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Review Article

Non-thermal plasma applications on fruits and fruit juices

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Cold plasma (CP) is an advanced, non-thermal plasma processing technology with significant potential for preserving fruits and fruit juices. Recent research shows that CP processing has attracted attention in fruit processing and storage. The inactivation of microorganisms and extended shelf life of fruits by CP treatment is influenced by several factors, including the type of plasma reactor, discharge power, treatment time, and the inert gas used. This review highlights how CP can effectively extend the shelf life of fruits, eliminate harmful bacteria and maintain the nutrients, flavour, and colour of the fruits and fruit juices. Unlike conventional high-temperature treatments, CP uses low temperatures to keep fruits fresh and safe without causing damage to quality. Additionally, the study describes various plasma systems, their principles of operation, and their applications in the fruit processing industry. Overall, non-thermal plasma demonstrates significant potential in ensuring the safety and freshness of fruits and fruit juices while meeting consumer demands for high-quality products.

Keywords: *cold plasma, plasma reactor, self life, quality, preservation, fruit juices*

Introduction

The fourth state of matter, known as plasma, consists of ionized gas made up of molecules, atoms, electrons, and ions, making up most of the observable universe. Plasma technology is widely utilized to enhance various properties in several fields, including materials processing like printing and adhesive properties of polymers, semiconductor manufacturing, display technology, printed circuit board, plasma-enhanced chemical vapour deposition, surface treatments to increase functionalization, thin film deposition, surface coating and cleaning, medical applications, agricultural applications, environmental remediation, wastewater treatment, air pollution control, aerospace and defence, energy production, nuclear fusion, lasers, lighting etc. Cold plasma (CP), also known as low-temperature atmospheric pressure plasma or non-thermal plasma, consists of charged and neutral particles, including free radicals and ions (Kong & Deng, 2003). Cold plasma technology operates at or near room temperature, unlike most plasmas, which can reach temperatures of hundreds of degrees Celsius (Angela et al., 2009). Cold plasma is an effective, versatile, and promising technology that has captured the attention of experts worldwide (Chizoba Ekezie et al., 2018). This technology plays a crucial role in enhancing performance and functionality across various industries. Many researchers have explored the numerous commercial and biological applications of cold plasma technology, including food purification, sterilisation of dental and medical equipment, and the elimination of surface and airborne pathogens (Niemira, 2012). Over the past five years, plasma technology has become widely adopted as a powerful processing method, extending its applications to the fruits, vegetables, and food industries.

It has been shown that non-thermal plasma can be used in fruits for surface microbial inactivation, decontamination, reduction of pathogens and quality enhancement through improved sensory properties and preservation of nutritional

value (Misra et al., 2011), enzyme inactivation, and packaging applications for enhanced food safety and improved product quality (Misra et al., 2016), pesticide removal (Misra et al., 2015), food quality improvement, fruits (Wang et al., 2025) and fruits juices (Panklai et al., 2025) curing of meat, and wastewater treatment (Sarangapani et al., 2016).
Experts have investigated the use of cold plasmas on fruits and found that they can effectively disinfect certain microbes, including *Salmonella Typhimurium, Escherichia coli,* and *Listeria monocytogenes* (Ziuzina et al., 2015). By inactivating harmful and spoilage microorganisms with cold plasma, it is possible to extend the shelf life of food products while reducing processing time (Pankaj et al., 2018). This review aims to provide a concise overview of cold plasma technology, plasma processing, and the quality assessment of fruits and vegetables treated with cold plasma.

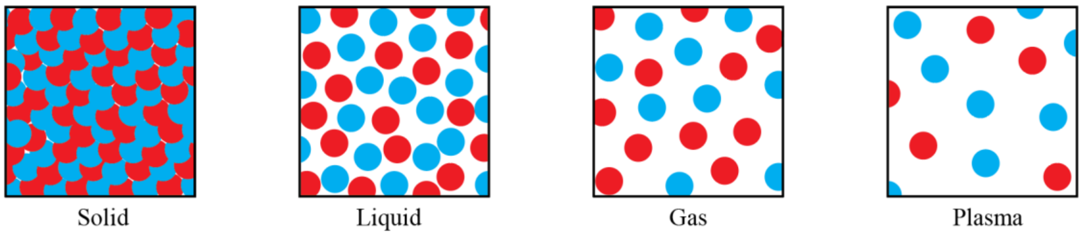

Figure 1. Molecular arrangement in different states of matter

Types of plasma reactors

Plasma can be generated through various methods, each methods have its unique characteristics and applications. Common methods for generating plasma include thermal energy, laser ablation, nuclear reactions, combustion, and various types of electrical discharge such as dielectric barrier discharge (DBD), atmospheric pressure plasma jet (APPJ), plasma needle, microwave discharge, corona discharge, and radio frequency (RF) discharge (Conrads & Schmidt, 2000). These methods increase the kinetic energy of electrons in the gas medium under non-equilibrium conditions, resulting in more collisions and the formation of plasma products. These products include reactive species, charged particles, free radicals, and excited atoms, such as electrons and ions. Additionally, this process generates radiation across a range of wavelengths, including ultraviolet radiation. Both low-pressure and atmospheric pressure can contain cold plasma, which includes low-pressure DC and RF discharges (silent discharges), discharges from fluorescent tubes (such as neon), and dielectric barrier discharges (DBDs) (Rossi et al., 2009). Historically, dielectric barrier discharges (DBDs) were also referred to as "silent discharges". Additionally, it can function at atmospheric pressure, which is normally between 0.1 and 1 atm. A dielectric layer, composed of materials such as glass, quartz, ceramic or polymers, is placed in between the positive and negative electrodes. An alternating current (A.C.) voltage with an amplitude ranging from 1 to 100 kV and a frequency of a few Hz to MHz is applied to the discharge. Plasma can be generated using an electric field that maintains a constant or varying amplitude between positive and negative electrodes along with gas molecules. Direct current (D.C.) glow discharge is created when a potential difference between the cathode and anode is introduced, causing a continuous current to flow through the discharge. The food industry's system is subject to harsh conditions due to non-thermal gas discharges at atmospheric pressure.

Applications of cold plasma on fruits

According to Wang et al. (2012) *Salmonella*-contaminated cucumber, carrot, and pear slices were decontaminated by using direct-current atmospheric-pressure cold plasma. Over 60% of the Salmonella on cucumber slices were inactivated, while 90% of the bacteria on carrot slices were inactivated in less than one second. Whereas the bacteria on cucumber and pear slices were inactivated by over 80% after just one second of treatment. Moiseev et al. (2014) discovered that strawberries can be treated with atmospheric cold plasma created in an airtight container with 42% relative humidity. The cold plasma was generated using a 60 kV dielectric barrier discharge (DBD) pulsed at 50 Hz across a 40 mm electrode gap. The researchers found that after a five-minute treatment, the levels of aerobic mesophilic bacteria, yeast, and mold on the strawberries were reduced by two log10 units after 24 hours following the atmospheric cold plasma treatment. Tappi et al. (2016) demonstrated that plasma treatment extends the shelf life and preserves the quality of melons when they are exposed to plasma for approximately 15 to 30 minutes. Research on blueberries exposed to cold plasma treatment has shown more effective against aerobic bacteria. The treated samples of the blueberries were analyzed for yeast, molds, and total aerobic plate counts. A reduction of 0.8 to 1.6 log CFU/g and 1.5 to 2.0 log CFU/g was observed compared to the control after 1 and 7 days, respectively (Lacombe et al., 2015). In a study, kiwifruit was treated for 10 or 20 minutes and stored for four days. Results showed that plasma treatments improved color retention and reduced dark spots, while the texture remained unchanged. Although there was a slight initial loss of pigments, they were better retained over time. Antioxidant activity and content were similar between the treated samples and the control group (Ramazzina et al., 2015).

Cold plasma generated in a sealed container via dielectric barrier discharge was used to extend the shelf life of cherry tomatoes by reducing respiration rates (Misra et al., 2014). Weight loss and respiration were monitored, and at the end of storage, treated tomatoes showed differences in weight loss, pH, and hardness compared to the control group. The study concluded that cold plasma effectively decontaminates cherry tomatoes while preserving their quality. Park et al. (2017) discovered that microwave-integrated cold plasma treatments effectively reduced the levels of *Bacillus cereus, Aspergillus brasiliensis,* and *Escherichia coli* spores in onion powder. Specifically, the treatment achieved a reduction of 2.1 log spores/cm² for *Bacillus cereus*, 1.6 log spores/cm² for *Aspergillus brasiliensis*, and 1.9 CFU/cm² for *Escherichia coli* after 40 minutes of exposure to the plasma treatment. The atmospheric cold plasma was utilised to inactivate Salmonella Sp. on grape tomatoes (Min et al., 2019). Tomatoes were packaged in polyethene bottles and they were treated with cold plasma for three minutes at 35 kV and 1.1 A. This treatment effectively inactivated Salmonella ($p < 0.05$) without altering the hardness or colour of the grape tomatoes.

Applications of cold plasma on fruits and fruit juices

Almeida et al. (2015) studied the effects of ozone and plasma treatments on preserving the quality of prebiotic orange juice. In their study, the juice was exposed to a 70 kV plasma field both directly and indirectly for different treatment durations—15, 30, 45, and 60 seconds—and varying ozone loads (0.057, 0.128, and 0.230 mg/O_3 per ml of juice). The researchers found that, unlike plasma processing, ozone treatment resulted in a greater reduction in the concentration of oligosaccharides in the juice. Bursać Kovačević et al. (2016) examined the effects of cold atmospheric gas phase plasma on the anthocyanins and colour of pomegranate juice. The study monitored the gas flow, the volume of juice treated, and the duration of treatment. The findings revealed that the highest stability of anthocyanins, which ranged from 21% to 35%, was achieved with a sample volume of 4 cm³, a gas flow rate of 0.75 dm³/min, and a treatment time of 3 minutes. Additionally, the results indicated that plasma treatment positively influenced both the stability of the anthocyanins and the colour change of the hazy pomegranate juice. Pankaj et al., (2017) proved the potential of using high-voltage atmospheric cold plasma as an alternative treatment for white grape juice instead of the traditional thermal pasteurization method. They concluded that applying cold plasma to grape juice for about 4 minutes at 80 kV potentially reduced the concentration of *Saccharomyces cerevisiae* by 7.4 log10 cfu/mL, without significantly altering the juice's quality such as pH, electrical conductivity and acidic content.

In contrast to untreated chokeberry juice, Bursać Kovačević et al. (2016) found that plasma treatment resulted in higher levels of hydroxycinnamic acids. However, there was a 23% reduction in anthocyanins, along with significant alterations in flavonols after exposure to cold atmospheric gas phase plasma. Rodríguez et al. (2017) investigated the indirect effects of cold plasma treatment on cashew apple juice. They found that this treatment increases the levels of vitamin C, polyphenols, and flavonoids, along with enhancing antioxidant activities. However, overexposing the juice to plasma treatment led to a decrease in most bioactive compounds. Xu et al. (2017) observed that high-voltage atmospheric cold plasma treatment positively affects the inactivation of *Salmonella enterica* and *Serovar Typhimurium* in orange juice. They optimized the inlet gas molecules such as air or a mixed gas of 65% O_2, 30% N_2, and 5% CO_2. The results showed that mixed air is more effective than normal air in inactivating the microbes. Herceg et al. (2016) found that the total phenolic content of the plasma-treated pomegranate juice increased from 29.55% to 33.03%. Song et al. (2015) investigated the effects of cold plasma on extending the shelf life of fresh lettuce and preventing food-borne infections. To suppress *Salmonella Typhimurium* and *Escherichia coli*, they treated samples with cold plasma using nitrogen, a nitrogen-oxygen mixture, and helium. This treatment resulted in a reduction of both pathogens by up to 2.8 log CFU/g when applying 400 W and 900 W for 10 minutes. Furthermore, the results indicated that this treatment enhanced the microbiological safety of the vegetables without affecting their physicochemical or sensory qualities.

Conclusion

In summary, cold plasma processing has shown significant potential for various applications in fruits and fruit juices. The quality of fruits and fruit juices is essential for consumers worldwide. However, fruit quality often declines due to softening, a common process involving textural changes in plant cell walls. By preventing this softening, fruits can be kept fresher for a longer duration. Cold plasma is a new non-thermal technology that has been employed to preserve the freshness of fruits and their quality. For effective preservation, it is crucial to ensure their physicochemical and microbiological stability. The cold plasma treatment not only guarantees microbiological safety but also extends the shelf life and nutritional value of the fruits. Therefore, cold plasma processing are essential for prolonging the shelf life of fruits and their products while maintaining their inherent qualities and meeting consumer expectations.

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