**A NON-THERMAL TREATMENT: COLD PLASMA TECHNOLOGY IN FOOD PROCESSING**

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**INTRODUCTION**

In the ultimate two decades, non-thermal processing applied sciences have gained enormous attention from the food industry fascinated by moderate and fantastic processes. These alternative technologies may extend functionality and shelf-life, lowering the negative influence on food nutrients and natural taste (Huang *et al.,* 2017). Some of the most successful non-thermal techniques are high-pressure processing (Kalagatur *et al.,* 2018), ultrasound (Pinon*et al.,* 2020), pulsed electric-powered area (Clemente *et al.,* 2020; Schottroff *et al.,* 2020), ultraviolet mild (Correa *et al.,* 2020), high-intensity pulsed light (Moraes and Moraru, 2018), gamma irradiation (Deshmukh *et al.,* 2020), and, most recently, bloodless plasma (CP) (Govaert *et al.,* 2020; Kim *et al.,* 2020). Plasma can be described as an ionized gasoline containing reactive oxygen species (ROS: O, O2, ozone (O3), and OH), reactive nitrogen species (RNS: NO, NO2, and NOx), ultraviolet radiation (UV), free radicals, and charged particles (Bourke *et al.,* 2018; L. Han *et al.,* 2016a, 2016b). Typically, plasma is generated when electrical power is applied to a gas present or flowing between two electrodes with a high electrical potential difference that reasons gasoline ionization (Mandal *et al.,* 2018) due to free electrons colliding with those gas molecules. When the ionized gasoline is formed by means of extraordinarily low power (1–10 eV) and digital density (up-to 1010 cm− 3), it is referred to as CP (Roualdes and Rouessac, 2017). In the CP, there is a thermodynamic non-equilibrium between electrons and heavy species. Hence, the temperature between them is distinct because electrons are a whole lot lighter than ions and impartial molecules, and solely a small fraction of the complete strength is exchanged (Misra *et al.,* 2018, 2019b). Thus, the cooling of the ions and uncharged molecules is more effective than electricity transfer from electrons, and the gas stays at a low temperature (Misra *et al.,* 2016b). The common electron energy of CP, up to 10 eV, is perfect for the excitation of atomic and molecular species and breaking chemical bonds (Eliasson and Kogelschatz, 1991). All natural molecules having similar ionization and dissociation energies from three to 6 eV can without problems be destroyed by plasma (Suhr, 1983). CP science has been used in many manufacturing industries, such as scientific devices, textiles, automotive, aerospace, electronics, and packaging substances (Bermudez-Aguirre, 2020; Olatunde *et al.,* 2019a). Recently, CP has been integrated into the meals enterprise to limit microbial count (Govaert *et al.,* 2020; Kim *et al.,* 2020; Mahnot *et al.,* 2019; Moutiq *et al.,* 2020; Olatunde *et al.,* 2019a; Zhao *et al.,* 2020; Zhou *et al.,* 2019), degrade mycotoxin (Puligundla *et al.,* 2020; Sen *et al.,* 2019), inactivate enzymes (Chutia *et al.,* 2019; Kang *et al.,* 2019), increase the concentration of bioactive compounds (Silveira *et al.,* 2019), enhance antioxidant pastime (X. Li *et al.,* 2019a, 2019b), and decrease pesticides (Phan *et al.,* 2018; Toyokawa *et al.,* 2018) and allergens (Ekezie *et al.,* 2019b; Venkataratnam *et al.,* 2019) in meals products. However, CP therapy is nevertheless a rising process concerning unfavorable effects in meals (e.g., lipid oxidation), safety evaluation, and regulatory approval.

Matter on Earth exists basically in three distinct phases (gas, liquid and solid) however when the universe is viewed as the fourth state of matter which abundantly exists. So, Plasma is hence referred to as the fourth kingdom of matter, next to solids, liquids and gases. The time period ‘Plasma’ was once first employed by means of Irving Langmuir in 1928 to define this fourth kingdom of remember which is a partially or wholly ionized state of fuel and observed plasma oscillations in ionized gas. The trade of phase from solid to liquid and further to fuel happens as we increase the energy input likewise increasing the electricity input past a certain level in gasoline state motives ionization of molecules which yields their plasma state. Agostino et al. pronounced that plasma can be got both in low temperature, non-equilibrium glow discharge or high temperature, equilibrium thermal plasma. Based on the residences of plasma, it is used in various fields like textile, electronics, life sciences, packaging etc. The application of plasma technology as a floor cleaning tool has been commercially adopted for the removal of disinfection chemicals utilized in scientific units manufactured from heat-touchy plastics. In the biomedical sector plasma technological know-how is used for bloodless sterilization of instruments and prostheses as well as many thermo labile materials used in the biomedical science region for its unique advantages, including its average or negligible impact on substrate materials and use on nontoxic compounds. Conventionally, sterilization strategies such as heat, chemical solutions are used for the surface disinfection of fruits, seeds, and spices etc., which are often time-consuming and negative or have toxic residues. Van de Veen et al. suggested that the impact of cold plasma on bacterial spores is extra than the conventional techniques like heat, chemical compounds and UV treatment. The objective of this assessment are first, to current expertise on effect of bloodless plasma on microbial inactivation and structural modifications of packaging materials as many critiques has been published on these topics. Secondly, the impact of cold plasma on endogenous enzymes, seed germination, starch modifications and limitations for its practicable software in the meals sector as novel technology. One of the essential challenges associated with bloodless plasma technology is ensuring high microbial inactivation while preserving sensory qualities that make a certain their sparkling appearance.

**COLD PLASMA TECHNOLOGY**

In 1928, Langmuir invented the time period “plasma” to outline an ionized fuel with a macro-scopically neutral electrical charge. Since the 17th and 18th centuries, plasma, a semi-ionized fuel composed of excited electrons, ions, and neutrals, has been studied. Plasma is the fourth country of depend and is composed of particles such as high quality and bad ions and free radicals. Plasma can be created with the usage of many kinds of strength that can ionize gases, including electrical, thermal, optical (UV light), radioactive (gamma radiation), and X-ray electromagnetic radiation. Despite this, CP is often generated using electric or electromagnetic fields. To generate CP, a plethora of methods are being developed at a speedy pace. These can operate at regular air pressure or in a partial vacuum. Several gases can technically be applied in CP; the fuel about to be ionized should be as simple as both nitrogen and air. Alternatively, it should be a more composed mixture containing components of noble gases such as helium, argon, or neon. Electricity, microwaves, or lasers may additionally be used as the driving energy. This diverse set of diagram elements demonstrates CP methods’ adaptability and the diploma to which special types of CP mechanisms are invented and tested. All CP techniques for meal processing are labeled into one of three groups. The position of the food to be handled with the CP being generated specifies these groups: a significant distance from the origin of plasma generation, a sensible nearness to the generation source, or even within the region of the era itself that produces plasma. These companies are based specifically on the half-life and homes of charged, active species inner the plasma and originate nearly solely from the essence of CP chemistry.

**PLASMA SOURCES**

Even though low-pressure plasmas are now not necessary for a direct cure of meals merchandise due to the vapor strain of water, which is around 23 hPa, they are of incredible activity in the subject of packaging material processing. Their advantage is that large-volume filling plasmas can easily be generated at low pressure. The drawback of high-priced technology such as vacuum vessels and vacuum pumps is often compensated with the aid of the reality that smaller quantities of pricey working gases are consumed. At the turn of the millennium, the opportunity of making use of very thin barrier layers to Polyethylene terephthalate (PET) bottles in particular, using the plasma-enhanced chemical vapor deposition (PECVD) process, met with outstanding activity in industry. Many widespread manufacturers of filling machines often in Europe and Japan but also in the USA developed approaches partly on glass layers but additionally based on amorphous hydrocarbon layers to improve the barrier properties. This science used to be transferred to production and machines with throughput quotes of up to 46,000 bottles per hour had been realized. A precise overview can be observed in Nakaya et al. (2015, 2018).

**Dielectric Barrier Discharge**

The dielectric barrier discharge is the workhorse of plasma technology. This precept of discharge technology is also the foundation for the ozone tube mentioned earlier. The principle is based totally on limiting the energy consumption of the plasma device. If a sufficiently high voltage is utilized between two electrodes at atmospheric pressure, an electrical breakdown occurs. Due to the excessive conductivity of this breakdown, an excessive cutting-edge flow is induced. This motivates a contraction of the discharge due to its magnetic field so that an arc discharge with excessive power density and temperatures of up to 50,000 K can result (pinch-effect). If one or each electrode are insulated by way of a dielectric, the cutting-edge waft is interrupted locally right now after the breakdown by using a local charge of the dielectric. By further growing the voltage, an in additional discharge can then be ignited at another location in the electrode arrangement. Due to this principle, the person discharges are evenly disbursed over the entire electrode area, even in large electrode arrangements. Due to the shortness of the individual discharges of a few 10–8 s, solely little power can be deposited in the machine (Fig. 2A). Typically, dielectric discharges are operated with alternating voltages in the frequency range from 50 Hz to numerous 104 Hz. Typical voltages range from a few kV to over one hundred kV. Therefore, such discharge systems are frequently used in ozone generators, for floor modification of plastic motion pictures or for exhaust air purification (Kogelschatz *et al.,* 1999). A direct use of food has been shown e.g. on eggs for consumption (Wan *et al.,* 2017). Other promising applications can be located in the treatment of packaged food. Examples are the remedy of sausages (Jung *et al.,* 2015a), fruits and packed fresh-cut salads (Misra *et al.,* 2014b; Ziizika*et al.* 2016).

**Plasma-Jet**

The plasma jet is a discharge that takes the area in a dielectric tube and is expelled from the tube via an excessive fuel flow. The electrical power coupling generally takes vicinity in the range of a few kHz up to 27 MHz with powers of a few W up to the kW range and pronounced with the aid of Ehlbeck *et al*., (2011). The two electrodes required for the power coupling are regularly positioned in a ring on the outside of the tube with a distance between them depending on the experimental conditions. Often, this association can only be used to operate plasmas in without difficulty ignited by noble gases such as argon or helium. For operation in air, therefore, an association with only one ring and a needle-shaped counter electrode concentrically placed in the tube is often used. The drawback of this arrangement is that countless jets have to be linked collectively for a high vicinity output, whereby the system prices and the operating expenses due to the greater gasoline consumption have to be taken into account.

**Microwave Discharge**

Microwave discharges at atmospheric stress are usually plasma torches, which are operated with excessive fuel flows similar to the plasma jets (Fig. 2C). The torches are generally operated at 2.45 GHz in the power range from some 10 W up to about 6 kW. For higher powers, multi-stage systems can additionally be used (Schnabel *et al.,* 2019b). For very high strength levels, it makes extra sense to set up systems working at a frequency of 915 MHz At this frequency, plasma torches up to 70 kW are available. The torches can be operated at atmospheric pressure with noble gases as properly as with air. However, plasma ignition poses a problem due to the low electrical field strength on hand in ordinary waveguide arrangements. To overcome this subject a number of options are found using resonance and top results to gain the electric-powered discipline power for plasma ignition. The excessive temperatures reached in the plasma torches are at first a quandary for the use of this technological know-how for food treatment. For decreased power, a solution can be completed with the aid of increasing the distance. The then still sturdy impact of the plasma effluent could be demonstrated with biofilms (Handorf *et al.,* 2019). A technologically very fascinating opportunity is the use of the gas modified with the aid of the plasma torch. In the case of air as a working gas, a strong antimicrobial impact is effects from the reactive nitrogen species (RNS) shaped in the gasoline (Drost, 1978). Due to its high temperatures, this technique of gasoline can be used for simultaneous drying and inactivation of existing microorganisms in bulk materials. If the method gas is cooled, it can also be used for temperature-sensitive products, for example, for the remedy of fruit to improve storage properties (Schnabel *et al.,* 2014). Furthermore, the technique gasoline can also be added into contact with water and this water can be used for washing of sparkling produce.

**APPLICATION OF COLD PLASMA IN THE FOOD INDUSTRY**

A CP device has been investigated for an extensive range of functions at several phases of meal manufacturing, which include the remedy of substances or closing products, as well as the therapy of processing equipment, facilities, and the environment, due to the fact of its several advantages. Among the CP benefits are low-temperature operation, short time frames, power efficiency, and great antibacterial efficacy with negligible effects on food great and the environment. Many researchers have mentioned the achievable uses of CP for distinct purposes. Some of the CP makes use of related to meal production.

**Wastewater treatment**

The food processing industry uses plenty of water in cleaning, washing and processing of food and their equipment. Therefore effluent of food processing flora is prosperous in natural loads and other chemicals. In addition effluent water of meal processing flora is bountiful in diet and their disposal without any treatments leads to hazard of the pathogenic outbreak. Hence masses of technologies are developed for the food industry discharge. Reactive species are reported in decontamination, and degradation of chemical compounds from waster of a range of industries therefore it can be suited in food processing industry for chemical compounds elimination barring decontamination of waste effluent. 120s or 150s publicity of 25KV plasma jet was efficient in the decontamination of waste from date and tomato processing industries. Whilst Benidris *et al.,*pronounced AG25 dye removal in 10 min after GAD plasma treatment. Jovic et al. investigated the DBD application in the degradation of mesotrione and compared it with three more process, specifically Fenton, ozonation and photocatalysis. Interestingly, similarity between DBD and ozoniation was discovered with the frequent position of O3 in degradation. However they suggested efficient and speedy removal of mesotrione-by using DBD compared to others. The superb have effect on of technological know-how has led the demand for wonderful scale-up of the science with customized gear design to be healthy for the food processing enterprise to deal gaint-scale waste disposal.

**Packaging material processing**

The bactericidal effect of plasma is well confirmed and protected herewith however its utility is not restrained to microbial exposure but it can be utilized for surface redress and surface sterilization of packaging materials too. The surface amendment includes the addition or elimination of specific useful crew or turn-able floor energies to the packaging fabric floor for improving antimicrobial efficiency and extending mechanical power like adhesion, absorbance, sealing, veneering, coating etc. Plasma can be beneficial for depositional barrier coating on the surface of polymers. Conditioning coating would assist to decrease gas permeation and undesirable contaminants besides any traces. Furthermore, plasma therapy helps to preserve sealing homes of polymers and laminates. Non-thermal plasma sterilization is unique, much less time eating and secure sterilization approach for packaging materials like polyfilms, plastic bottles, containers and lids, besides any aspect effects and zero waste residues. Moreover it is very advantageous for the sterilization of heat-touchy materials like polycarbonate and polythene at low temperatures. Recently Oh et al. demonstrated plasma software on edible film made from defatted soyabean meal (DSM) for smoked salmon covering. Exposer of DSM movie to argon plasma at 400 W for 15min has shown increase in 24.4 pp. moisture barrier property, 13.4% elongation and 6.8 % tensile electricity while reduction in lipid peroxidation in the course of 4°C storage. Similarly Kim et al. said 3-4 log CFU/cm2 discount in E coli O157:H7, S. Typhimurium and L. monocytogenes biofilm after 10 min of 50 W jet plasma treatments on food containers.

**EFFECTS ON FUNCTIONAL FOOD PROPERTIES**

Up to now, the consequences of plasma remedy on the surface of meals have solely been studied in a few papers applying unique plasma sources. For example, the plasma remedy of plant ingredients appears to have the plausible to exchange the structure of the surface of the meal, thereby increasing the bioavailability of the phytochemicals contained in the plant material. Treatment of lamb’s lettuce with argon plasma resulted in an increase in floor wettability (Grzegorzewski *et al.,* 2010) and in damage to the microstructure of the lettuce (Grzegorzewski *et al.,* 2011). The thick platelets and small-sized granular wax characteristics on untreated samples disappeared with increasing exposure time. The erosion of the top epidermal tissue layers most probably induced with the aid of vigorous AR ions and/or ROS leads to the plasma-induced removal of wax crystals on the floor of remoted apple cuticle discs and a lowering thickness of the cuticle discs with growing exposure to plasma (Khanal *et al.,* 2014). With regard to chicory, floor erosion on leaves by using plasma was attributed to the oxidation of telephone aspects (Pasquali *et al.,* 2016). Plasma utility on plant seeds and sprouts for decontamination, coating, acceleration of germination and growth, as well as the change of ingredient profiles has attracted broad interest in agricultural and food sciences. Plasma-induced effects on the surface homes of seeds had been said to result in a trade in wettability and to motivate a limit in the apparent contact attitude of for instance lentils, bean, and wheat surfaces (Bormashenko *et al.,* 2012). Different seeds had been discovered to be influenced at some point of the early boom (Sera *et al.,* 2010; Mihai *et al.,* 2014). Plant increase response of seeds to plasma remedy was once discovered to be depending on plant species with a correlation between the boom enhancement and O3 and NOx awareness (Shiratani *et al.,* 2016). Different contents of treasured secondary plant metabolites between control sprouts and sprouts from handled seedlings illustrated adjustments in metabolism strategies in tested species (Bubler *et al.,* 2015a; Shiratani *et al.,* 2016). Applied to different grains, CP was similarly determined to reduce cooking time, enhance cooking houses and positively have an impact on the surface characteristics (Sarangapani *et al.,* 2017c), to expand a-amylase activity and water absorption (Lee *et al.,* 2016). CP ought to provide a modern future approach to modify seed germination characteristics and may also similarly be applied for decontamination, coating, acceleration of germination and boom of seeds and seedlings for different agricultural and food-related issues. Application of CP to intermediate products from grains e.g. flour, pellets etc. brought about a growing flour water maintaining capacity with extent in plasma energy and publicity time (Thirumdas *et al.,* 2016, 2017) as nicely as vast effects on solubility and swelling electricity alongside a discount in pasting viscosity. Mild oxidation in the proteins accompanied by an make bigger in carbonyl corporations and floor hydrophobicity as well as the reduction of free SH organizations had been attributed to reactions of reactive oxygen and nitrogen plasma species with whey protein isolate (Segat *et al.,* 2015). A certain diploma of unfolding may also be responsible for the enhancement in foaming and emulsifying potential determined. Water and fats binding capacities in protein-rich pea flour increased following CP redress in air (Bubler *et al.,* 2015c). Comparing the plasma-induced outcomes to those triggered by way of warmth treatment, the applicability of semi-direct CP cure during postharvest processing of Tenebrio molitor flour (Bubler *et al.,* 2016) validated the specificity of plasma modification. The secondary structure of gluten grew to be steadier following the publicity of wheat flour to air plasma and substantial modifications in the rheological residences of the corresponding dough’-s have been bought (Misra *et al.,* 2015). Plasma-induced outcomes on viscosity and elasticity have been located to rely on the treatment conditions, applied voltage and exposure time. The findings point out that CP may additionally serve as a modern approach to modulate the performance of wheat flour at some point of processing of wheat-based merchandise such as bread, pasta, noodles, cookies, and others. The floor change of bakery merchandise might also provide every other plasma application, considering that caused an increase in the hydrophobicity of freshly baked biscuit surfaces resulting in multiplied spreading of any oil sprayed and as a result decreased seepage (Misra *et al.,* 2014e). As the interplay of plasma with water consequences in the era of reactive oxygen and nitrogen species, along with nitrates and nitrites (Oehmigen *et al.,* 2010), frankfurters had been manufactured by replacing the nitrites of the curing salts with the aid of plasma-treated water (Jung et al. 2015ab) leading to residual nitrite content which was 30% lower in sausages processed with plasma-treated water. Comparable findings were acquired by immediateplasma-treating meat butter at extraordinary levels for the duration of sausage manufacturing. As a result, a patent to eliminate nitrites in meat products through CP science was once lately utilized for (Lim *et al.,* 2015). Results of recent studies are current a whole branch of plasma purposes in the discipline of inactivation of deteriorating enzymes, improvement of bodily and mechanical traits of films, as nicely as of techno-functional residences of meals components, and a discount in food allergenicity. Based on the kingdom of the art, the doable for in addition investigation on the enhancement of understanding of these plasma-underlying mechanisms at the molecular scale and of the improvement of kinetics of reactions is great. Considering that plasma in humid air, relying on the gasoline mixture and the voltage applied, consists of more than seventy-five species (Misra *et al.,* 2016b), the chemistry of CP is complex and the several plasma-immanent species will lead to almost 450 reactions(Kossyi *et al.,* 1992).

**ADVANTAGES AND DISADVANTAGES OF COLD PLASMA**

Despite numerous studies, countless components of the CP technique in the food industry remain unknown. For example, there are nevertheless some research gaps related to the effects of CP on allergens and antioxidants. Furthermore, research on the safety, toxicity, and/or health effects of CP-treated meal products on human beings is required. Because different plasma components have unique results on exceptional meal products, optimization studies for the type, intensity, and period of plasma treatments, as properly as the food type, are required. The growing use of inexperienced maintenance strategies has led to the improvement of di-verse technologies, each pursuing software in the food enterprise worldwide. Regrettably, most counseled inexperienced applied sciences are both restricted due to the high price of equipment, have an impact on product quality, are not appropriate for all meal types, or are inadequate for maximum meal product protection. On the one hand, most literature only described CP utility at pilot-scale stages with restrained surface coverage. As a result, increasing the plasma-generating electrode dimension may increase the plasma’s quantity and coverage. Regrettably, this complete progress is time-consuming and high-priced. On the other hand, CP enhances the dietary first-rate of some meal merchandise with the aid of increasing complete phenolic compounds, amino acids, and sugars. Such improvements, however, are structured on the gas mixture used to generate plasma and the mode of exposure/penetration over the food material.

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