

Chapter 7

Application of Cold Plasma in Fruits and Vegetables



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Abstract Consumers' demands for fresh fruits and vegetables have been increased over the last decades due to the pursuit of a healthy lifestyle. However, fresh produce are susceptible to microbial contamination, consequently shortening the shelf-life, which poses a challenge to the food industry. Cold plasma with abundant reactive species is considered as a promising decontamination technology against microorganisms. In this chapter, various factors (e.g., processing parameters, microbial characteristics, food properties) affecting the microbial inactivation efficacy of cold plasma were systematically summarized. Additionally, the effects of cold plasma on the quality attributes of fresh produce were provided in detail. The application of cold plasma for the inhibition of endogenous enzymatic activities in fruits and vegetables was also introduced. Furthermore, the existing challenges for the application of cold plasma on the fresh produce preservation were also discussed.

Keywords Cold plasma · Fruits and vegetables · Microbial inactivation · Food quality · Endogenous enzyme

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7.1 Introduction

Fruits and vegetables, as the major source of nutrients, vitamins, and fiber, have become an indispensable part of the total dietary structure of human beings. It is found that adequate daily intake of fresh fruits and vegetables could decrease the risks of cardiovascular diseases (Oyebode et al. 2014) and cancers (Boffetta et al. 2010). Microbial contamination and spoilage are the major concern in fresh fruits and vegetables. In China, the vegetable output is increased at a rate of 1.7% each year and it has reached more than 90 million tons in 2019. However, the proportion of vegetables rotting caused by microbial contamination was as high as 12%, leading to significant economic losses and risks in food safety (Lung et al. 2015; Mari et al. 2016). Additionally, the poor hygiene could also result in cross-contamination (Fernandes et al. 2019). The European Food Safety Authority issued guidance that identified five major risk factors in the contamination of berries: (i) environmental factors (climatic and proximity to animal farming); (ii) contact of the animal with berry fields; (iii) use of contaminated manure or compost during production; (iv) contaminated water used for irrigation, application of agricultural chemicals (e.g., fungicides), or washing; and (v) contamination and cross-contamination among equipment, food handlers, and harvesters (Patange et al. 2019).

Chemical sanitizers, especially chlorine-based products, have been widely used for the microbial decontamination of fresh fruits and vegetables. However, the potential risks in the formation of harmful chlorinated organic compounds cause concerns about human health and environment. Thermal treatment is very effective in microbial inactivation, but it could compromise the nutrients and qualities of food. To overcome these issues, novel technologies have been developed to control microbial contamination without affecting phytochemicals and sensory properties (Bilek and Turantaş 2013; de São José et al. 2014; Lung et al. 2015), including irradiation (Kong et al. 2014), UV light (Liu et al. 2015), high hydrostatic pressure (Sarvikivi et al. 2012), ultrasound (Aday et al. 2013), and more recently cold plasma (Mir et al. 2019). Cold plasma has been successfully applied for the microbial decontamination of fresh produce (Sarangapani et al. 2018). The bactericidal efficacy of cold plasma is influenced by various factors, including voltage, frequency, gas type, and exposure time (Misra et al. 2016). This chapter aims to provide a comprehensive understanding of the application of cold plasma for the preservation of fruits and vegetables, including the factors affecting microbial inactivation efficacy, the effect on food quality, and the future challenges.

7.2 Inactivation Efficacy of Microorganisms on the Surface of Fruits and Vegetables

As commonly known, cold plasma is an active ionized medium sustained by a constant energy supply under ambient pressure and room temperature. Cold plasma treatment is suitable for heat-sensitive and/or vulnerable objects, such as organic materials, fresh produce, liquids, and living biological tissue (Stoffels et al. 2008). The main active components in plasma are as follows:

1. Charged particles (electrons and positive and negative ions).
2. Free radicals (dissociated molecules).
3. Stable conversion products (e.g., ozone).
4. Excited (metastable) atoms and molecules.
5. Energetic photons (e.g., UV).

7.2.1 DBD Plasma

As shown in Fig. 7.1a dielectric barrier discharge (DBD) is produced from a large-space uniform discharge with a glow discharge under the atmospheric pressure and wide frequency ranging from 50 Hz to 1 MHz (Bovi et al. 2019). DBD has been used for the surface decontamination of fresh produce in a closed space or fluidized bed. The factors affecting the inactivation efficacy include the type of food produce,

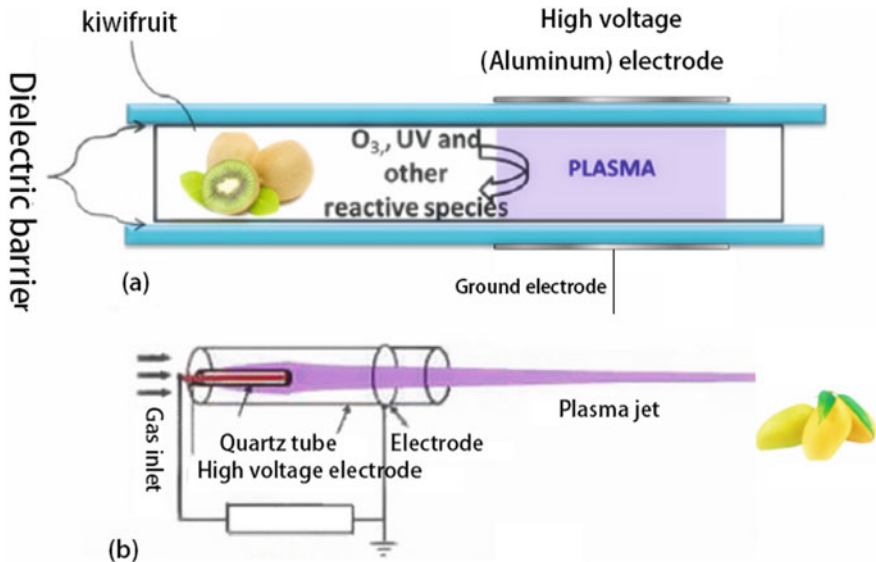


Fig. 7.1 Two main generation modes of cold plasma used in preservation: (a) DBD and (b) APPJ

inherent surface characteristics, microbial characteristics, attachment strength, exposure time, discharge powers, gas flow rate, electrode shape, and the diffusion capacity of various plasma species. Generally, longer exposure time and higher applied voltage or power result in higher antimicrobial capacity of cold plasma (Ziuzina et al. 2014; Zitong et al. 2020). Regarding microbial characteristics, Ziuzina et al. (2015) found that an in-package DBD treatment for 30 s could achieve 7 log reduction of planktonic *Salmonella Typhimurium*, *L. monocytogenes*, and *E. coli* in lettuce broth, while 300 s exposure was required to reduce biofilm populations by 5 log CFU/ml. Pasquali et al. (2016) made use of DBD plasma system with a dominant frequency of 12.5 kHz and found that *E. coli* O157:H7 inoculated on radicchio leaves was significantly reduced after 15 min cold plasma treatment (1.35 log MPN/cm²), while it took longer exposure time (30 min) to achieve a significant reduction of *L. monocytogenes* counts (2.2 log CFU/cm²). Therefore, the affecting factors should be carefully optimized to achieve efficient inactivation by DBD (Pasquali et al. 2016; Timmons et al. 2018; Ziuzina et al. 2014; Zhou et al. 2019).

7.2.2 Plasma Jet

Plasma jet is capable of producing cold plasma in an open space rather than in interstitial space (Matsusaka 2019). High intensity of reactive species generated from the plasma jets react with microorganisms, as shown in Fig. 7.1b. Ziuzina et al. (2014) found that plasma jet treatment for 10, 60, and 120 s resulted in the reduction of *Salmonella*, *E. coli*, and *L. monocytogenes* populations on the tomatoes to undetectable levels from initial populations of 3.1, 6.3, and 6.7 log CFU/sample, respectively. It is found that *Cladosporium fulvum*, a common pathogen on tomatoes could be significantly inactivated by an atmospheric pressure plasma jet (APPJ) (Lu et al. 2014). APPJ treatment resulted in a 40% reduction of *Pectobacterium carotovorum* subsp. *carotovorum* (*Pcc*) compared to untreated samples (Go et al. 2020). Perni et al. (2008) found that the inactivation ability of plasma jet was different for various bacterial strains. It was reported that *P. agglomerans* and *G. liquefaciens* on both mango and melon were reduced below the detection limit (corresponding to 3 log values) after only 2.5 s plasma jet exposure, whereas *E. coli* and *S. cerevisiae* required over 5 s to reach the same level of inactivation. Additionally, the surface characteristic of treated fruits is also an important factor affecting the microbial inactivation efficacy of plasma jet (Bhide et al. 2017; Fernandez et al. 2013). Fernandez et al. (2013) demonstrated that a 2-min APPJ treatment resulted in a 2.71 log reduction of *S. Typhimurium* on membrane filters whereas a 15-min treatment was necessary to achieve 2.72, 1.76, and 0.94 log reductions on lettuce, strawberry, and potato, respectively. Scanning electron microscopy revealed that the topographical features of lettuce, strawberry, and potato protected *S. Typhimurium* cells from the attack by the active plasma species.

7.3 Effects of Cold Plasma on the Quality Attributes of Fruits and Vegetables

Food quality is the important factor affecting consumers' choices, such as color, texture, shape, and size. Thus, the effect of cold plasma on the quality of fruits and vegetables should be carefully evaluated (Tournas and Katsoudas 2005).

7.3.1 Color and Texture Characteristics of Fruits and Vegetables Influenced by Plasma Treatment

So far, a lot of studies have evaluated the changes in color and texture characteristics of fruits and vegetables (Lacombe et al. 2015; Min et al. 2018; Misra et al. 2014a, b). Lacombe et al. (2015) found that APPJ treatments for over 60 s could result in significant reductions in the firmness as well as the color characteristics of blueberries. Comparing with APPJ, DBD resulted in no significant changes in color of blueberries (Sarangapani et al. 2017). Similarly, Misra et al. (2014a) applied an air DBD plasma for the in-package decontamination of strawberries and found no significant impact on the color and firmness. DBD plasma has lower working temperature, which could further avoid the thermal damages on the qualities of fruits. It was reported that the DBD plasma resulted in efficient inactivation of *Salmonella* in grape tomatoes without changes in color or texture (Min et al. 2018). A microwave-driven air plasma torch was used for the indirect treatment of whole pieces of fruits and vegetables in a remote exposure chamber for up to 10 min. The results indicated that the color of tomatoes and carrots and the chlorophyll of cucumbers were severely affected, whereas the elasticity remained almost unaffected in all produce (Baier et al. 2015).

7.3.2 The Effect of Plasma Treatments on the Nutrients of Fruits and Vegetables

Fruits and vegetables are considered as the major source of dietary nutrients. The effect of plasma treatments on the nutritious properties of fruits and vegetables has also been evaluated by researchers (Misra et al. 2015; Rana et al. 2020; Sarangapani et al. 2017). Misra et al. (2015) found that DBD treatment caused minor degradation of ascorbic acid and anthocyanin in strawberries. In addition, DBD plasma treatments were also found to decrease the ascorbic acid levels of whole strawberries and blueberries (Misra et al. 2014a, b; Sarangapani et al. 2017). However, it is demonstrated that DBD plasma treatment could increase the concentrations of sugar, vitamin C, and total anthocyanin of blueberry by 1.5-fold, 2.2-fold, and 79.3%, respectively compared with those in the control groups (Dong and Yang 2019). The

total phenol and flavonoid contents were found to be enhanced significantly in DBD-treated blueberries (Sarangapani et al. 2017), and the concentrations of chlorogenic acid, hyprin, phloretin, vanillin, gallic acid, 4-hydroxybenzaldehyde, and rutin were also enhanced in plasma-treated blueberries during 5-day in-package storage compared with the control ones (Rana et al. 2020).

7.3.3 The Effect of Plasma Treatments on the Quality Characteristics of Fruits and Vegetable Juices

Recently, cold plasma has been reported for the preservation of fresh juices, which can maintain the nutritional and sensory attributes. Silveira et al. (2019) used cold plasma to treat whey beverages and the results indicated that plasma treatment contributed to enhanced pH values and lower viscosity of the whey beverages. Garofulić et al. (2015) applied an atmospheric pressure plasma to treat sour cherry Marasca juice, and it was found that the concentrations of anthocyanins and phenolic acids were enhanced compared to thermal pasteurized and untreated juice. Herceg et al. (2016) evaluated the effect of plasma on the phenolic content of pomegranate juice. Pasteurization at 80 °C for 2 min and argon plasma treatment resulted in an increase in the total phenolic content of pomegranate juice by 29.55% and 33.03%, respectively. The increase in anthocyanins and phenolic compounds is attributed to the rupture of the cell walls. Cold plasma was also found to pose a positive effect on the bioactive compounds of fruit juices. Kovačević et al. (2016) evaluated the effect of an argon plasma jet on the anthocyanins of pomegranate juice and the results indicated an increase in anthocyanin content from 21% to 35%. Fernandes et al. (2019) reported that APPJ exposure enhanced the concentrations of hydroxycinnamic acids, and resulted in a 23% loss of anthocyanins in Chokeberry juice. It is found that cold plasma with a high voltage resulted in a decrease in total phenols, total flavonoids, DPPH free radical scavenging, and antioxidant capacity of grape juice as the thermal pasteurization did (Pankaj et al. 2017). de Castro et al. (2020) reported that corona discharge plasma technology promoted the concentration of ascorbic acid and monomeric anthocyanins in the juice, while the activity of peroxidase and polyphenol oxidase were reduced after treatment.

7.3.4 The Effect of Plasma Treatments on the Quality Characteristics of Fresh-Cut Fruits and Vegetables

Microbial contamination could lead to compromise in color and flavor, aging, softening, and deterioration of fresh-cut fruits and vegetables (Olaimat and Holley 2012). Cold plasma can be an alternative to thermal blanching for the enzyme inactivation and microbial decontamination (Fig. 7.2a) (Huang et al. 2017). A direct

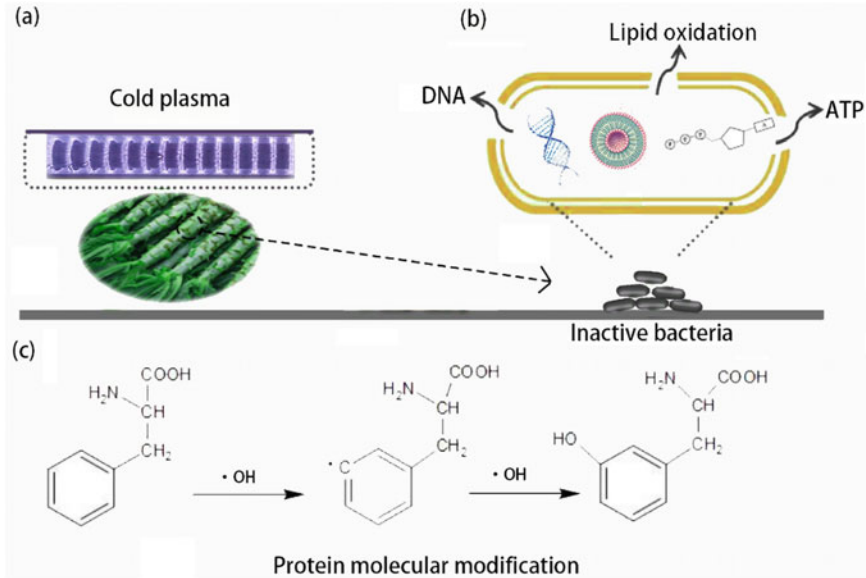


Fig. 7.2 (a) The principles of cold plasma for the preservation of fruits and vegetables, (b) the microbial inactivation mechanisms of cold plasma, and (c) the cold plasma-induced molecular modification in enzymes

current, atmospheric-pressure air cold plasma microjet was applied to treat the slice surface of cucumbers, carrots, and pears. And the water content, color parameters, and vitamin C content were found to be minimally affected by plasma treatment (Wang et al. 2012). Using a DBD plasma reactor operating with air resulted in insignificant changes in the antioxidant activity of radicchio leaves (Pasquali et al. 2016). Similarly, Ramazzina et al. (2015) evaluated the effect of DBD plasma treatment on the quality of fresh-cut kiwifruit. It is found that plasma treatment caused a slight loss of pigments, but brought in better quality retention during storage. No significant changes in antioxidants content and antioxidant activity were observed between the treated samples and control ones. Recent studies found that microwave plasma treatment increased the total phenolic content and antioxidant activity of the peel of mandarins (Won et al. 2017). A combination of green tea extract and atmospheric RF plasma jet was used for the decontamination of the fresh-cut dragon fruits, resulting in higher levels of total phenolic content, proteins, and fiber (Matan et al. 2015).

7.3.5 The Effect of Plasma Treatments on the Enzymatic Inactivity of Fruits and Vegetables

The endogenous enzymes could contribute to the enzymatic browning of fruits and vegetables. Some studies found the potential application of cold plasma for enzymatic inactivation to inhibit the browning process (Bußler et al. 2017; Han et al. 2019; Tappi et al. 2016) (Fig. 7.2b). Han et al. (2019) used an APPJ to treat Horseradish Peroxidase (HRP) and found that the residual activity of HRP was decreased to around 17% with the structure destruction and microstructure deformation. Bußler et al. (2017) employed a microwave plasma torch for the efficient inactivation of PPO and POD activities of fresh-cut apples and potatoes. They reported that the PPO activity was reduced by about 62% and 77% in fresh-cut apple and potato tissue, respectively, after 10 min treatment. Similarly, the POD activity was reduced by about 65% and 89% in fresh-cut apples and potatoes, respectively, after 10 min plasma treatment. Tappi et al. (2014) applied DBD plasma to treat fresh-cut apples for 10, 20, and 30 min and found that the PPO residual activity was reduced linearly as the treatment time increased (up to about 42%). Similarly, Tappi et al. (2016) reported a decrease in the activity of PME and POD in plasma-treated fresh-cut melon.

7.4 Challenges of Cold Plasma in the Fresh Preservation Area

Cold plasma has been proven to exhibit a high inactivation efficacy of microorganisms on the surfaces of fresh produces and also to activate partial endogenous enzymes. However, more studies are required to investigate the changes in quality characteristics of plasma-treated produce. The plasma sources, gas compositions, inactivation kinetics, and species interaction between plasma and targets are distinct in various studies, which has been identified as a challenge for researchers, users, and manufacturers. Therefore, the standardization of cold plasma treatment for food processing applications is required in future.

7.4.1 Scale-up for the Industrial Applications of Food Processing

Up to now, cold plasma has been successfully applied in the preservation of fruits and vegetables (Table 7.1). However, most of studies are still in the lab scale. In addition, plasma-activated water (PAW) or in combination with modified atmospheric packaging (MAP) under storage conditions could contribute to the commercial and industrial application (Table 7.1) (Thirumdas et al. 2018).

Table 7.1 The summary of cold plasma for the preservation of fruits and vegetables

Plasma source	Gas type	Frequency	Voltage/ power	Exposure time	Samples	Treatment scale	References
Plasma jet	Ar	20– 600 kHz	20–40 W	60 s	Fresh-cut dragon	3 cm × 3.5 cm	Lacombe et al. (2017)
Plasma microjet	Air	Direct current	500 V/ 15 W	60 s	Cucumber/carrot/pear slices	3 cm × 3.5 cm	Khan et al. (2017)
Cold plasma jet	He, O ₂	30 kHz	12– 16 kV	10–90 s	Mango and melon	Diameter = 1.5 mm	Fulcheri et al. (2015)
Direct plasma jet	Air	RF/ 2.45 GHz	30 W/ 1.2 kW	30 min	Black pepper	Diameter = 8 mm	Stoffels et al. (2008)
Cold plasma jet	Ambient air	47 kHz	549 W	0–120 s	Blueberries	Diameter = 10 mm	Ziuzina et al. (2014)
A diffuse coplanar surface DBD	Dry air/O ₂ /N ₂ , CO ₂ , and CO ₂ -Ar	15 kHz	20 kV/ 350 W	15 min	Almonds	200 mm × 80 mm	Mari et al. (2016)
A novel DBD ACP device	Air	50 Hz	120 kV	30–300 s	Cherry tomatoes, strawberries	Container of 310 × 230 × 40 mm	Cui et al. (2016)
DBD	Air, 60%RH	12.5– 91 kHz	15 kV	15– 30 min	Radicchio, paprika	3 × 10 ⁻² m ³	Agun et al. (2020)
DBD plasma discharge	Air		36 V/ 6 W	0–10 min.	Blueberry	Diameter = 9 cm	Lung et al. (2015)
A surface DBD	Ambient air	3.0 kHz	6–12 kV	1–10 min	Pea seeds	Pea seeds, D = 100 mm	Bovi et al. (2019)
A submerged DBD plasma	N ₂	20 kHz	18 kV	10 min	Sliced onion	3 × 3 cm	Lafarga et al. (2019)
Microwave plasma	He, O ₂	2.45 GHz	50– 1000 W	20 min	Red pepper flake	3 × 1.5 cm	Vardar et al. (2012)
Microwave-driven plasma torch	Air	2.45 GHz	1.2 kW	10 min	Apples, cucumbers, toma- toes, and carrots	Chamber of 40 × 30 × 30 cm	Bilek and Turantaş (2013)

7.4.2 *Market Acceptance from Consumers*

With the development of food information traceability technology, the circulation process of fresh food in the whole industry chain will be monitored (Zoroja et al. 2017). For successful adoption and acceptance of a novel processing technology, it is essential to understand the needs of consumers and their recognition of the new technologies. So far, limited data has been available on the large-scale consumers' sensory evaluation of plasma-treated food, such as color, texture, odor, and surface oxidation.

7.5 Conclusions

Cold plasma is an emerging technology for the preservation of fruits and vegetables, which has attracted much attention from producers, researchers, and consumers in recent years. Cold plasma treatment could efficiently inactivate microorganisms while maintaining nutrition and quality attributes of fresh produce. There are various factors affecting the antimicrobial efficacy of cold plasma, such as exposure time, gas type and flow rate, microbial strains, the surface characteristics of treated fruits or vegetables, and so on, which should be carefully evaluated to achieve efficient microbial removal. Additionally, it is found that cold plasma could preserve fresh-cutting slices and fresh-squeezed juices through the inactivation of endogenous enzymatic activities. Further research works are required to explore the effect of cold plasma on the food quality characteristic, the large-scale equipment as well as the consumers' acceptance of plasma-treated food.

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