DR-2164
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REVIEW ARTICLE Asian Journal of Dairy and Food Research

Exploring the Effects of Cold Plasma on Preserving and Processing of Foods: A Review

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10.18805/ajdfr.DR-2164

ABSTRACT

In the current scenario, global food productions need to be incredibly enormous to feed everyone. Though food supply plays a tremendous role in reaching out to the people, meanwhile advancement in food processing technology is a predominant factor in increasing food availability. In the food industry, there was a huge number of technologies for food processing that made food more convenient to eat and might be stable for extended storage. Among the food processing technologies, cold plasma may be one of the novel non-thermal technology that functions at atmospheric pressure or low-pressure processing technology. Cold plasma is an eco-friendly technique involved in food preservation, mainly destructing microbes in food thereby extending its shelf life. Cold plasma processes the food without degrading the physical, chemical, biological, nutritional and sensory qualities of food products. This review elaborates on cold plasma utilization and its quality changes in various foods.

Key words: Cold plasma, Food quality, Processing and preservation, Reactors.

Cold plasma is a novel evolving technology; which attracted scientists globally. It had been initially formed for perfecting the printing and binding properties of polymers. Within the last couple of decades, its application has become a strong tool for novel non-thermal processing methods (Chizoba *et al.,* 2017). Cold plasma consists of both charged and neutral particles including free radicals and helps to destroy or inactivate the microbes (Brany *et al.,* 2020). Microbial toxins and spores are predominant contaminants of foodstuffs. In the process of preparing food, these spores or microbes or microbial toxins are diminished or inactivated by the process of preservation or processing methods.

Most of the researchers examined plasma technology which will be used as a broad spectrum in the field of food preservation, biomedical and commercial applications (Sen *et al.,* 2018). Inward the food industry, the new trend is cold plasma technology which is highly profitable and safer. The custom of cold plasma in the food industry has been demonstrated for wastewater treatment (Sarangapani *et al.,* 2016), inactivating enzymes (Misra *et al.,* 2016), removing toxins (Misra *et al.,* 2015) and food decontamination (Misra *et al.,* 2011). Many researchers investigated, the application of cold plasma on fruits and vegetables using minimum levels successfully decontaminated harmful microorganisms like *Listeria monocytogenes*, *Escherichia coli* and *Salmonella typhimurium* (Ziuzina *et al.,* 2014; Jeyasena *et al.,* 2015; Albertos *et al.,* 2017). Thus, sterilization using cold plasma offers minimal cost with the least changes in food. Moreover, in the agriculture and food industries, there is an increasing need for innovative sustainable technologies due to the growing population, which increases the need for food, water and energy resources.

Cold plasma is a novel non-thermal processing technology which has exhibited noteworthy prospects within the food processing industries to produce safer foods. This technology helps to inactivate harmful microorganisms and extend the shelf life of foods (Pankaj and Keener, 2018). The purpose of this review is to provide an overview of cold plasma technology, its use in the food processing sector and the quality exposure of cold plasma-treated food products.

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How to cite this article: Punniyamorthy, S., Shanmugavel, K., Shanmugavel, C.P., Thiyagamoorthy, U. and Sakthivel, K. (2024). Exploring the Effects of Cold Plasma on Preserving and Processing of Foods: A Review. Asian Journal of Dairy and Food Research. doi: 10.18805/ajdfr.DR-2164.

Submitted: 04-09-2023 **Accepted:** 14-02-2024 **Online:** 11-03-2024

Plasma chemistry and generation

Plasma is an ionized gas that becomes the fourth state of matter (liquids, solids, gases). Plasma is attained once adequate energy is applied to a gas. Application of energy to a gas will generate an electrical field which will increase the speed of free electrons within the gas. The accelerated electron undergoes contact with neutral gas atoms, leading to incitement or electrolysis. This ionization releases the surplus amount of free electrons faster causing an avalanche effect of highly reactive chemical species that are capable of inactivating enormous amounts of microorganisms. Cold atmospheric plasma is generated using direct current (DC) or electricity power supply and Alternating current (AC) power supplies. The frequency varies in a wide range from AC power of low (kHz) frequencies through Radio frequencies (MHz) to Microwave (GHz) frequencies which finally release plasma discharges. Differet reactors mentioned in Table 1 and Fig 1.

Application of cold plasma in food preservation and processing

Fruits and vegetable sector

Cold plasma technology offers a wider benefit in the food processing industry, decontamination, surface modification and improvised products with desired properties (Warne, 2021). According to Wang *et al.* (2012), *Salmonella* sp. were inactivated up to 90% in carrot slices and 60% in cucumber slices and reported to be less effective in pear slices by about 40% by cold plasma treatment. After one second of treatment, the rate of inactivation on cucumber and pear slices reached above 80%; however, this effect was time and dose-dependent. Kovacevic *et al.* (2016), studied the effect of cold plasma on anthocyanin and colour in pomegranate juice and chokeberry juice. The results showed an optimistic effect on anthocyanin content and slight changes in pomegranate juice colour; whereas increased level of hydroxycinnamic acids in chokeberry juice. There were increased levels of colour, citric acid and ascorbic acid in prebiotic orange juice treated by the effect of cold plasma (Almeida *et al*., 2015); these scenarios revealed that cold plasma technology protects the functional compounds (polyphenols). The plasma application on fresh-cut melon probably increases the shelf life and keeps quality (Tappi *et al*., 2016). The plasma treatment improved the colour and reduced dark area formation in freshly cut kiwifruit. The kiwi fruit-treated samples and control were observed to record same antioxidant content and antioxidant activity (Ramazzina *et al*., 2015). Misra *et al.* (2014) attempted to increase the cherry tomatoes shelf life by applying cold plasma and concluded that plasma technology could be an effective method of decontamination and retaining the quality of cherry tomatoes (Misra *et al*., 2014).

Microbial inactivation of aerobic mesophilic bacteria, molds and yeast was observed in treated strawberries where

Table 1: Different reactors used in cold plasma.

Different reactors	Operating principles	References
Dielectric barrier discharge	Dielectric barrier discharge (DBD) is made with two electrodes in-between separated by an insulating dielectric barrier. DBD materials encompass polypropylene, glass and metals like copper, aluminium and brass It can suppress sparks by regulating the current and operating in a wide range of pressures (104 - 106 Pa)	Albertos *et al.* (2017)
Gliding arc	Gliding discharges are low-temperature plasma which is operated by multi-electrode reactors using air pressure. The plasma is produced by two different aluminum electrodes, which comprise a plasma generator along with two copper electrodes. Gas input is given at the top of the nozzle. High voltage up to 9kV or higher is used for plasma generation.	Moreau *et al.* (2007)
Corona discharge	Corona discharge is a form of electrical discharge produced by the action of fluid ionization with the help of air surrounding a conductor that's electrically charged. The plasma is a self-maintained discharge that occurs at the tip of a pointed electrode where an inconsistent electric field is present.	Scholtz *et al.* (2015)
Radiofrequency discharge	A radio frequency field that is provided externally creates radio frequency plasma in an extremely fast flow of gas. The plasma is created at the tip of the needle electrode and it then expands to the grounded ring electrode outside the ceramic nozzle. The ceramic nozzle is connected with the above two RF voltage (often 13.56 MHz) electrodes.	Hertwig *et al.* (2015)
Microwave discharge	Microwaves' electrical discharges are produced with the help of electromagnetic waves at a frequency range of greater than 300 MHz. The plasma is formed by a magnetron cooling system with open, closed and resonance of three structures.	Won *et al.* (2017)
Plasma jet	A powered electrode creates the plasma, which then flows to another surface. There are four different types of plasma jets *viz*., DBD jets, single electrode jets, dielectric-free electrode jets and DBD-like jets.	Lu *et al.* (2012)

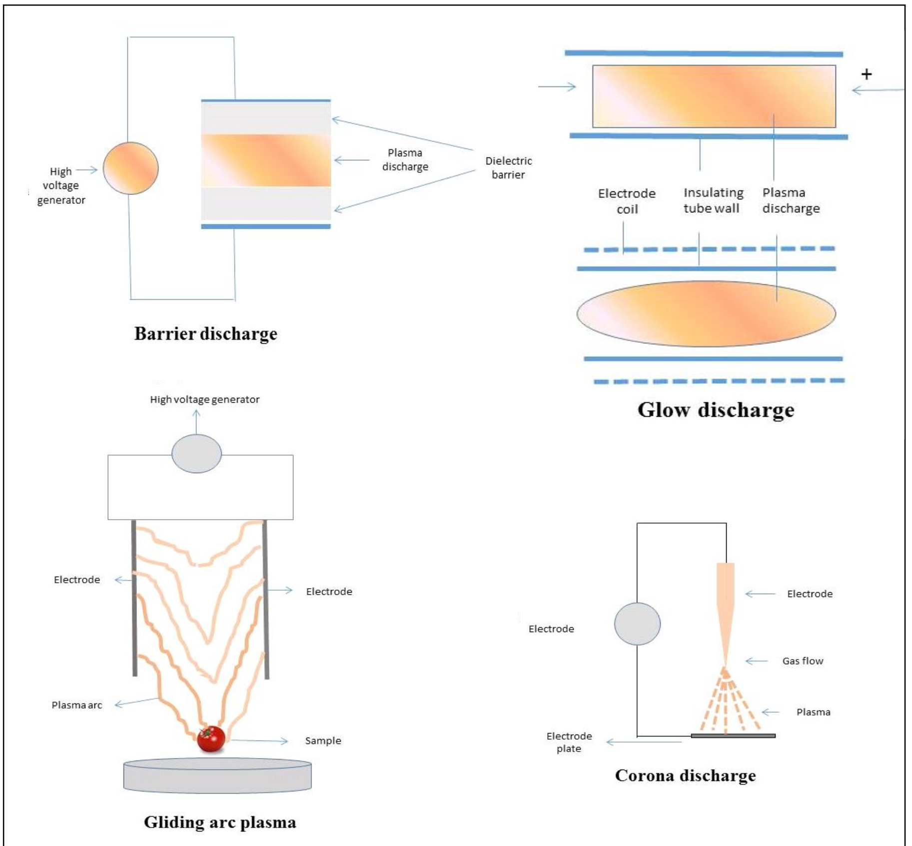
Note: RF: radio frequency; AC: Alternating current; DC: Direct current; DBD: Dielectric barrier discharge.

the microbial load got reduced by 2 log10 by treating for 5 minutes in atmospheric cold plasma (Misra *et al*., 2016). Xu *et al.* (2017) conducted a study on the application of high-voltage atmospheric cold plasma technology in orange juice and reported a positive effect against *Salmonella enterica* serovar *typhimurium* (*S. enterica*). A similar study was conducted by Pankaj and Keener (2018) described that plasma-treated juices had a significant reduction of *S.cerevisiae* and deprived of any change in pH and acidity. Kim *et al.* (2017) studied that cold plasma against spores of *A. brasiliensis*, *B.cereus* and *E.coli* on onion powder for 40 minutes which was known to effectively reduce the number of spores. Min *et al.* (2016) reported that DBD atmospheric cold plasma effectively inactivated *Salmonella sp.* without any change in color or firmness. Cold plasma could be used to inhibit food-borne pathogens and increase the shelf life of fresh lettuce storage life (Song *et al*., 2015). As a result, cold plasma technology is still widely used in the processing and preservation of fruits and vegetables.

Meat and poultry sector

Microorganism plays an important role in meat decay. Due to their highly perishable nature meat and poultry products are easily attacked by microbial populations and lead to deterioration. Depending upon the way cold plasma therapy, the effects on the microbiology of meat and meat product differs. Ulbin-Figlewicz *et al.* (2013) investigated the use of cold plasma treatment to inactivate microorganisms and effect on their colour using nitrogen, argon and helium plasma on meat surfaces. The researchers found that helium and argon plasma treatment for 10 minutes effectively reduced the total number of microorganisms (3 log cfu/cm^2). The mold and yeast were observed to be 6 log cfu/cm^2 and 3 log cfu/cm2 respectively. Yeast and molds were slightly low in nitrogen plasma and reduction of 1 log cfu/cm^2 after 10 minutes of exposure. The atmospheric pressure plasma promotes a current innovation in the meat industry for curing process without nitrite additives. At this identical time, the sample received an improved score in organoleptic score and overall acceptability (Lee *et al*., 2018). Ulbin-Figlewicz and Jarmoluk (2015) proved the consequences of low-pressure plasma on the stability of raw pork samples. After 14 days of meat samples storage, ferric reducing ability reduced from 1.93 to 1.40 mmol Trolox Eq.kg. In numerous studies with *E.coli*, *L. monocytogenes* and *Salmonella sp*., the plasma treatment reduced the counts of pathogenic bacteria and did not influence the textural properties of tested food (Jeyasena *et al*., 2015; Albertos *et al*., 2017).

Yong *et al.* (2017) found an alternate method for pork manufacturing, using cold plasma along with sodium



a) Barrier discharge b) Glow discharge, c) Gliding arc plasma d) Corona discharge.

Fig 1: Pictorial representation of types of discharge.

nitrite, there was an increase in quality parameters such as texture, colour and in case of microbial quality, pathogens like *Staphylococcus aureus* and *Bacillus cereus* were significantly reduced. The application of cold plasma using modified air condition (65% O_2: 30% CO_2:5% N_2) study revealed that bacterial isolates were completely inactivated at 120 seconds in ambient air condition, while modified atmospheric condition is needed for complete inactivation of *S. typhimurium* (90 seconds) and *P. fluorescens* (180 seconds), whereas minimum time of 30 seconds for killing *C. jejuni* (Rothrock *et al*., 2017). Microbial population in the atmosphere cold plasma-treated meat exposed below level was compared with control (Wang *et al*., 2018) and Zhuang *et al.* (2019) reported that DBD ACP possesses positive consequences on decontamination of meat surface against Campylobacter, Salmonella and improving meat quality. Finally, numerous researchers reported that there is no significant loss of texture and colour of the meat products when treated with cold plasma.

Grains and flour sectors

According to Misra *et al.* (2015), the use of cold plasma technology improves the viscosity moduli and elastic properties of wheat flour. Plasma technology increased the water uptake and simultaneously it reduced the hardness and chewiness in textural parameters (Thirumdas *et al*., 2016). The study by Sarangapani *et al.* (2015) reported that low-pressure plasma technology increased the water absorption of rice and reduced the cooking period by up to eight minutes and at the same time, the surface energy was increased. Plasma treatment reduced the amylose content within the amylose to amylopectin ratio and sequentially increased the gelatinization temperature and crystallinity of flour. It also enhanced physicochemical properties like proximate composition and textural properties of black gram with reduced hardness with the range of 22.50 to 23.36 N by cold plasma treatment (Sarangapani *et al*., 2016). Wu *et al.* (2018) found that corona electrical discharge applied to raw banana starch analysis doesn't showed any significant changes within the amylose content and resistant starch but it reduced the area of diffraction peak and viscosity.

According to Lee *et al.* (2016), after 5 minutes of treatment, cold plasma modestly lowered the pH of brown rice. In germinated brown rice, Chen *et al.* (2016) discovered an increased amount of gamma aminobutric acid from 19 to 28 mg/100g. Application of low-temperature plasma technology helped to improve functional properties like flour hydration, antioxidant, hydration properties and gelatinization temperature on basmati rice. The researcher also observed increased water holding capacity and water binding capacity with the rise in plasma and time of treatment (Thirumdas *et al.* 2016). Chen *et al.* (2012) reported an application of cold plasma technology to decrease the brown rice cooking time, expansion ratio and elongation ratio. Indica brown rice showed a noteworthy amount of decrease in viscosity and breakdown. The application of low-pressure plasma offered a promising method to decrease the time of cooking on brown rice.

Milk and dairy sector

Milk decay occurs when the pH of the milk got reduced, the pH of milk is lowered as a result of the lactose in the milk being converted to lactic acid. According to Kim *et al.* (2015), utilizing DBD plasma, aerobic bacterial count got decreased along with pH level. Korachi *et al.* (2015), studied the application of cold plasma to milk indicating biochemical alterations in the form of elevated levels of free fatty acids, protein and volatile compounds. Following a 10-minute flexible thin layer DBD plasma treatment, the amount of *E.coli, S.thyphimurium and L.monocytogens* on slices of cheddar cheese got significantly decreased. The results proved that DBD plasma could probably be an efficient technique to sterilize food products and also this condition should be evaluated for food industry application.

The bacterial count in the entire batch of milk was reduced from 7.78 to 3.63 Log CFU/ml after 20 minutes of plasma treatment (Gurol *et al.,* 2012). To treat the *E. coli, L. monocytogenes* and *S. typhimurium* bacteria present in the cheese slices, Yong *et al.* (2015) proposed using atmospheric pressure DBD plasma. The results showed 2.67, 3.10 and 1.65 decimal reductions after plasma treatment. Therefore, developed plasma treatments have a positive effect on improving the protection of cheese products and increase the shelf life of the products. Cold plasma technology has a positive role as an alternative to the chocolate industry. According to Coutinho *et al.* (2019), the physicochemical properties, fatty acid composition, pH and volatile component profiles of chocolate milk drinks revealed that processing had a negative impact on the amount of bioactive and fatty acids present.

Effects of cold plasma in food processing

The behavior of food during the cold plasma treatment and the relationship between the food molecules are of great interest to researchers. Additionally, cold plasma clearly defines the relationship between each food properties physical and chemical indexes and can have a significant impact on how food is processed and preserved.

Cold plasma is effective in water treatment. However, to verify the effects of cold plasma certain analyses must be conducted on the combination of water and beverage components. Hou *et al.* (2019), conducted a study on the effect of cold plasma on blueberry juice. The results emphasized significant increase in phenolic content in juice, which could better preserve the natural colour of blueberry juice.

Misra *et al.* (2018), studied DBD cols plasma on xanthan gum to increase the viscosity and emulsion stabilizing properties. Treated xanthan gum possessed more benefits for salad dressing and instant dry soup formulations with high viscosity at lowering shear rates.

Proteins are predominantly used as a thickening agent, development of dairy products, texturizing agent and gel formation. Cold plasma penetrates whey protein and isolates structural modification along with foaming quality, functionality and emulsifying properties (Segat *et al*., 2015). Atmospheric plasma treatment improved oil binding and reduced water binding capacities which enhance the food texture and functionality (Bubler *et al*., 2015). It provoked the properties within crystallinity and gelatinization of starch. This phenomenon extended surface energy and hydrophilicity and the splitting of the amylose side chain. Plasma treatment persuades similar variations in the functional properties of starch viscosity and the rheological properties of weal wheat flour (Misra *et al*., 2015).

Pankaj *et al.* (2017), reported that cold plasma treatment increased the glass transition temperature, surface oxygenation and surface roughness of starch films. DBD cold plasma treatment increased the solubility of peanut protein isolates (Ji *et al*., 2018). Low-pressure plasma increased the hydrophobic properties of whey protein (Terpilowski *et al*., 2017). Cold plasma treatment positively degrades the mycotoxins (Shi *et al*., 2017), lowering the pesticide residues (Sarangapani *et al*., 2016).

CONCLUSION

A non-thermal food processing technique is well known as cold plasma innovations. The uses are enthused with responsive gases to inactivate contaminating microorganisms and antagonistically extend the timeframe of food products. Cold plasma technology can be applied to a wide range of food as they an effective and flexible antimicrobial process. Since, consumer preference shifted towards healthy and tasty foods that are easily available, ready to eat and easily stored. Cold plasma technology plays a challenging role in food industries for the distribution and mass production of foods without affecting their texture, flavor and colour and it is technically complex and expensive.

Future studies

More research is needed in the field of the beverage industry specifically on sports drinks, naturally fortified drinks *etc*. The effect of cold plasma on such beverages on its organic molecules and its bioactive compounds needs to be extensively studied. One most important research on the conversion of ocean water into drinking water also can be attempted by using cold plasma.

Conflict of interest

All authors declare that they have no conflicts of interest.

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