challenging. During the treatment of plant foods, properties such as porosity, sensitivity to oxidation, surface-to-volume ratio, and permeability of cuticle to gas are among the things that should be given special attention. Also, during the treatment of food with cold plasma, parameters such as treatment time, frequency, type of gas and voltage can be adjusted to optimize the efficiency of the process with the aim of achieving the desired levels of microbial inactivation and at the same time maintaining the quality of the food.

Physical Quality

Color

The conditions of plasma treatment, the conditions and duration of storage and the characteristics of the product itself are among the things that affect the change in the color of foods treated with plasma. The color of fresh products treated with plasma often changes during storage as a result of the inactivation of some enzymes and microorganisms, which can initiate undesirable chemical reactions. Bermu'dez-Aguirre et al. [13] small changes in tomato and carrot color after cold argon plasma treatment using a plasma needle array (3.95-12.83 kV, 60 Hz, exposure time 0.5 to 10 minutes) reported [13]. In relation to dielectric barrier depletion (DBD) plasma treatments in air, cut kiwi fruits showed a lower degree of darkening during storage time compared to untreated samples [14]. An increase in darkness and a decrease in lightness were also reported in blueberries after treatment with dry air plasma [15].

Firmness

Major changes in the texture of fruits and vegetables are usually due to changes in their cell wall polymers [16]. In most studies, acceptable firmness retention has been reported in plasma-treated fruits and vegetables. For example, acceptable firmness retention has also been reported for strawberries treated with indoor air plasma (voltage 60 kV, 50 Hz) after 24

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h of storage at 10 °C [17]. In a study investigating cold plasma treatments on strawberries in modified atmosphere packaging (MAP), it was stated that firmness retention was better in a high oxygen environment (65% O_2, 16% N2, 19% CO_2) than in a It is high in nitrogen (90% N_2, 10% O_2). Plasma rich in nitrogen components leads to a significant loss of strength in the product. Also, insignificant changes in the elastic modulus of cucumber, apple, tomato and carrot were reported after cold microwave plasma treatment for 10 minutes with conditions of 2.45 GHz, 1.2 kW power, 20 L/min flow rate [18].

Chemical Quality

Change in pH: Acidification of liquids exposed to air plasma is one of the things that has been widely reported in different studies. The change in pH and acidity of plasma treated products is closely related to the dynamics of plasma chemistry used. Chen et al., [19] confirmed that the concentration of NO_3- originating from acid HNO_3 in the discharge increased with exposure to plasma, which resulted in fluid acidification. When fresh fruits and vegetables are treated with plasma, the chemical components in the gas phase react with the liquid water on the surface of the food to form acids. However, Ma et al. [20] stated that contrary to most theories and reports, no significant changes in the pH of strawberries treated with plasma-activated water (PAW, 98% Ar+ 2% O_2) were observed. This is most likely due to the absence of nitrogen, which is primarily responsible for the drop in pH [20].

Proteins and Enzyme Activity: Pankaj et al., [21] showed that cold plasma treatment caused rapid inactivation of peroxidase (POD) in crude tomato extract. They stated that the treatment time and its voltage had significant effects on this deactivation. Surowsky et al. [22] also reported the inactivation of POD as well as polyphenol oxidase (PPO) in model solutions using a cold plasma jet with different gases. Misra et al. [23] stated that the secondary structure of gluten became more stable in weak wheat flour that was exposed to cold plasma treatment in air under atmospheric pressure. Using infrared spectroscopy, they showed that an increase in DBD plasma treatment of more than 60 kV for 5 min increased both parallel and antiparallel β-sheets, indicating a loss of regular protein structure. Finally, these things led to improvement in dough strength in mixography studies.

Antioxidant Activity: Some reports stated that treatment with cold plasma does not have a significant effect on antioxidant activity in food. In a study on cold plasma treatment on red chicory (*Cichorium intybus L.)* and freshly cut kiwifruit using a DBD operating in air, there was no significant effect on the antioxidant activity of the extracts for treatments for 30 and 20 minutes did not show [24]. Song et al., [25] using a microwave plasma source with N_2, He, (N_2+O_2) and (He+O_2) reported negligible changes in the antioxidant activity of plasma-treated lettuce. The fact that the antioxidant activity of foods remains affected by plasma treatments is actually illogical. This is because antioxidants in food can be expected to react with free radicals. However, the rate of such reactions is determined by the diffusion of plasma radicals in the food matrix, the concentration of plasma species and the rate of antioxidant reaction against radicals [26].

Starch: Starch granule consists of crystalline and amorphous structure. The crystal structure of starch is divided into three groups A, B or C depending on the placement of the amylopectin side chain in the double helices [27]. Using X-ray diffraction, Zhang et al. [28] observed that oxygen plasma treatment resulted in greater degradation of amorphous materials and relatively minor changes in crystalline structure in corn and potato starch. Investigations showed that oxygen plasma changes the hydroxyl group to the carbonyl group on the C6 position of wheat starch [29].

Lipids: The effect of free radicals on lipids causes oxidation and the formation of primary and secondary oxidation products that are responsible for causing bad odors in foods. However, not much research has been done in the field of plasma in this connection [30]. Recently, a report has been published regarding the rapid oxidation of lipids during plasma treatment for fish oil [31], and cold plasma has been used for the rapid esterification of frying oils to produce biodiesel [32]. However, fruits and vegetables are poor sources of fats and oils, and plasma oxidation does not appear to be a significant issue in plant foods. However, it is said that the oxidation of lipids during grain and flour treatment may cause some problems [30].

Ascorbic Acid: Shi et al., [33] reported that following treatment with DBD plasma, vitamin C content decreased in the tested sample. However, the authors noted that this reduction was negligible compared to the control sample. Song et al. [25] using a microwave plasma source in N_2, He, N_2+O_2, and He+O_2, observed insignificant changes in the ascorbic acid content of lettuce treated with plasma, regardless of the applied power and also the storage temperature. In a study that included the plasma treatment of cut cucumber, pear, and carrot, a 4% decrease in vitamin C was reported [34]. Also, in another study, it was stated that DBD plasma treatments at voltages of 60 and 80 kV significantly reduced the content of ascorbic acid in whole strawberries [35].

Pigments and phenolic constituents: Chlorophyll is the green pigment found in the leafy parts of plants. When treating leafy vegetables and green fruits, a certain degree of oxidation of pigments due to the presence of free radicals has been reported. In the case of freshly cut kiwifruit, a significant decrease in chlorophyll content during storage has been reported. However, the amount of pigment degradation was observed in cut fruits treated with DBD plasma compared to untreated samples. It is said that this is due to the inactivation of the chlorophyllase enzyme present in the fruit structure [14].

Carotenoids are responsible for the orange-yellow and red color of fruits and vegetables. There is not much information about the effect of plasma treatment on carotenoids. In 2015,

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it was reported that the carotenoid content of cut kiwifruit was reduced by treatment with DBD plasma in the air [14].

Anthocyanins are polyphenolic flavonoids that are often responsible for the red to blue color of many fruits and vegetables. In research on pure flavonoid compounds and compounds present in lamb's lettuce, it was observed that the degradation of flavonoids was highly time-dependent after treatment with oxygen plasma [36]. In another study, it was reported that cold plasma treatments at 60 and 80 kV for 5 minutes had no significant effect on the anthocyanin content of whole strawberries. It was also reported that the content of phenolic acids remained almost unchanged after plasma treatment [35]. Bursac´ Kovacˇevic et al. [37] stated that anthocyanin content in pomegranate juice increased by 21-35% after treatment with Ar plasma jet [37].

Application of Cold Plasma for Food Safety

Food products with minimal processing, despite their advantages, unfortunately can be a means of transmitting bacterial, parasitic, and viral pathogens that lead to disease in humans [38]. Although conventional anti-pollution methods such as the use of disinfectant compounds such as chlorine and hydrogen peroxide, addition of bio-preservative compounds, vacuum packaging, high-intensity electric pulse, pulsed light irradiation, ionizing radiation, mild heat treatment, microwave processing, ozone technology, technology High hydrolytic pressure, reduction of water activity, chemical protection by ascorbic acid and calcium salts and hurdle technologies have effective results in some cases such as biofilm formation, firm adhesion of pathogens to surfaces and internalization of pathogens But on the other hand, it limits the usefulness and effectiveness of most chemical processing and disinfection methods. Other disadvantages of this method include the high initial costs of the equipment, the creation of some undesirable changes in the properties of food such as color, taste and smell or damage to their structure and the formation of toxic by-products [7]. The lack of success in eradicating food pathogens and bacterial biofilms, as well as the increase in the number of food-related human diseases, have led to searches for new methods that can prevent contamination during processing and at the same time maintain quality characteristics. Preserve the product and increase its useful life.

Critzer et al., [39] investigated the efficacy of uniform atmospheric discharge plasma generated at 9 kV and reported that a 2-log reduction in *E. coli* O157:H7 inoculated on apples was observed after 2 min of treatment, this in However, only 1 minute treatment resulted in a similar level of inactivation for Salmonella bacteria inoculated on cantaloupe. Also, treatment for 3 and 5 minutes reduced the population of L. monocytogenes in lettuce by 3 and 5 log. In this regard, Niemira and Sites [40] reported a significant reduction of 3.7 log of the population of *E. coli* and *Salmonella* inoculated on apples after 3 minutes of treatment with cold atmospheric plasma produced in the gliding arc discharge.

The characteristics of the bacterial cell wall may also play an important role in the overall resistance of the bacteria to various disinfectants and thus may interfere with the optimal use of cold plasma. In one study, the population of *E. coli* O157:H7 inoculated on radicchio leaves was reduced to 1.35 log MPN/cm2 after 15 min of treatment with 15 kV air-generated plasma. However, to achieve a significant reduction in the number of L. monocytogenes up to 2.2 log CFU/cm2, about 30 minutes of treatment is needed [24].

Surowsky et al. [41] investigated the inactivation of *C. freundii* in apple juice using an atmospheric plasma jet operating at a gas flow rate of 5 L/min, with a distance of 10 mm between the nozzle outlet and the juice sample. The obtained results showed a reduction of about 5 logarithms in association with *C. freundii* in apple juice using longer plasma exposure time (8 minutes) and higher oxygen concentration (0.1% oxygen) in argon gas mixture. It was also stated that the increase in oxygen concentration in the gas during the process led to the formation of hydrogen peroxide in fruit juice, which has antimicrobial properties.

Butscher et al. [42] tested a low-pressure fluidized bed plasma reactor for the treatment of wheat grains to inactivate *B. amyloliquefaciens* endospores on the product surface. They stated that at a temperature of 90 degrees Celsius and at 900 watts, the concentration of *B. amyloliquefaciens* endospores was effectively reduced by 2.15 log units in 30 seconds of treatment time.

Jayasena et al. [22] treated fresh pork and beef meat using flexible DBD thin film plasma with an average power of 2 W of bipolar square wave voltage at 15 kHz inside sealed plastic packages. They noted that a 10-minute treatment resulted in the reduction of *L. monocytogenes*, *E. coli* O157:H7, and Salmonella Typhimurium by 2.04, 2.54, and 2.68 log CFU/g in pork samples, respectively, and 1.90, 2.57 and 2.58 log CFU/g respectively in beef samples.

Kim et al. [43] used an RF-based atmospheric pressure plasma system in Ar (flow rate: 20,000 sccm; power 200 W) to treat beef infected with S. aureus ATCC 12600. The results stated that a 3-4 log reduction in beef was reported after 10 minutes of treatment. However, when the cells were seeded on the polystyrene surface, the inactivation rate was much faster, indicating that the product surface morphology is a determining factor for the efficiency of the process.

It has also been shown that the use of radio frequency (RF) plasma jet has a synergistic effect on the inhibitory effects of clove oil and sweet basil oil against Escherichia coli, Staphylococcus typhimurium, and Staphylococcus aureus on eggs [44]. This study showed that the growth of these three bacteria on eggshells supplemented with clove oil at 10 μL/mL or its key chemical compound (eugenol at 5 μL/mL) after plasma exposure at 40 W to It is completely restrained. Also, plasma treatments have had an

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important effect in reducing pathogenic microorganisms in eggs and egg products.

Yong et al. [5] stated that cold plasma treatment could potentially be part of food packaging. They stated that the populations of *E. coli* O157:H7, L. monocytogenes and Salmonella Typhimurium on sliced cheddar cheese after 10 minutes of plasma treatment were decreased 2.3, 2.1 and 8 log CFU/g, respectively.

Application of Cold Plasma in Food Packaging

Food packaging plays an important role in the food industry. Food packaging fulfills several functions such as protecting food, preserving the properties of ingredients, traceability, and character traits. Food packaging materials mainly include paper, glass, metals such as aluminum, tin foil and tin-free steels, and plastics such as various polyamides, polyolefins, polyesters, and polystyrene. In the meantime, all kinds of plastics have the major share of the market due to their low price, light weight, flexibility in construction, appearance and resistance to breakage, tearing and perforation. Most plastic materials are coated with non-polar chemically inert surfaces that make them unacceptable for joints, printing inks, coatings and adhesives. This requires the use of various surface treatments to improve these properties. The physicochemical methods used to modify polymer surfaces include the use of ultraviolet light, gamma rays, ion beam techniques, laser treatments, and the use of cold plasma.

Cold plasma is the most suitable method to modify polymers. Cold plasma production can vary depending on purification parameters, gas compositions and complex plasma chemistry, pressure changes of energy sources, and electrode type and shape. To modify the polymer surface, it is very common to use corona cold plasma and dielectric barrier discharge (DBD).

Cold plasma has been used in the polymer industry for decades and has been used to modify the surface properties of polymers. Also, this technique has great potential in creating new functional polymers, coatings and antimicrobial systems specifically for the food packaging industry. Cold plasma has great potential to be used as a simple, safe and environmentally friendly alternative in the food packaging industry [45].

Future of Cold Plasma in Food Processing

The future of using cold plasma technology in the food industry looks very promising. Cold plasma can be used to remove biological agents, toxins, surface contamination from food, modify packaging materials, improve food performance, and reduce pollutants in water and wastewater. Cold plasma treatment can be defined as a “dry process”, where there is no water or wet environment of concern.

It is clear that in order to meet the growing demand for food in the world, the food industry needs to improve and update the methods of production technology, food safety methods and environmental sustainability. This requires dedicated research and development in new technology. Cold plasma technology takes many forms and provides countless opportunities to improve production performance, food safety, and environmental sustainability. It has been observed that research on cold plasma in food is growing exponentially with more than 100 papers published annually [46-56].

Conclusion

Today in the world, the need for high quality food products is an ever-increasing need, and in the meantime, the world is moving towards the consumption of minimally processed foods. However, food safety is still the biggest challenge facing the food industry. For this reason, the use of new technologies in the food industry is welcomed. The use of cold plasma technology is a relatively new approach whose main goal is to improve food safety by maintaining the sensory characteristics of treated foods. However, some problems such as the lack of standard methods in this connection and the difference in initial microbial load and different types of food make it difficult to compare the reduction of microbial load resulting from different cold plasma systems. Nevertheless, it can be said that cold plasma has a very high potential for increasing use in the food industry.

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