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INVESTIGATION OF THE POTENTIAL APPLICATIONS OF COLD PLASMA TECHNOLOGY IN FOOD SAFETY

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ABSTRACT
Nowadays, the demand for the consumption of healthy foods is increasing day by day. Although fruits, vegetables, and foods made from them come first among these foods, meat and meat products are of great importance. However, there have been reports of food poisoning from such meals. Furthermore, problems are encountered in exports due to the microbial load of many such products. Different chemicals are used to reduce the microbial load of these products. However, due to the residue, these compounds are not utilized in many countries. Therefore, different methods are being investigated, and new technologies are being developed. Hydrostatic pressure, ultrasound, pulsed electric fields, irradiation, and pulsed light are some of these technologies. The purpose of this review is to investigate the possibilities of using the cold plasma system, which is one of these technologies, for the sterilization of foods. In simple terms, cold plasma is the fourth state of matter and is defined as a gaseous composition of ionic gas, polar ions, and gas atoms produced under atmospheric or low-pressure conditions. In addition to the many advantages of cold plasma, it has the possibility of being used for different purposes. Besides surface disinfection and detoxification, it is also used in the sterilization of packaged products, fresh fruits and vegetables, liquid foods, and meat and meat products.
Keywords: Cold plasma, non-thermal technology, food safety, sterilization, new technology

SOĞUK PLAZMA TEKNOLOJİSİNİN GIDA GÜVENLİĞİ ALANINDAKİ POTANSİYEL UYGULAMALARININ ARAŞTIRILMASI

ÖZ
Günümüzde sağlıklı gıdaların tüketimine yönelik talep giderek artmaktadır. Her ne kadar bu gıdaların başında meyve, sebzeler ve onlardan yapılan gıdalar gelse de et ve et ürünlerinin de önemi büyük olmaktadır. Ancak bu gıdalardan meydana gelen gıda zehirlenme vakaları bulunmaktadır. Ayrıca pek çok ürünün mikrobiyal yükü sebebinden dolayı ihracatta sorunlar ile karşılaşılmaktadır. Bu ürünlerin mikrobiyal yükünün azaltılması için farklı kimyasallar kullanılmaktadır. Ancak bu kimyasalların bıraktıkları kalıntı sebebi ile pek çok ülkede kullanılmamaktadır. Dolayısıyla farklı yöntemler araştırılıp yeni teknolojiler geliştirilmektedir. Bu teknolojilerden bazıları hidrostatik basınç, ultrases, vurgulu elektrik alan, ışınlama ve vurgulu ışık gibi yöntemlerdir. Bu derlemenin amacı ise bu teknolojilerden biri olan soğuk plazma sisteminin gıdaların sterilizasyonu amacı ile kullanım olanaklarının

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araştırılmasıdır. Basit bir ifadeyle, soğuk plazma maddenin dördüncü hali olup atmosferik veya düşük basınç koşulları altında üretilen iyonik gaz, polar iyonlar, gaz atomlarından oluşan gaz bileşimi olarak tanımlanabilmektedir. Soğuk plazmanın pek çok avantajı bulunmasının yanı sıra, farklı amaçlar için kullanım olanağı da bulunmaktadır. Yüzey dezenfeksiyonu ve detoksifikasyonun yanı sıra ambalajlı ürünlerin, taze meyve ve sebzelerin, sıvı gıdaların, et ve et ürünlerinin sterilizasyonunda da kullanılmaktadır.
Anahtar kelimeler: Soğuk plazma, ısıl olmayan teknoloji, gıda güvenliği, sterilizasyon, yeni teknoloji

INTRODUCTION

In the globalizing world, satisfying customer needs, responding to expectations, and food safety, which concerns human health, are the main topics that come up (Dalgıç, 2021). Thermal inactivation has traditionally been applied to protect food safety. However, thermal inactivation methods may have negative effects on components such as color, taste, and aroma. In recent years, foods to which non-thermal methods are applied have gained economic importance depending on the combination of factors such as ease of use, nutritional value, desired sensory properties, and environmental friendliness (Korkmaz and Gündüz, 2018, Dinçer and Topuz, 2018, Bhatt et al., 2018). For all these reasons, studies on cold plasma applications, which is a sustainable technology among non-thermal methods, have increased (Gündüz and Kışla 2014; Göçmen et al., 2017, Yüksel and Karagözlü, 2017). Cold plasma technology provides microbial inactivation, does not cause significant changes in the structure of food, and its applicability for safe food production is being investigated (Fernandez et al., 2013, Bozkurt, 2014, Şen, 2015, Fıratoğlu, 2015, Daşan, 2016, Aktop, 2016, Devi et al., 2017, Kim and Min, 2018, Mehta et al., 2019). Cold plasma can be formed by many methods in terms of characteristics and applications. Some of these methods can be counted as dielectric barrier discharges (DBD), atmospheric pressure plasma jets, radio frequency and microwave plasmas (Scholtz et al., 2015, Keskin, 2017). The environmental friendliness of cold plasma technology increases its potential applications (Yüksel and Karagözlü, 2017). For the creation of plasma, environmental parameters such as pressure are important. However, depending on the plasma device, plasma may be generated in a variety of pressure conditions. It is still preferred in some applications due to the ease of forming plasma in a low pressure environment. However, although plasma formation under atmospheric pressure can be performed under higher voltage, it is preferred because of the advantages it provides in terms of applicability to industry. This study was conducted to investigate the possibilities of using the cold plasma system, which is an alternative method to reduce the microbial load in foods, and to be a source for researchers.

COLD PLASMA TECHNOLOGY

There are different methods for generating plasma. Some of the most commonly used ones for sterilization of foods can be categorized as dielectric barrier discharge (DBD), plasma jet (PJ), radio frequency (RF), and microwave (MW).

DIELECTRIC BARRIER DISCHARGE (DBD)

The DBD plasma consists of two metal electrodes, one or both of which are coated with a dielectric material such as polymer, glass, quartz, or ceramic (Fig.1). By applying high voltage, cold plasma is formed in this device, which has a changeable gap ranging from 0.1 mm to a few centimeters (Kogelschatz, 2003, Chizoba et al., 2017). Commonly used gases in DBD plasma are atmospheric air, nitrogen, argon and helium (Kim et al., 2018, Srangsomjit et al., 2022, Roy et al., 2023). Furthermore, this system is one of the most suitable forms of plasma production due to the dielectric material configuration and flexibility used (Ziuzina et al., 2013).

PLASMA JET (PJ)

In this system, which has various configurations, the outer electrode is grounded, the central electrode is excited by RF, and the gas flowing at a high flow rate pushes the formed plasma out of the electrode region (Nishime et al., 2017) (Fig.1). This system, which is not suitable for application to a wide area, produces a stable, homogeneous, and smooth discharge at atmospheric pressure (Nehra et al., 2008, Bermudez-Aguirre, 2020).

RADIO FREQUENCY (RF)

Radio frequency plasma is usually obtained by oscillating gas in an electromagnetic field (Fig.1). Radio frequency plasma operating at frequencies between Hz and MHz is produced by an induction coil or different electrodes kept outside the reactor (Ekezie et al., 2017).

Figure 1

MICROWAVE (MW)

Microwave discharges are produced by electromagnetic waves released by a magnetron in microwave plasma generators (Fig. 1). Thus, cold plasma is created in the microwave electric field without electrodes. In this system, where plasma is produced at low and atmospheric pressure, gas requirements are low and generally large quantities of reactive species are released (Thomas and Mittal, 2013, Ekezie et al., 2017).

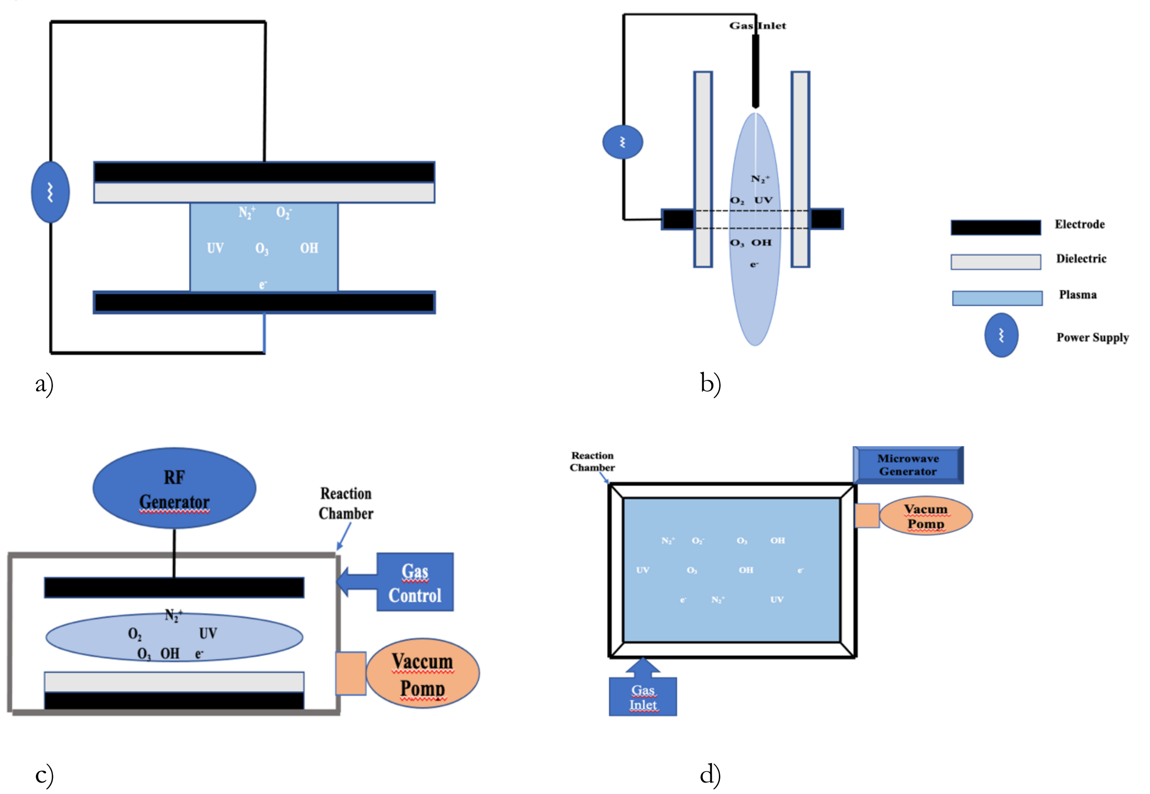

Fig.1. A type of DBD plasma configurations (a), A type of plasma jet configuration (b), A type of Radio Frequency plasma configuration(c), A type of microwave plasma configuration (d)

PENETRATION POWER OF COLD PLASMA

Gelatin gel and agarose gel are commonly employed to investigate the penetration of plasma-induced reactive oxygen species (ROS). It was stated that inactivation depths of up to 3.2 mm were reached with plasma application. It has been reported that the depth of plasma penetration varies depending on both the plasma application time and the type of microorganism (Guo et al. 2020). Yadav et al. (2019) reported that 180 seconds of plasma applied to 2 mm thick slices of ham (1 cm^2) significantly decreased the number of *Listeria innocua* (1.43 log CFU/cm^2). In another study, there was a significant decrease in the total number of aerobic mesophilic bacteria with 60 kV-5 min of cold plasma applied to 1 cm-thick pitaya fruit slices (Li et al., 2019).

Roh et al. (2020), reported that chicken breast samples were boiled for 90 minutes, cut into cubes (1.5 × 1.5 × 1.5 cm), covered with an edible coating (whey protein), and then plasma was applied to the samples for 39 kV-3.5 minutes. In chicken breast samples, the number of E. *coli* O157: H decreased by 3.90, *Salmonella* by 3.70, and *L. monocytogenes* by 3.50 logarithmic units as a result of the application. In a study, *Escherichia coli* inoculated lettuce was placed in different layers and exposed to cold plasma (Min et al., 2017). In their other study, they arranged two tomatoes inoculated with *Salmonella* in a two-layer and then applied cold plasma (Min et al., 2018). In these studies, it was stated that a significant logarithmic unit reduction was achieved in each microorganism due to the spaces between both lettuce and tomatoes. Thus, in future studies, a clearer result could be obtained by applying cold plasma to thicker foods.

THE MECHANISM OF ACTION OF COLD PLASMA IN STERILIZATION

In the cold plasma environment, positive and negative ions, photons, electrons, free radicals, active or unactived molecules and atoms, and their use in combination lead to microbial inactivation (Fig.2) (Moisan et al., 2002, Laroussi, 2005). These reaction species erode cell materials such as the shell lipoprotein on the bacterial cell surface and the inner fat amylase of the cell membrane. Thus, the cell membrane ruptures and the contents flow out, which eventually leads to the death of the bacteria (Miao and Yun, 2011). Several researchers have claimed that UV radiation in the cold plasm ambient causes the splitting of DNA strands by inducing the development of thymine dimers (Laroussi, 2005, Gallagher et al., 2007, Wunderlich and Langowski, 2010, Fernandez and Thompson, 2012). However, other studies suggest that the power density of UV radiation emitted in the cold plasma ambient is very low and does not directly affect the sterilization process (Laroussi and Leipold, 2004, Boudam et al., 2006). It has also been reported that reactive oxygen species were more effective on the outer surface of microbial cells by causing significant oxidative stress conditions, which resulted in cell damage, enzyme deactivation, and DNA rupture (Misra et al., 2011, Pankaj and Keener, 2017). In another study, it was stated that the effect of plasma is largely dependent on the presence of water, with a stronger effect in moist organisms (minute amount of non-liquid water) than in dry organisms (complete drying of a drop with bacteria in a biological hood) (Thirumdas et al., 2015).

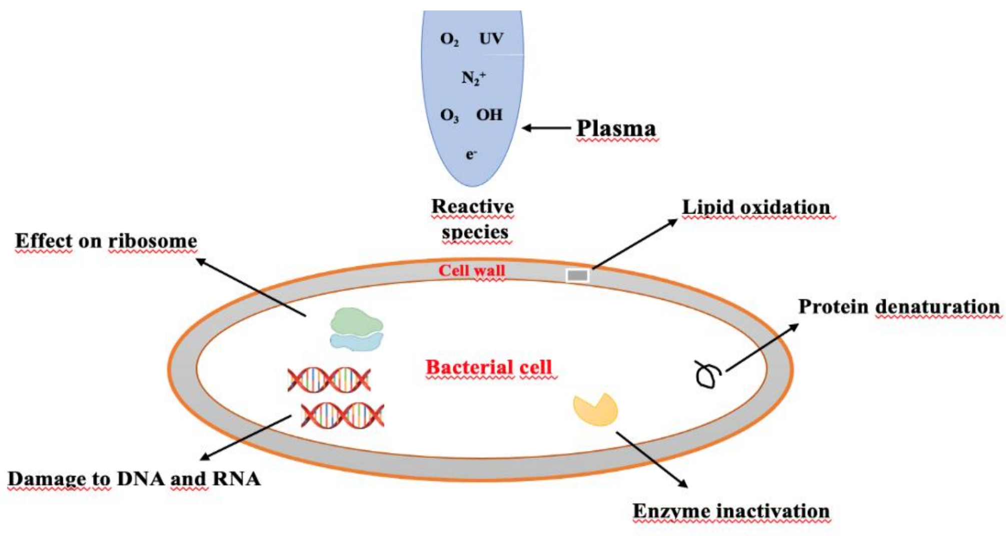

Fig.**2.** Mechanism of microbial inactivation by cold plasma treatment.

THE USE OF COLD PLASMA TECHNOLOGY FOR THE STERILIZATION OF FOODS

Due to the limited depth of penetration of plasma technology, it is considered to be advantageous, especially for foods with a high surface/volume ratio. Hence, microbial decontamination is provided on the product surfaces with the application of plasma, while the low penetration depth prevents the damage of important nutrients in the food (Surowsky et al., 2016). The effects of various cold plasma systems on different products have been investigated (Table 1).

Table 1. The effect of various plasma systems on different products

Plasma type	Food matrix and Microorganisms	Observation	References
Atmospheric Pressure Fluidized Bed Plasma Jet	Hazelnut And Corn (molds and yeasts in the natural flora)	3.84 and 3.45 CFU/g	(Mutlu., 2014)
DBD Plazma	Ground Almond Milk (molds and yeasts)	Below the Determination Limit	(Muhammad et al. 2019).
Atmospheric Pressure DBD	Tomato-Based Beverage (Mold and yeast)	1 log CFU/ml	(Metha et al., 2019)
Low Pressure Plasma with Microwave Power	Red Pepper Powder (Aspergillus flavus)	2.5 CFU/g	(Kim et al., 2014)
Microwave-Assisted Cold Plasma	Onion Powder (Aspergillus brasiliensis spores)	1.6 log spores/cm^2	(Kim et al., 2017),
Radiofrequency Assisted Low Pressure DBD Plasma	Peanuts (Aspergillus brasiliensis)	3.5 log CFU/g	(Pignata et al., 2014)
Atmospheric Pressure Plasma Jet	Hazelnut (Aspergilus parasiticus and Aspergilus flavus spor)	5.6 and 4.7 log CFU/g	(Şen et al., 2019
DBD system with radio frequency power source	Peanuts (Aflatoxin)	%97.9 and %99.3	(Devi et al., 2017)
DBD Plasma	Corn (Aflatoxin)	%62 and %82	(Shi et al., 2017)
DBD Plasma	Hazelnut (Aflatoxin)	%70	(Siciliano et al, 2016)
Microwave-Assisted Atmospheric Pressure Plasma Jet	On the petri dishes (Aflatoxin)	Completely Removed Aflatoxins	(Park et al., 2007)
Cold Atmospheric Plasma (CAP)	Chicken breasts (Pseudomonas aeruginosa)	100 % inactivation efficiency	(Zhao et al., 2022 a)
Atmospheric Cold Plasma	Apple Cider (Acid-adapted E. coli K12)	5 log CFU/mL	(Ozen et al., 2022)
Cold Atmospheric Pressure Plasma	Tiger Nut Milk (Bacillus cereus)	5.28 log CFU/mL	(Muhammad et al., 2019)
Cold plasma jet	On the petri dishes (Pseudomonas aeruginosa)	100 % inactivation efficiency	(Zhao et al., 2022 b)
DBD Plasma	Apple juice (Alicyclobacillus contaminants)	4.5 log CFU/mL	(Wang et al., 2023)

In the literature, there are atmospheric cold plasma applications created with different systems (DBD, plasma jet) (Surowsky et al., 2013, Pankaj et al., 2013, Bozkurt, 2014, Almeida et al., 2015, Kim et al., 2018, Filho et al., 2019, Li et al., 2019, Amanpour et al., 2019). In the studies, enzyme inactivation (Pankaj et al., 2013, Khani et al., 2017, Amanpour et al., 2019, Chutia et al., 2019) and microbial inactivation (Basaran et al., 2008, Mutlu, 2014, Şen, 2015, Fıratoğlu, 2015, Gök et al., 2019) experiments were carried out on different products. For these purposes, cold plasma application has been researched for fresh fruits and vegetables such as tomatoes, spinach, kiwi, strawberries, mango, melon, and tangerines (Niemira and Sites, 2008, Perni et al., 2008, Misra et al., 2014, Ramazzina et al., 2015, Won et al., 2017, Jiang et al., 2017), fruit juices such as orange juice and cherry juice (Almeida et al., 2015, Garofulic et al., 2015), and dried products such as hazelnut, corn, wheat, paprika, black pepper, dried figs, and dried apples (Selçuk et al., 2008, Mutlu, 2014, Lee et al., 2015, Bubler et al., 2017, Choi et al., 2018). When the studies in the literature are examined, there are some studies that determine the effects of cold plasma application on mold and aflatoxin.

As a result of the studies conducted by Mutlu (2014), the use of atmospheric pressure fluidized bed plasma jet reduced the number of molds and yeasts in the natural flora of hazelnut and corn by 3.84 and 3.45 logarithmic units, respectively. As a result of the 12-minute DBD plasma applied to the ground almond milk, it was determined that the total number of molds and yeasts fell below the determination limit (Muhammad et al., 2019). Also, 1 log CFU/ml reduction was achieved in mold and yeast numbers by using the atmospheric pressure DBD system in a tomato-based beverage (Metha et al., 2019).

Aspergillus flavus number decreased by 2.5 log CFU/g in red pepper powder, in which low pressure plasma with microwave power source was applied (Kim et al., 2014). In other studies, in which microwave-assisted cold plasma was applied, 1.6 log spores/cm^2 reduction was achieved in the number of *Aspergillus brasiliensis* spores inoculated into onion powder (Kim et al., 2017), while *Penicillium italicum* in orange peel was reduced by 84% (Won et al., 2017). As for the number of *Aspergillus brasiliensis* inoculated on peanuts, a 3.5 log CFU/g reduction was achieved with radio frequency assisted low pressure DBD plasma application (Pignata et al., 2014). As a result of the application of the atmospheric pressure plasma jet, a decrease of 5.6 and 4.7 logarithmic units was detected in the numbers of *Aspergilus parasiticus* and *Aspergilus flavus* spores inoculated into the hazelnut sample, respectively (Şen et al., 2019).

In apple cider vinegar inoculated with acid-adapted *E. coli* K12, 5 log CFU/mL reduction was achieved as a result of atmospheric cold plasma application (Ozen et al., 2022). In another study, there was a decrease of 5.28 log CFU/ml in tiger nut milk inoculated with *Bacillus cereus* after atmospheric cold plasma application (Muhammad et al., 2019). Also, 4.5 log CFU/ml reduction was achieved as a result of DBD application to *Alicyclobacillus contaminans* inoculated into apple juice (Wang et al., 2023). In another study, the effect of cold plasma on the total bacterial count in sheep milk was compared with that of pasteurization (65 °C ± 2 °C for 30 min). According to this study, cold plasma application for 5 minutes resulted in 1.7 log reduction, while pasteurization resulted in 2.1 log reduction. There was no statistical difference between the two applications (Wang et al., 2022). In addition, after 3 minutes of high-voltage atmospheric cold plasma application, the amount of *Listeria monocytogenes* inoculated Queso Fresco cheese was significantly reduced (Ott et al., 2022). In a study examining the effect of cold plasma on chicken meat samples inoculated with *Staphylococcus aureus*, a 2-log reduction was achieved after 5 minutes of application (Abdel-Naeem et al., 2022). In another study, 100% inactivation was achieved after 5 minutes of cold plasma application to chicken breasts inoculated with *Pseudomonas aeruginosa* (Zhao et al., 2022 a).

With the DBD system, whose power source is radio frequency, 97.9%-99.3% reductions were achieved in the number of aflatoxins in peanuts, in which cold plasma was applied. In the same study, the samples were kept at 30°C for 5 days after the plasma application, and a decrease of 65%–95% was achieved in the amount of aflatoxin B1 production depending on the strength and duration of the plasma application (Devi et al., 2017). While low-pressure cold plasma jet treatment provided a 2 log CFU/g reduction in 10 minutes for aflatoxins inoculated into hazelnut, peanut, and pistachio, it was said that 20 minutes of plasma treatment resulted in a 50% reduction in overall aflatoxin content (Basaran et al., 2008). Another study found that microwave-assisted atmospheric pressure plasma jet treatment for 5 seconds completely removed aflatoxins placed on the slide (Park et al., 2007). When DBD plasma was applied to aflatoxin-added corn sample for 1 and 10 minutes, the amount of aflatoxin was reduced by 62% and 82%, respectively (Shi et al., 2017). Another study found that applying DBD plasma to an aflatoxin-added hazelnut sample reduced it by 70% (Siciliano et al., 2016). In particular, the employment of such technologies in dry foods is of great importance. Because in the dried fruit and vegetable sector, besides thermal processes, non-thermal technologies such as chlorine-based disinfectants, ozonated water, and electrolyzed oxidizing water (EYS) are carried out, in order to reduce the microbial load (Öztekin et al., 2006, May and Fickak, 2007, Zorlugenç et al., 2008). The use of these non-thermal technologies has some disadvantages, such as the product's water intake and subsequent drying requirement. For these reasons, such technologies come to the fore.

CONCLUSION

The demand for healthy nutrition, respect for nature, and therefore green technology is increasing in the world. Due to this awareness among most people, green technologies are gaining more importance. It is known by everyone that the chemicals used in the disinfection of fruits and vegetables leave a residue. Although laws impose restrictions on the use of these chemicals, it is known that they are still used today. However, the new technologies being developed can be an alternative to these chemicals. The cold plasma system is a green technology that is utilized in food safety. Despite having a high initial cost, cold plasma has numerous advantages, such as providing strong sterilization at low temperatures, not affecting the structure of the packaging, working continuously at atmospheric pressure, and not containing chemicals.

Cold plasma is produced by different methods. However, the most commonly used methods in foods are jet plasma, DBD, and cold plasma produced by radiofrequency and microwave. Studies show that these methods can be used for surface disinfection, detoxification, liquid foods, meat, and meat products, as well as the disinfection of packages. When the studies are examined, it is seen that all of the cold plasma methods can be used with both liquid and solid foods. However, there is no clear information about which method is used for which foods. This shows that there are few studies on the penetration power of cold plasma. Although it is thought that the penetration power of the plasma jet is higher than other methods, there is no clear information. For the reasons mentioned above, it is necessary to investigate the possibilities of using this system in the industry.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Janan Hossein Zadeh: investigation, writing-review & editing
Fikret Pazır: investigation, editing & supervising

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