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Impacts of Cold Plasma Treatment on the Food Quality and Safety during Storage

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Abstract: Food quality is critically important for the acceptability of any food product by consumers. This quality consists of a combination of physical, chemical, sensory, and microbiological parameters. To prevent any adverse effects on human health during storage, foods must undergo the necessary processing before reaching consumers. For this purpose, many traditional processing methods are used in the industry. The primary objectives of all these methods are to enhance product quality, ensure food safety, and extend shelf life. However, considering the high temperature and long-duration conditions of traditional processing methods, they negatively impact the nutritional and sensory properties of foods. In this context, non-thermal technologies have recently gained interest in the food industry to minimize the disadvantages of thermal treatments. The impact of novel food processing methods has become an increasingly researched topic in both the literature and the food industry. Cold plasma treatment is a novel non-thermal food processing technology that offers numerous advantages and has attracted significant attention from researchers and the food sector. It is a well-explored, non-destructive technique used in various applications, including preserving or enhancing nutritional and sensory quality, microbial inactivation, and sterilization. Researchers have tested different cold plasma applications on various food products, and the results have been evaluated. Findings indicate that novel methods such as cold plasma, due to their non-thermal properties, are more effective in maintaining the nutritional and sensory quality of the final product during food sterilization while extending shelf life. This review investigates the effects of cold plasma treatment on sensorial quality, nutritional value, and microbial characteristics during the storage of various foods. Based on the study results, it has been concluded that cold plasma is a promising method for the future of the food processing industry.

Keywords: Cold plasma, food quality, food safety, shelf-life extension.

Soğuk Plazma İşleminin Depolama Süresince Gıda Kalitesi ve Güvenliği Üzerindeki Etkileri

Özet: Gıda kalitesi herhangi bir gıda ürününün tüketiciler tarafından kabul edilebilirliği açısından kritik bir önem taşımaktadır. Söz konusu bu gıda kalitesi fiziksel, kimyasal, duyusal ve mikrobiyolojik parametrelerin bütününden meydana gelmektedir. Gıdaların raf ömrü süresince insan sağlığında herhangi bir olumsuz etkiye neden olmaması açısından tüketiciye ulaşıncaya dek gerekli proseslere tabii tutulması gerekmektedir. Bu amaçla endüstride birçok geleneksel işleme yöntemleri kullanılmaktadır. Tüm bu gıda işleme yöntemlerinin temel amacı ürünün kalitesini artırmak, gıda güvenliğini sağlamak ve raf ömrünü uzatmaktır. Ancak bu geleneksel işleme yöntemlerinin yüksek sıcaklık ve süre koşulları göz önüne alındığında gıdaların besinsel ve duyusal özellikleri üzerindeki olumsuz etkilere neden olmaktadırlar. Bu anlamda son zamanlarda, gıda endüstrisinde ısıl işlemlerin dezavantajlarını en aza indirmek amacıyla ısıl olmayan teknolojilerin kullanımı ilgi görmeye başlamıştır ve yenilikçi yöntemlerin gıdalar üzerindeki etkisi literatürde ve gıda endüstrisinde giderek daha fazla araştırılan bir konu haline gelmiştir. Soğuk plazma işlemi, birçok avantaj sunan ve araştırmacılar ile gıda endüstrisinin büyük ilgisini çeken yenilikçi ısıl olmayan bir gıda işleme teknolojisidir. Soğuk plazma prosesi, besinsel ve duyusal kaliteyi koruma veya artırma, mikrobiyal inaktivasyon ve gıda ürünlerinin sterilizasyonu gibi çeşitli alanlarda kullanılan, tahribatsız ve iyi araştırılmış bir gıda işleme tekniğidir. Farklı gıda ürünleri üzerinde çeşitli soğuk plazma uygulamaları araştırmacılar tarafından test edilmiş ve sonuçlar değerlendirilmiştir. Çalışmalardan elde edilen bulgular, soğuk plazma gibi yeni yöntemlerin, ısıl olmayan özellikleri sayesinde gıda sterilizasyonu sırasında nihai ürünün besin ve duyusal kalitesini korumada daha etkili olduğunu ve gıdaların raf ömrünü uzattığını göstermektedir. Bu derleme, soğuk plazma uygulamasının çeşitli gıdaların depolanması süresince duyusal kalite, besin değeri ve mikrobiyal özellikler üzerindeki etkilerini incelemektedir. Çalışma sonuçlarına dayanarak, soğuk plazmanın gıda işleme endüstrisinin geleceği için umut verici bir yöntem olduğu sonucuna varılmıştır.

Anahtar Kelimeler: Soğuk plazma, gıda kalitesi, gıda güvenliği, raf ömrü uzatma.

Review Article

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1.Introduction

Quality is a critical factor in the acceptance of the food product in terms of food characteristics and the perception of consumers (Grunert, 2005). Food quality is composed of physical, chemical, and microbiological parameters, which include sensorial quality parameters (like color, and texture), pH, food enzymes, nutrition, etc. The essential aim of all food processing is to provide food safety, extend the shelf life and enhance the quality of the product (Misra et al., 2016).

Food safety and shelf life have been mainly improved by thermal processing. However, undesirable effects like loss of nutritional and bioactive compounds, and changes in sensory parameters may be induced by heat treatment. Recently, the use of non-thermal technologies has gained interest because of minimizing the disadvantages of thermal treatments in the food industry (Kumar et al., 2023). Cold plasma (CP) treatment is a non-thermal, novel, non-destructive, and well-explored food processing technique that has been utilized in several fields of the food industry, such as retaining or enhancing the nutritional and sensorial quality, microbial inactivation, and sterilizing food products as a substitute for thermal processes. Several studies indicated that quality parameters of products such as color, texture, polyphenols, and flavor showed a significant increase after CP treatment (Ali et al., 2021; Bao et al., 2021; Hou et al., 2019; Illera et al., 2019; Luo et al., 2020; Rodríguez et al., 2017), or had no scientific changes (Gavahian et al., 2020). It was also reported that CP application inactivated *Staphylococcus aureus* (Lee et al., 2015), endospores of *Bacillus atrophaeus* (Schnabel et al., 2012), *Salmonella Typhimurium* (Dasan & Boyaci, 2018), and *Listeria monocytogenes* (Ziuzina et al., 2015).

In the field of food processing, CP technology has been used for microbial decontamination, enzyme inactivation, and the removal of food allergens. Additionally, changes in food components resulting from CP application have also been examined in the literature. In these studies, the effects of CP application on the microbial, nutritional, and sensorial quality properties of food have been investigated, and changes in food quality and shelf life have been evaluated (Pan et al., 2019). This review aims to provide a broader perspective by examining the observed changes in the microbial, nutritional, and sensorial quality properties of food samples subjected to cold plasma technology, as well as the corresponding changes in shelf life. According to the results of studies in the literature, cold plasma application, due to its non-thermal nature, is seen as a promising method for preserving food quality and extending the shelf life of foods compared to conventional methods.

2. Cold Plasma Technology

Cold plasma technology has emerged as a promising non-thermal approach for food decontamination and shelf-life extension. Owing to its non-thermal nature, numerous studies have demonstrated that cold plasma induces minimal or negligible alterations in the physical, chemical, sensory, and nutritional attributes of food products. Compared to conventional processing methods, cold plasma offers distinct advantages, including energy efficiency, design flexibility, environmental sustainability, and cost-effectiveness (Pankaj et al., 2018).

Plasma is generally referred to as an ionized gas, which is the fourth phase of the matter, including various free radicals, reactive species, charged particles, and ultraviolet (UV) radiation (Bourke et al., 2018; Han et al., 2016; Misra et al., 2016). Plasma can be divided into equilibrium (thermal) and non-equilibrium (low-temperature), where the thermal plasma is obtained by heating to gas up to 20000 K for ionization while the low-temperature plasma is provided by heating the gas below 60°C (non-equilibrium plasma) and between 100-150°C (quasi-equilibrium plasma). Thermodynamic equilibrium displays between the species in the thermal plasma, whereas non-equilibrium plasma caused the gas to remain at a low temperature due to more effectiveness of ions and uncharged molecules regarding cooling. Therefore, non-equilibrium plasma is also known as NTP or cold plasma (Misra et al., 2016). The presence of free electric charges, such as electrons and ions, renders the plasma both electrically conductive and highly responsive to electromagnetic fields, thereby enhancing its reactivity and effectiveness in food applications (Thirumdas et al., 2015).

Although numerous types of energy sources that are capable of ionizing gas, like thermal, electrical, radioactive, UV-light, and X-ray can be utilized for the generation of plasma, electric or electromagnetic fields are commonly referred to as CP generation (Pankaj et al., 2018). Dielectric barrier discharge (DBD), plasma jet (PJ), corona discharge (CD), radiofrequency (RF), and microwave (MW) are the most applied plasma generation methods for the food processing (Bermudez-Aguirre, 2019). As shown in Figure 1, DBD system is composed of two metal electrodes, where at least one of them is powered, and the application of high voltage between these electrodes generates DBD plasma (Laroque et al., 2022; Pankaj et al., 2018). On the other hand, two concentric electrodes where the inner electrode is commonly connected to the high radio frequency power are placed into the plasma jet system, which includes a nozzle (Pankaj et al., 2018).

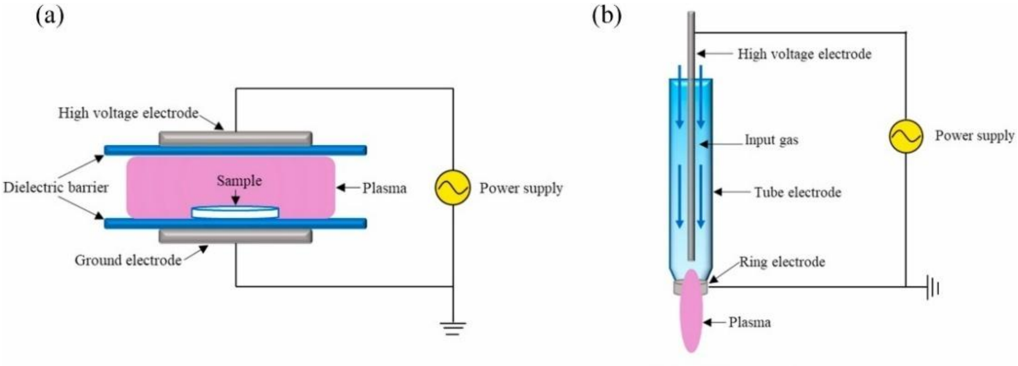

Figure 1. Schematic diagram of dielectric barrier discharges plasma (DBD) (a) and atmospheric pressure plasma jets (b) (Wu et al., 2021b).

Şekil 1. Dielektrik bariyer deşarjlari plazmasının (a) ve atmosferik basınç plazma jetlerinin (b) şematik diyagramı (Wu vd., 2021b

Dielectric Barrier Discharge (DBD) technology is well-suited for applications involving large surface areas. It can be applied without direct contact with the food surface. DBD has been employed in the processing of various food categories, including fruits and vegetables, meat and dairy products, and cereals. However, it may cause certain quality-related changes such as color alteration, texture modification, and lipid oxidation. The efficacy of microbial inactivation in DBD processes depends on parameters such as discharge power, gas composition, and treatment duration. Additionally, the moisture content and surface roughness of the food product play a critical role. In this context, DBD is considered particularly appropriate for relatively dry and smooth-surfaced products such as nuts, seeds, and grains. This is mainly because in low-moisture foods, the reactive compounds produced by the plasma, such as free radicals, can interact more effectively with microorganisms. As a result, plasma reactivity increases, leading to enhanced microbial inactivation (Butscher et al., 2016; Figueroa-Pinochet et al., 2022).

On the other hand, plasma jets are more suitable for localized and focused applications. Compared to DBD systems, they typically operate at higher energy densities. Due to their ability to produce reactive species at a higher flux and velocity, plasma jets are advantageous for treating foods with irregular surfaces or liquid matrices. Relative to DBD systems, their greater flux of reactive species can induce more pronounced effects on food components. Depending on the treatment parameters, changes in phenolic compounds, color pigments, and enzymatic activity—either increases or decreases—have been reported following plasma jet applications (Kodaira et al., 2023; Yu et al., 2020).

Since studies in the literature employ different plasma systems under varying conditions and on diverse food products, direct comparisons between plasma types remain inconclusive. Nevertheless, available data generally suggest that DBD offers a more homogeneous and gentle treatment, whereas plasma jets provide stronger microbial inactivation due to their higher reactive species flux (Imran et al., 2023).

Due to the irregular surface structure of fresh produce, the uniformity of CP applications has not yet reached the desired levels. Consequently, in recent years, studies involving plasma-activated water (PAW) -produced by the interaction of active components in cold plasma with water- have gained increasing attention in the literature. Findings from these studies have shown that PAW exhibits strong antimicrobial properties. Moreover, evidence suggests that the reactive species present in PAW remain stable over extended periods, thereby ensuring prolonged antimicrobial activity. Compared to cold plasma, PAW possesses superior fluidity, which contributes to a more uniform and efficient decontamination process. Studies in the literature have also demonstrated that microbial activity on fresh food products can be effectively controlled using PAW, without compromising overall food quality (Chen et al., 2019a). Further explanations of these and other systems are accessible elsewhere (Laroque et al., 2022; Misra et al., 2016; Sruthi et al., 2022).

Plasma agents directly influence the effectiveness of a process in which plasma is applied. The concentrations of these agents within the plasma vary depending on the gas composition, pressure, flow rate, and the frequency and power of plasma excitation. According to the literature, when the inactivation effects of various gas plasma sources and temperatures on Bacillus spores are examined, it has been determined that oxygen-based plasma is more effective than pure argon plasma. Another parameter that determines inactivation efficiency is whether the surface to be sterilized is in direct contact with the plasma or positioned at a distance from the plasma source. In cases where the sample is located remotely, the charged particles lose their effectiveness due to recombination before reaching the food sample. Considering that the reactive compounds generated by plasma are self-quenching and have relatively short half-lives, a shorter 'time of flight' is regarded as a critical parameter for inactivation efficiency. It is important that, during plasma generation, process parameters are adjusted based on the intended target, allowing for the activation of multiple potentially synergistic mechanisms within the system.

Reactive species present in plasma have been associated with oxidative effects on the outer surface of microbial cells during the inactivation process. Oxygen and nitrogen gases, which are commonly used in cold plasma processes, serve as critical sources for the generation of reactive oxygen and nitrogen species (ROS and RNS), such as O, O_2, O_3, OH, NO, and NO_2. Considering that atomic oxygen exhibits an oxidation reaction rate at room temperature approximately one million times higher than that of molecular oxygen, it is considered highly effective in terms of sterilization. The choice of gas used in plasma generation plays a decisive role in determining the types of reactive species formed. Reactive compounds generated in plasma are the primary mechanism behind microbial inactivation, and the selection of gas for plasma production directly influences the efficiency of microbial inactivation (Misra et al., 2011).

Although the oxidative reactive species generated by cold plasma are effective in denaturing microbial membranes, DNA, and proteins, they can also lead to lipid oxidation, vitamin degradation, and sensory changes in food products. Prolonged cold plasma treatment has been shown to alter the fatty acid profile of foods, particularly affecting polyunsaturated (PUFA), monounsaturated (MUFA), and saturated fatty acids. In high-fat food products, cold plasma application may result in color and texture loss as well as aroma deterioration, primarily due to protein and lipid oxidation. These quality degradations are influenced by processing parameters such as gas type, flow rate, power, and exposure duration. While extended exposure time enhances microbial inactivation, it also increases contact duration between reactive species and food components, thereby intensifying nutritional and sensory quality losses. Additionally, air- or oxygen-based plasmas, though highly effective in microbial inactivation, generate greater quantities of reactive oxygen and nitrogen species (ROS/RNS), which in turn may elevate lipid and vitamin oxidation. In cases involving remote exposure, heat transfer to the food is reduced and the penetration of reactive compounds is limited, which may help preserve taste and texture but also results in decreased inactivation efficiency due to lower reactive species concentrations. Therefore, in cold plasma applications, the optimization of process parameters (e.g., gas type, flow, power, exposure time) is crucial to maximizing microbial reduction while minimizing adverse quality effects. Furthermore, there is a need for mechanistic studies to elucidate the specific kinetic interactions between plasma-generated reactive species and the biomolecules present in food matrices (Aguilar Uscanga et al., 2022).

One of the research topics in food processing is the comparison of energy consumption costs between cold plasma technology and traditional methods. Findings from studies conducted in this context indicate that cold plasma technology can significantly enhance efficiency by optimizing energy use. Considering the obtained results, the industrial adoption potential of cold plasma technology is quite high in terms of energy efficiency and sustainability (Sharma et al., 2025).

A study conducted by Shishir et al. (2020) utilized cold plasma technology to accelerate the drying process of shiitake mushrooms while preserving their nutritional value. In this study, the mushrooms were subjected to direct cold plasma (CP) treatment and cold plasma-activated water (CPAW) treatment before the drying process. The CP application reduced energy consumption from 53.4 kWh/kg to 42.6 kWh/kg, achieving approximately 40% energy savings, and shortened the drying time from 13.1 hours to 10.6 hours. The results of this study demonstrated that CP technology is an effective pre-treatment strategy that optimizes energy management and significantly reduces energy consumption. Compared to other traditional processing methods, cold plasma technology has lower energy costs. The use of CP technology enables significant savings in drying energy costs. However, it should also be noted that these savings may vary depending on the design of the plasma devices used (Sharma et al., 2025).

Despite the numerous advantages and growing interest in cold plasma (CP) technology as a green preservation method in food processing, its widespread adoption remains limited due to insufficient research on its effects on food quality, uncertainties in process parameters, high investment costs, potential adverse impacts on product quality, limited applicability across different food types, and suboptimal preservation efficiency. Although numerous studies have been conducted on various food products, many aspects of cold plasma (CP) technology remain unknown. Comprehensive scientific investigations are needed to evaluate the safety, toxicity, and potential health effects of CP-treated food products on humans. Furthermore, the diverse interactions between different plasma components and various food matrices necessitate careful optimization of process parameters such as plasma type, intensity, treatment duration, and the specific characteristics of the target food (Cherif et al., 2023).

A clear understanding of the working mechanisms of this technology is crucial for its optimal utilization. Reactive plasma species, such as free radicals generated during CP treatment, can cause auto-oxidation in lipids present in food compositions, leading to irreversible changes in food product quality (Sharma et al., 2025). CP applications can also impact the physiological activity and sensory properties of food. Findings from studies indicate that CP treatments affect photosynthetic activity in cucumbers and fresh corn leaves, while also causing color changes in tomatoes and carrots (Chen et al., 2020).

One of the significant drawbacks of cold plasma technology is its limited penetration depth. This limitation poses a challenge in sterilization processes, as microorganisms located beyond the penetration range of CP may survive, leading to incomplete sterilization (Sharma et al., 2025). Another major constraint of CP technology in industrial applications is its high capital investment costs. These financial barriers can hinder its widespread adoption across different sectors. To address this issue, developing economically viable scaling-up methods is essential for promoting the broader application of CP technology (Misra et al., 2016).

Furthermore, the lack of clear regulatory frameworks for this technology presents another challenge to its commercialization. Establishing well-defined legal standards and guidelines for CP technology could accelerate its integration into commercial applications and promote its safe use in the industry. Compiling comprehensive literature on the effects of CP on various food products could facilitate regulatory approval processes and contribute to its broader societal acceptance. Considering these factors, overcoming these barriers is crucial for the successful implementation of cold plasma technology in the food industry (Misra et al., 2016; Sharma et al., 2025).

3. Effects of Cold Plasma on the Shelf Life of Food Products

In recent years, the potential application of cold plasma technology to food products to improve safety and extend shelf life has drawn a lot of attention. CP technology is used in many research due to its sterilization ability as well as to help preserve the quality of food. Due to being a fast, non-destructive, cheap, and non-toxic application, CP has become an effective treatment for decontamination of food. CP has also microbial, nutritional, and sensory effects on foods, which are directly related to the shelf life of the food (Sonawane et al., 2020; Wu et al., 2021a).

Plasma technology has a well-established history of use in semiconductor processing and the electronics industry, and more recently, its application has expanded into biological and food-related fields. Within the context of agriculture and food systems, plasma presents both promising opportunities and notable challenges in terms of consumer acceptability. Public perception may be adversely influenced by the association of terms such as ionization, radiation, radicals, and reactive species with food irradiation -a concept that often carries negative connotations. Conversely, the use of common activation gases like air, instead of chemical agents that may leave harmful residues, offers an appealing alternative for food processing. Nevertheless, enhancing the sterilization efficiency of plasma treatments requires the deliberate selection of gases with inherent antimicrobial properties. Furthermore, consumer acceptance may also be shaped by the specific applications of cold plasma in areas such as agricultural treatment, wastewater purification, and food packaging. Therefore, to fully understand the potential of cold plasma in the food industry, it is essential to critically assess both its advantages and its limitations (Misra et al., 2016).

Cold plasma (CP) is an emerging non-thermal technology that employs reactive and energetic gas species for the effective inactivation of microorganisms on food surfaces. The presence of free electrical charges such as electrons and ions render plasma electrically conductive, chemically active, and highly responsive to electromagnetic fields. These reactive species exert both chemical and physical antimicrobial effects, making cold plasma particularly effective against resistant microbial forms, including bacterial spores. Several studies have reported that CP outperforms conventional methods such as thermal processing, chemical disinfectants, and ultraviolet radiation in microbial reduction efficiency. Consequently, cold plasma treatments play a crucial role in enhancing food safety and prolonging the shelf life of perishable products Notably, CP has shown high efficacy against major foodborne pathogens such as *Escherichia coli*, *Salmonella Typhimurium*, *Staphylococcus aureus*, and *Listeria monocytogenes* (Birania et al., 2022; Misra et al., 2016; Rathod et al., 2021; Thirumdas et al., 2015).

In addition to microbial inactivation, CP has been applied for enzyme inactivation targeting endogenous enzymes like polyphenol oxidase and peroxidase that contribute to enzymatic browning in fresh produce (Thirumdas et al., 2015). Furthermore, cold plasma technology has gained growing significance within the food industry for its potential use in toxin removal, surface modification of packaging materials, and even wastewater treatment (Misra et al., 2016).

Preserving the nutritional value of the food throughout shelf life is important for the quality of the food. Protein, fat, carbohydrates, vitamins, minerals, and bioactive compounds contained in the food constitute the nutritional value of the food. It is important that foods are not adversely impacted by the treatment and can be preserved throughout their shelf life. It is a potential technology used especially in studies conducted on fresh products to protect and increase the nutritional values of quality features as well as sterilization and to positively affect shelf life. In studies conducted with fresh vegetables and fruit, it has been stated that cold plasma generally preserves the nutritional composition, that is, it is not affected by the treatment. Moreover, an increase in some values such as total phenolic content with the application of CP has been observed (Chen et al., 2020; Wu et al., 2021a). However, the extent of such enhancements in food components is influenced by the composition of the gas mixture employed in cold plasma technology and the manner in which the plasma interacts with or penetrates the food matrix (Cherif et al., 2023). For the food to be preferred by the consumer, sensorial quality properties of the food, such as color and texture, must be preserved throughout its shelf life. Cold plasma has a minimal effect on sensorial quality parameters (Birania et al., 2022). Studies on fresh fruits and vegetables show that cold plasma treatment can control respiration and thus better preserve sensorial quality properties such as texture, but more studies are needed to understand the mechanism (Chen et al., 2020).

As a result, in recent years, cold plasma technology has become a frequently recommended technology for food preservation and sterilization. In addition to this effect, cold plasma technology protects and increases the quality of food by preserving the nutritional and sensorial quality properties of foods. Thanks to these benefits, it helps to extend the shelf life of food. Due to the limited number of studies conducted, further studies are needed to better understand the mechanism of extending the shelf life of foods.

3.1. Sensorial Quality Changes during Storage of the Food Product

Color is a critical sensorial quality parameter that not only influences the customer preference for one food product over another but also has a direct relationship with product quality (Pankaj et al., 2018; Sruthi et al., 2022). The chemical changes due to enzymatic or non-enzymatic reactions and the presence of natural or synthetic pigments are primarily responsible for the color of food products. Any adverse effect on product color that may occur during processing or storage time will be a crucial barrier to the acceptability of the food (Pankaj et al., 2018).

As illustrated in Table 1, several research has been carried out on the effect of CP treatment on the color of food based on the different treatment conditions. Illera et al. (2019) determined that 5-minute treatment resulted in a significant increase in the L value from 39.5 ± 0.1 to 43.9 ± 0.6, representing the highest lightness observed among all treatments. As the duration of cold plasma treatment increases, the lightness (L) of the juice tends to rise, while both redness (a*) and yellowness (b*) values decrease. This indicates that the product retains a fresher appearance with greener and lighter tones. Such changes suggest that both enzymatic and non-enzymatic browning processes are effectively inhibited by prolonged plasma exposure. Consequently, treatments lasting 4 to 5 minutes have been found to yield the most favorable results in terms of color quality preservation. Polyphenol oxidase (PPO) is one of the key enzymes responsible for enzymatic browning in fruit juice. Its inactivation following cold plasma treatment led to an improvement in juice color, resulting in a lighter appearance that was maintained throughout the storage period. In chicken breast, there were no significant changes in the a* (green-red) and b* (blue-yellow) values of control and CP-treated samples over 24 days, although the blue-yellow value was found to be statistically different only on the 15th day of the storage period. Cold plasma treatment did not substantially alter the chromatic color parameters (a* and b*) of chicken breast meat. However, it effectively preserved the lightness (L*) value during the initial stages of storage, thereby delaying the onset of spoilage. These findings suggest that cold plasma slows down microbial deterioration, contributing to the prolonged visual quality of the product (Moutiq et al., 2020).

The texture originated from the structural properties of food has a valuable impact on eating quality and the acceptance of food products (Chen & Rosenthal, 2015; Sruthi et al., 2022). Similar to the color of the food, the texture is sensitive and prone to be affected by any process and storage conditions that affect the food structure.

Many of the previous studies suggest that the potential of CP treatment is to retain food texture. Regarding to fresh fruits and vegetables, no significant differences were reported after CP treatment of Chinese bayberries, fresh-cut carrots, and fresh-cut melons (Ma et al., 2016; Mahnot et al., 2020; Tappi et al., 2016). However, Giannoglou et al. (2020) demonstrated that the CP-treated ready-to-eat rocket leafy salad was relatively softer (approximately 8.8%) than the control samples. Although a slight difference was reported in this study, the hardness of the both control and CP-treated samples was decreased and was not different statistically at the end of the 5-day storage. No statistical change in the hardness, springiness, and cohesiveness of the control and HVACP-treated fresh cheese was found after 24 h storage (Wan et al., 2021).

3.2. Nutritional Changes during Storage of the Food Product

3.2.1. Carbohydrates

Carbohydrates are biological molecules composed of carbon, hydrogen, and oxygen, present in many food products, and play a significant role in food quality (Pankaj et al., 2018; Saremnezhad et al., 2021). The chemistry of carbohydrates involved in food formulation can be altered by cold plasma treatment, thereby influencing the properties of the final product (Saremnezhad et al., 2021).

Studies have shown that the implementation of cold plasma to carbohydrates results in the breakdown of reducing sugars such as fructose, glucose, and non-reducing sugars like sucrose. Additionally, research suggests a rise in sucrose content due to the breakdown of oligosaccharides after applying cold plasma to food products (Pankaj et al., 2018; Zhang et al., 2022). These fluctuations in these carbohydrate compounds are related to food content and the breakdown of glycosidic bonds (Pankaj et al., 2018).

The impacts of cold plasma on carbohydrates have been particularly examined in starches found in grains and legumes (Pankaj et al., 2018; Saremnezhad et al., 2021). The cold plasma process induces structural, functional, and rheological changes in starch (Pankaj et al., 2018; Zhang et al., 2022). These alterations are associated with depolymerization, cross-link formation, changes in hydrophilic nature, and the creation of new functional groups within starch molecules (Saremnezhad et al., 2021). Changes are observed in amylopectin and amylose, components of starch structure, during the plasma process. Post-treatment, amylose is broken down into simple sugars, leading to an increase in the amylose amount within the structure by virtue of a similar breakdown of amylopectin (Dharini et al., 2023).

Table 1. The microbiological, nutritional, and sensorial quality effects of cold plasma treatment on food.

Tablo 1. Soğuk plazma işleminin gıda üzerindeki mikrobiyolojik, besinsel ve duyusal etkileri.

Product	**Condition/Parameter/Method**	**Category**	**Effect/Result**	**Reference**
Apples	Atmospheric Air Dielectric Barrier Discharge (DBD) (25 kV) Exposure time: 20 min Distance gap: 520 mm Storage: Ambient (27±3°C) and cold (10±1°C)	Microbial	● A microbial load reduction was 0.87 ± 0.34 log CFU g^{-1} for total aerobic mesophilic bacteria. ● CP decontamination method was more effective in reducing the pesticides compared to conventional methods.	(Sreelakshmi et al., 2024)
		Nutritional	● PPO (65% residual activity) and PAL (47% reduction compared to the untreated samples) activities showed an important reduction while POD activity showed a lower reduction. ● TPC increased (highest value of 0.312 ± 0.00205 g GAE kg^{-1}) and carotenoid content was retained.	
		Sensorial Quality	● The higher red color retention was provided. ● The firmness was maintained during the storage period after CP application. ● The shelf life of untreated apples, determined as 13 days at room temperature, was increased to 41 days with the improved quality parameters after the CP process.	
Red Globe Grapes	Non-equilibrium Cold Plasma Jet (NECPJ) (3.5 kV at 20 kHz) The optimized plasma process parameters: -The applied voltage 3.36 kV -Exposure time: 1 min -Gas flow rate: 2.87 SLPM	Microbial	● NECPJ application provided a complete reduction in aerobic bacteria and a 2.44 log reduction in E. coli bacteria.	(Mishra et al., 2024)
		Nutritional	● Higher shelf-life provided in NECPJ-treated grapes up to 28 days. ● The treated grapes have higher levels of vitamin C (0.0364 g ascorbic acid L^{-1}) and total soluble solids according to the controls. ● NECPJ can help decrease red globe grape deterioration and retain quality during post-harvest storage.	
		Sensorial Quality	● The treated grapes have higher firmness and red grape color index.	
Strawberry	Dielectric Barrier Discharge (DBD) (60 kV) (260 V at 50 Hz) Exposure time: 10, 15 and 30 min Distance gap: 30 mm	Microbial	● ACP treatment of 15 min resulted in 2 log reduction of microbial load. ● At 4 °C and 25 °C, the shelf life was extended by 9 days and 5 days, respectively.	(Rana et al., 2020)
		Nutritional	● An increase in the amount of chlorogenic acid, gallic acid, 4-hydroxybenzaldehyde, hyphrin, phloretin, vanillin, and routine was observed during 5 days of storage at 25 °C. ● Total phenolic content and antioxidant activity also increased after 15 minutes of plasma at 60 kV. A decrease in TPC was observed at 25 °C due to overexposure at 30 min. ● No change was observed in the amount of total soluble solids and humidity.	
Blueberries	Dielectric Barrier Discharge (DBD) (36 V, 1.8 A) Exposure time: 0, 2, 4, 6, 8, 10 min Distance gap: 3 mm Storage:0, 4, 8, 12, 16, 20 days at 25 °C and 50% relative humidity	Microbial	● Fungi and bacteria decreased by 25.8% and 93.0% respectively. ● In 6, 8, and 10 minutes, decay rates decreased by 17.7%, 14.3%, and 5.2%.	(Dong & Yang, 2019)
		Nutritional	● Both sugar and vitamin C increased by 1.5 times. ● The total amount of anthocyanin increased by 2.2 times. ● SOD activity level increased by 79.3%.	

SLPM: Standard litre per minute

Table 1. The microbiological, nutritional, and sensorial quality effects of cold plasma treatment on food *(continue).*

Tablo 1. Soğuk plazma işleminin gıda üzerindeki mikrobiyolojik, besinsel ve duyusal etkileri (devamı).

Fresh-Cut Pears	Plasma Activated Water (PAW) (6, 8, 10 kV) Exposure time: 5 min Storage: 12 days at 4 °C	Microbial	For 8 kV PAW treatment/12th day: • Total aerobic bacteria (log CFU/g) was 5.11 ± 0.01 in the control group and 4.46 ± 0.05 in the treated sample. • Yeast mounts (log CFU/g) were 5.29 ± 0.02 in the control group and 4.25 ± 0.02 in the treated sample. • Mold mounts (log CFU/g) is 2.48 ± 0.06 in the control group and 1.71 ± 0.13 in the treated sample.	(Chen et al., 2019a)
		Nutritional	• The decrease in the amount of ascorbic acid increased from 52.90% to 63.52% on the 12th day. • After 12 days of storage, the TPC of the control group was 15.26%, and the TPC of pears treated with 6-kV, 8-kV and 10-kV was 24.18%, 24.45% and 16.08%, respectively.	
Fresh-Cut strawberries	Dielectric Barrier Discharge (DBD) (45 kV) Exposure time: 1 min at 20°C Distance gap: 40 mm Storage: 7 days at 4°C	Microbial	• The treated strawberries' total aerobic bacterial count was only 3.98 log CFU/g, compared to 5.39 log CFU/g for the control group.	(Li et al., 2019)
		Nutritional	• On the 7th day, total flavonoid content increased by 31.39% and 43.58% in control and treated samples, compared to day 0. • The anthocyanin content of the control samples and treated samples was 0.5550 mg g^{-1} and 0.6911 mg g^{-1} respectively on day 3. • On day 3, treated samples showed a 17.85% increase in DPPH radical scavenging activity compared to day 0, whereas control samples showed only a 5.64% increase.	
Fresh-Cut Melon	Dielectric Barrier Discharge (DBD) (15 kV at 12.5 kHz) Exposure time: 30 min (15 + 15) and 60 min (30 + 30) Gas: Air at 22 °C and 60% of relative humidity Gas flow rate: 7 SLPM Distance gap: 70 mm Storage: 4 days at 10 °C	Microbial	• 3.4 log reduction for mesophilic bacteria and 2 log reduction for lactic acid bacteria. • Psychrotrophic bacteria showed cell load reductions not exceeding 1 log CFU/g.	(Tappi et al., 2016)
		Nutritional	• Peroxidase (POD) and pectin methylesterase (PME) were inhibited by approximately 17% and 7%, respectively.	
		Sensorial Quality	• Qualitative parameters (color, texture, titratable acidity, dry matter, and soluble solid content) were only weakly affected. • All color parameters decreased during storage. By the end of storage, the product had a more translucent and darker appearance.	
Ready-to-Eat Rocket Leafy Salad	Surface Dielectric Barrier Discharge (SDBD) (6 kV at 45 kHz) Exposure time: 5, 10, 15, 20 min Storage: 5 days at 2, 5, and 9 °C	Microbial	• The initial counts of lactic acid bacteria and yeasts/molds were found to decrease by 0.996 and 0.493 log CFU/g respectively. • After 120 hours of storage, the shelf life increased by 53, 27 and 18 hours at 2, 5 and 9 °C, respectively.	(Giannoglou et al., 2020)
		Sensorial Quality	• No significant effect was observed on the color of CP processed samples. • The hardness of CP processed rocket leaves was decreased from approximately 0.68 N/h to 0.4 N/h. However, there was no scientific difference between the samples treated with CP and the control group.	

SLPM: Standard litre per minute

Table 1. The microbiological, nutritional, and sensorial quality effects of cold plasma treatment on food *(continue).*

Tablo 1. Soğuk plazma işleminin gıda üzerindeki mikrobiyolojik, besinsel ve duyusal etkileri (devamı).

Shiitake Mushroom	Arc Plasma Activated Water (PAW) and Dielectric Barrier Discharge (DBD) (1200 W) Exposure time: 20 min Gas ratio: Atmospheric air for PAW and 78% N_2 + 22% O_2 for DBD Storage: 7 days at 4 °C	Microbial	• Total bacterial count of PAW and DBD treated samples were 0.89 ± 0.01 and 0.6 ± 0.05 log CFU/g lower than those of control samples, respectively.	(Gavahian et al., 2020)
		Sensorial Quality	• Reduction in the overall color changes (ΔE) with the application of both PAW and DBD was observed in samples during storage. • Samples treated with PAW showed the greatest value of texture firmness (1.27 ± 0.16 N) after one week of storage time.	
Maize	Pulsed Dielectric Barrier Discharge (DBD) (6 kV at 20 kHz) Exposure time: 10 min Gas ratio: Helium with 0.5% and 0.75% (v/v) oxygen Gas flow rate: 2 SLPM	Nutritional	• A decrease of up to 66% was observed in both aflatoxin B1 and fumonisin B1. • The degradation products were tested on human hepatocarcinoma cells, with no increase in cytotoxicity occurring.	(Wielogorska et al., 2019)
Almond Slices	Atmospheric Pressure Plasma Jet (17 V, 2.26 A) Exposure time: 5, 10, 15, and 20 min Gas flow rate: 10 SLPM Distance gap: 20 mm Storage: 1 month	Microbial	• The total viable count was reduced by approximately 2.95 log CFU/g after 20 minutes of plasma treatment. • Molds and yeasts exhibited a reduction of about 1.81 log CFU/g under the same treatment conditions. • *Staphylococcus aureus* counts decreased by nearly 2.72 log CFU/g following 20 minutes of plasma exposure.	(Shirani et al., 2020)
		Sensorial Quality	• No significant color changes. • Approximately 15% increase determined for hardness (N/mm).	
Fresh and Dried Walnut (*Juglans regia L.*)	Plasma Jet Treatment (12 kHz at 15 kV) Exposure time: 3, 5, 7, 9, 10 and 11 min Gas ratio: 99.999% pure argon Gas flow rate: 1 SLPM Distance gap: 15 mm Storage: 15 and 30 days at 4 °C with 90% relative humidity	Microbial	• 11 min of plasma jet treatment caused complete elimination of *Aspergillus flavus* for fresh walnuts. • 10 min of plasma jet treatment eliminated *Aspergillus flavus* from the dried walnuts. • The number of survivors in the samples for 11 min was negligible after 15 and 30 days of storage (4°C).	(Amini & Ghorannevis, 2016)
		Nutritional	• No change was observed in total phenolic content and antioxidant activity after 11 minutes of plasma application. • An increase in total phenolic content and antioxidant activity was observed after 15 and 30 days of storage at 4 °C.	
Milk	Corona Discharge Cold Plasma Exposure time: 0, 1, 5, and 10 min Storage: 0-15 days	Microbial	• CP10 min treatment had a positive effect on the reduction of total plate count (TPC <6 log CFU/mL) and thermoresistant bacteria.	(Lee et al., 2024)
		Nutritional	• The shelf life of milk with CP10 min extended to 15 days. • Titratable acidity was <0.18%. • Lipid oxidation values in CP were positively correlated with storage time. • No important effects in nutritional value and xanthine oxidase activity.	
		Sensorial Quality	• Negligible color changes.	

SLPM: Standard litre per minute

Table 1. The microbiological, nutritional, and sensorial quality effects of cold plasma treatment on food *(continue).*
Tablo 1. Soğuk plazma işleminin gıda üzerindeki mikrobiyolojik, besinsel ve duyusal etkileri (devamı).

Mozzarella Cheese	Dielectric Barrier Discharge (DBD) (75 kV) Exposure time: 2, 3, and 5 min Gas ratio: 10:90 oxygen to nitrogen Distance gap: 50 mm Storage: 9 days at 4°C	Microbial	• DBD treatment at 3 and 5 min reduced total microbiota, mesophilic bacteria, Enterobacteriaceae, Pseudomonas, and yeasts (significant reduction in total viable count by more than 2 log). • EHEC was inactivated entirely after 3 and 5 min in both 4 and 6 log CFU/g.	(Nemati & Guimarães, 2024)
		Nutritional	• Moisture, fat and protein contents of treated mozzarella samples were maintained.	
		Sensorial Quality	• 3 min treatment maintained color, odor, and taste quality according to the control. • 3 min treatment extended the shelf life of mozzarella cheese by at least 2 days.	
Cheese	High Voltage Atmospheric Cold Plasma (HVACP) (60, 80, 100 kV at 60 Hz) Exposure time: 1 to 5 min Gas ratio: MA65 (65% O_2, 30% CO_2, 5% N_2) or dry air Gas flow rate: 1 SLPM Distance gap: 28 mm Storage: 4 °C for 24 h	Microbial	• 100 kV for 5 min led to a maximum of 1.4 log CFU/g reduction in L. *innocua* and 3.5 log CFU/g reduction in E. *coli* K-12.	(Wan et al., 2021)
		Sensorial Quality	• No statistical differences were found regarding textural changes. • There was a slight decrease in L* and a* values, whereas b* values showed an increase.	
Milk Powder	Dielectric Barrier Discharge (DBD) with Fluidized Bed Plasma (480 W, 4.4 kV) Exposure time: 0 to 2 min Gas ratio: 99.9% pure nitrogen Gas flow rate: 8–20 SLPM Distance gap: 65 mm	Microbial	• A 1.17–3.27 log reduction was observed in C. *sakazakii*. • This inactivation increased with increasing flow rate from 8 to 20 L/min.	(Chen et al., 2019b)
		Nutritional	• No significant changes in crystallinity, amino acid composition, or phenolic content occurred.	
		Sensorial Quality	• It was detected that there were no significant color changes (ΔE<1.5).	
Fresh Sea Bass (*Dicentrarchus labrax*)	Atmospheric Cold Plasma (30 kV at 20 kHz) Exposure time: 0.5, 1, 3, 5, 7, and 10 min Gas: Air or helium Distance gap: 70 mm Storage: 5 days at 2 ± 1 °C	Microbial	• After 7 and 10 minutes of application, mesophilic aerobic bacteria counts decreased significantly (from 4.66 log CFU/g to 3.37 log CFU/g).	(Mol et al., 2023)
		Sensorial Quality	• Sensory scores were over 7 (good) immediately after 0.5–7 minutes of air- or He-plasma treatments, and there was no change in the purchase intention of the consumer. • It was obtained that the 10 minutes treated samples were dryer and harder.	
Asian Sea Bass Slices (ASBS)	In-Bag Dielectric Barrier Discharge (IB-DBD) (0–120 kV) (input voltage 230 V at 50 Hz) Storage: Under the gas combination of argon and oxygen (10:90) (gas A), the mixtures of carbon dioxide, argon, and oxygen (60:30:10) (gas B) and the control (kept in the air) for 18 days at 4 °C	Microbial	• Lower microbial load (0.73–0.81 log CFU/g reduction) and 3 days longer shelf life obtained.	(Olatunde et al., 2020)
		Nutritional	• Trimethylamine and total volatile nitrogen base contents were found to be lower in the treated products throughout storage. • Regardless of the gas composition used, higher lipid oxidation and protein oxidation were observed in the treated products.	

SLPM: Standard litre per minute

Table 1. The microbiological, nutritional, and sensorial quality effects of cold plasma treatment on food *(continue).*

Tablo 1. Soğuk plazma işleminin gıda üzerindeki mikrobiyolojik, besinsel ve duyusal etkileri (devamı).

Mackerel Fillets	Dielectric Barrier Discharge (DBD) (80 kV) Exposure time: 5 min Distance gap: 37 mm Storage: 2, 5 and 7 days at 4, 8 and -20°C and 2 weeks for only -20°C	Nutritional	● No significant changes occurred in lipid oxidation and fatty acid composition. ● The carbonyl formation accelerated in the samples treated with plasma after storage at 4°C and 8°C.	(Pérez-Andrés et al., 2020)
Chicken Breast	Dielectric Barrier Discharge (DBD) (233 ± 5 W, 100kV) Exposure time:1, 3, 5 min Distance gap: 42 mm Storage: 24 days	Microbial	● 1.5, 1.4, and 0.5 log reduction in mesophiles, psychrotrophs, and Enterobacteriaceae population respectively, and 6 days longer shelf life.	(Moutiq et al., 2020)
		Sensorial Quality	● There is no statistical difference between the unprocessed and the processed sample in color analysis.	
Chub Mackerel (*Scomber japonicus*)	Dielectric Barrier Discharge (DBD) (0 to 70 kV) Exposure time: 0, 0.25, 0.5, 0.75, 1 and 1.25 min Distance gap: 38 mm Storage:14 days	Microbial	● After 1 min of exposure at 60 kV, the decrease in total viable count enlarged to 3.15 log cycles.	(Chen et al., 2019c)
		Nutritional	● The slow increase in peroxide value (PV) and thiobarbituric acid (TBA) amounts indicated that ACP delayed lipid oxidation. ● Observations by scanning electron microscopy showed that CP delayed the degradation of myofibrillar proteins and increased the stability of tissue structures.	
		Sensorial Quality	● The treatment of ACP resulted in the shelf-life extension of chub mackerel by 14 days.	
Pineapple Juice	Dielectric Barrier Discharge (DBD) (1 and 50 kV at 50 Hz) -The optimized plasma (38 kV/631 s) -The extreme plasma (45 kV/15 min) Distance gap: 15 mm Storage: 5, 15, and 25°C	Microbial	● Native microbiota in CP and thermally treated samples fell below the detection limit (<1 log CFU/mL).	(Pipliya et al., 2024)
		Nutritional	● All samples at high temperatures showed a higher degradation rate for bioactive compounds. ● After 90 days, optimum plasma-treated juices stored at 5℃ retained 91.55% total phenolics, 84.3% antioxidant capacity and 81.44% ascorbic acid compared to day 0.	
		Sensorial Quality	● The color parameters increased with time and storage temperature. ● All samples at high temperatures showed a higher degradation rate for color parameters. ● The shelf life of the optimized CP-treated juice sample packaged in glass bottles was determined as 90, 50 and 25 days at 5, 15 and 25°C, respectively.	

SLPM: Standard litre per minute

Table 1. The microbiological, nutritional, and sensorial quality effects of cold plasma treatment on food *(continue).*
Tablo 1. Soğuk plazma işleminin gıda üzerindeki mikrobiyolojik, besinsel ve duyusal etkileri (devamı).

Cloudy Apple Juice	Spark Discharge Plasma (7.9375 to 10.875 kV at 20–65 kHz) Exposure time: 1-5 min Distance gap: 5 mm Storage: 7-24 days at 4°C	Nutritional	● After 4 and 5 min of treatment, total phenolic content increased 69 and 64% respectively. ● After 3, 4, and 5 min of treatment, DPPH inhibition increased from 79.4 ± 0.8% to approximately 93%. ● Non-enzymatic browning increased from 0.12 ± 0.01 to approximately 0.22 after treatment. ● Following a 4- and 5-min treatment, the PPO's residual activity was 16 and 27.6%.	(Illera et al., 2019)
		Sensorial Quality	● 4 and 5 min of CP treatment resulted in better preservation of color quality. After 5 min, the L value significantly raised from 39.5 ± 0.1 (control) to 43.9 ± 0.6, and remained similar for 4 min.	
Fresh Tomato Juice	Atmospheric Cold Plasma (40W, 3.8 kV at 50Hz) Exposure time: 0.5 to 5 min Gas: Nitrogen Gas flow rate: 440 L/h Distance gap: 3 mm Storage: 5 days at 4 °C	Microbial	● 3.45 log CFU/ml total aerobic mesophilic bacteria, 3.55 log CFU/ml yeast and 3.32 log CFU/ml mold reduction and shelf-life extension.	(Starek et al., 2019)
		Nutritional	● No change was observed in the dry matter values of the samples after cold plasma. ● There was a slight increase in total carotenoid (13%) and lycopene (11%) content. ● Maximum (5%) loss in vitamin C was observed after 5 minutes of treatment.	
		Sensorial Quality	● After 5 days of storing the juice samples treated with plasma for 2, 3, and 5 minutes, an intense red color and a fresh smell of juice were preserved.	
Apple, Orange, Tomato Juices, and Sour Cherry Nectar	Atmospheric Pressure Plasma Jet (APPJ) (650 W) Exposure time: 0.5, 1, 1.5, and 2 min Gas flow rate: 3000 L/h	Microbial	● *E. coli* inactivation (Apple juice: 4.02 ± 0.03 log CFU/mL; cherry juice: 3.34 ± 0.09 log CFU/mL; orange juice: 1.59 ± 0.17 log CFU/mL and tomato juice: 1.43 ± 0.22 log CFU/mL)	(Dasan & Boyaci, 2018)
		Nutritional	● Compared to unprocessed juice, phenolic content increased by 10% to 15% after plasma.	
		Sensorial Quality	● There were no significant changes in color parameters, except for apple juice, after processing.	

SLPM: Standard litre per minute

An increase in the affinity of small sugar molecules to water molecules results in a rise in starch's water absorption rate and a decline in its cooking rate (Dharini et al., 2023; Pankaj et al., 2018). This occurrence is attributed to active reactive compounds created by cold plasma, breaking down starch and protein, thereby increasing water-binding regions within the structure. Additionally, a rise in gelatinization degree and a decline in gelatinization temperature, starch hydrolysis degree, and retrogradation tendency are observed in starches post-plasma process (Pankaj et al., 2018). Starch modifications are also among the applications of cold plasma treatment. OH group loss in different glucosyl groups in starches due to plasma application leads to cross-link formation between starches, enabling the production of enzyme-resistant starch. These modifications vary in products depending on the source of starch and the kind of gas used in cold plasma technology (Dharini et al., 2023; Saremnezhad et al., 2021).

The study carried out by Dong & Yang (2019) aimed to extend the shelf-life and improve the quality of blueberries by applying a cold plasma process. For this purpose, the fruits were subjected to dielectric barrier discharge (DBD) at 36 V at atmospheric pressure and 1.8 A for 0, 2, 4, 6, 8, and 10 minutes. After the process, the fruits were stored under laboratory conditions at 25°C and 50% relative humidity for 0, 4, 8, 12, 16, and 20 days. According to the obtained data, the sugar content of blueberries initially increased after the application. Compared to the control groups, different plasma treatments and storage times showed a maximum increase of 1.5% in sugar quantity. The maximum sugar amount in the fruits (54.7 g kg^{-1}) was found in plasma-treated blueberry samples for 8 minutes and then stored for 12 days. According to the results, when applied under specific cold plasma parameters, the observed increase in sugar content was sustained not only immediately after the treatment but also for several days thereafter. This indicates that cold plasma contributes not only to microbial inactivation but also to the preservation and even enhancement of nutritional components such as sugars. Additionally, another outcome suggested that cold plasma application delayed the storage time of fruits at room temperature.

3.2.2. Proteins and Enzymes

Proteins and enzymes are biomolecules with significant structural and functional roles in many foods (Saremnezhad et al., 2021). Cold plasma treatments induce denaturation in proteins and enzymes, resulting in observed alterations in the structural and functional properties of the food. According to studies and research, this denaturation mechanism is capable of affecting proteins in two different ways. The first involves the interactive relation of reactive compounds produced by the plasma process, such as ROS and RNS, with amino acids (Pankaj et al., 2018). Amino acids exposed to plasma undergo oxidation due to the effect of reactive compounds. Following oxidation, proteins break down, cross-link formation occurs, and conformational changes can emerge. These conformational changes can lead to alterations in the functional characteristics of proteins and enzymes (Saremnezhad et al., 2021). For instance, after 15 minutes of cold plasma treatment performed on whey protein isolates, findings revealed an increase in protein structure openness, resulting in a more elastic structure and improved positioning of proteins at the air-water interface, thus increasing their foaming properties (Zhang et al., 2022).

The second denaturation mechanism is associated with the loss of the protein's secondary structures responsible for α-helixes and β-sheets or the loss of tertiary and quaternary structures (Pankaj et al., 2018; Saremnezhad et al., 2021). The degree of denaturation of enzymes and proteins by cold plasma application can be different depending on the type of enzyme and protein, the sort of gas used in plasma production, the kind of cold plasma, and its parameters (Pankaj et al., 2018; Zhang et al., 2022). Particularly, the treatment of cold plasma plays a crucial role in enhancing the quality of foods by causing enzyme inactivation. The denaturation of enzymes responsible for undesirable quality changes during the shelf life of food can lead to improvements in key quality attributes such as nutritional content, color, and texture. Accordingly, this also contributes to a potential extension of the product's shelf life (Pankaj et al., 2018). The dissolvability of proteins is a significant parameter in these possible applications, and the structure of proteins is affected by factors such as pH, temperature, and ionic strength of the environment (Saremnezhad et al., 2021). Additionally, it is vital to study the protective effects of particular food components during the process and to understand better the mechanisms of enzyme and protein inactivation (Pankaj et al., 2018). Hence, several studies are required to determine the optimal processing parameters for cold plasma (Zhang et al., 2022).

Another essential aspect is that not all enzymes respond similarly to cold plasma application. Studies have shown that the activity of some enzymes can increase post-application. This increase is attributed to the increased permeability of food after plasma treatment, allowing water to penetrate more easily and rapidly. Generally, these observed increases and decreases in enzymatic activities diverge based on the kind of plasma and its parameters (Saremnezhad et al., 2021).

Dong & Yang (2019) aimed to prolong the shelf-life and improve the quality of blueberries by applying a cold plasma process, examining the activity of superoxide dismutase (SOD) enzyme in the fruits. For this purpose, the fruits were subjected to dielectric barrier discharge (DBD) at 36 V at atmospheric pressure and 1.8 A for 0, 2, 4, 6, 8, and 10 minutes. After application, the fruits were stored under laboratory conditions at 25°C and 50% relative humidity for 0, 4, 8, 12, 16, and 20 days. Superoxide dismutase (SOD) is an important antioxidant enzyme that assists in clearing endogenous ROS during storage. According to the findings, SOD activity increased significantly after cold plasma application. The plasma-treated samples for 8 minutes showed a 65.5% higher enzyme activity in comparison to the control group. Furthermore, a rise in SOD enzyme activities during storage was monitored in most processed products. In plasma-treated samples for 8 minutes, the enzyme activity was 79.3% higher after 16 days of storage in proportion to the control group. These results demonstrate that cold plasma application can increase SOD enzyme activity in blueberries. The observed increase in SOD activity following cold plasma exposure is indicative of an elevated antioxidant defense mechanism, which plays a pivotal role in mitigating oxidative stress during post-treatment storage. By converting harmful superoxide radicals into less reactive species, SOD contributes to the stabilization of cellular components, thereby preserving the nutritional, sensory, and structural quality of the product. This enzymatic enhancement not only delays senescence and spoilage processes but also effectively extends the shelf life of treated produce. Therefore, cold plasma technology offers a promising non-thermal intervention to improve oxidative stability and maintain product freshness over prolonged storage periods.

In the study conducted by Illera et al. (2019), cold plasma technology was investigated to preserve and enhance the quality of cloudy apple juices. The study observed its effects on the polyphenol oxidase (PPO) enzyme by altering process parameters such as plasma discharge type, voltage, and treatment duration. The highest enzyme inactivation was achieved with 10.5 kV for 5 minutes of spark discharge plasma treatment. The remaining enzyme activity post-treatment was 16%, and this deactivation was maintained during storage. The observed inactivation of PPO enzymes led to a significant reduction in enzymatic browning, resulting in favorable outcomes in terms of color retention.

Tappi et al. (2016) conducted a study on freshly cut melons, applying dielectric barrier discharge (DBD) at 15 kV power for 15 + 15 and 30 + 30 minutes, aiming to observe the effects on peroxidase (POD) and pectin methylesterase (PME) enzyme activities. Following treatment, the peroxidase (POD) enzyme activity decreased by up to 17%, and the pectin methylesterase (PME) enzyme activity decreased by up to 7%. After 15 + 15 minutes of treatment, the remaining POD enzyme activity was 91%, while this value was 82% after 30 + 30 minutes. Although 15 + 15 minutes of treatment did not induce a substantial change in PME activity, the enzyme's remaining activity was determined as 94% after 30 + 30 minutes of treatment. Peroxidase (POD) is an enzyme that contributes to color degradation and quality loss in foods through lipid peroxidation and the oxidation of phenolic compounds. Pectin methylesterase (PME), on the other hand, breaks down pectin structures, leading to textural softening in fruits and vegetables. The activity of these enzymes can negatively impact the color, texture, and overall quality attributes of foods during storage. Therefore, their inactivation by cold plasma treatment can result in significant improvements in product quality and shelf life.

Chen et al. (2019c) conducted a search on chub mackerel (*Scomber japonicus*) samples using dielectric barrier discharge (DBD) to apply a cold plasma process and investigate its chemical, microbial, and sensory effects. The optimal power level found was 60 kV with a treatment time of 60 seconds. Scanning electron microscope observations on the final products showed that cold plasma application delayed the breakdown of myofibrillar proteins effectively in the products and increased stability in tissue structures. The reduction in myofibrillar protein degradation observed following cold plasma treatment contributes significantly to the preservation of fish quality. By stabilizing protein structures, the treatment helps maintain the textural integrity and structural cohesiveness of the muscle tissue. This, in turn, supports desirable sensory attributes such as firmness and mouthfeel during extended storage. Therefore, limiting protein breakdown is a key factor in extending shelf life and ensuring the organoleptic quality of perishable seafood products.

3.2.3. Lipids

Undesirable taste, odor, and color formation are observed in food due to lipid oxidation, leading to significant decreases in the nutritional value and shelf-life of products (Pankaj et al., 2018; Zhang et al., 2022). Lipid oxidation occurs as a result of a mechanism of the free radical chain, producing primary oxidation products like peroxides and secondary oxidation products such as aldehydes, ketones, and alcohols in food products. These secondary peroxidation products cause rancid taste and odor formation in food, hindering its palatability (Ke et al., 2022; Saremnezhad et al., 2021).

As a result of cold plasma application, reactive compounds in the plasma induce oxidation reactions in lipids due to their strong oxidative effect (Pankaj et al., 2018; Zhang et al., 2022). Albertos et al. (2017) conducted a study where fresh mackerel fillets were exposed to dielectric barrier discharge (DBD) cold plasma at 80 kV for 5 minutes, resulting in a significant increase in peroxide values in the final product. An increase in peroxide value is indicative of primary lipid oxidation, which negatively impacts the quality of food products. Elevated peroxide levels lead to the development of off-flavors and rancid odors, compromising the sensory attributes and consumer acceptability of the product. Therefore, controlling peroxide formation is critical for maintaining the freshness, flavor, and overall quality of lipid-rich foods during storage.

In alternative important study was performed by Olatunde et al. (2020), Asian sea bass slices were subjected to in-bag dielectric barrier discharge (IB-DBD) cold plasma treatment, using two different gas types: gas A (10% argon and 90% oxygen mixture) and gas B (60% carbon dioxide, 30% argon, and 10% oxygen mixture). The shelf life, initially set at 6 days for control group samples, extended to 12 days when the Asian sea bass slices were packed with gas A after treatment and increased to 15 days when gas B was used. Although the improvements in microbial reduction achieved through cold plasma treatment have led to an extended shelf life, the results indicated that, regardless of the gas composition used, lipid and protein oxidation levels in the IB-DBD cold plasma-treated samples were higher compared to untreated and control samples. These findings suggest that, while IB-DBD-CP is highly effective in microbial decontamination and shelf-life extension, it may also induce oxidative modifications in proteins and lipids. Therefore, the optimization of treatment parameters and packaging conditions is crucial to ensure microbial safety while maintaining the biochemical and sensory quality of the product.

The degree of lipid oxidation in food subjected to cold plasma application varies based on the plasma gas and process parameters (Pankaj et al., 2018). Studies suggest avoiding oxygen-containing gas mixtures for highly fatty food products by virtue of the oxidation caused by reactive oxygen formed in plasma (Misra et al., 2016). Reactive oxygen atoms can initiate lipid molecules into a peroxidative chain reaction, leading to the formation of harmful lipid peroxidation products, especially malondialdehyde (Neuenfeldt et al., 2023). These adverse effects can be eliminated by optimizing cold plasma parameters and other conditions (Neuenfeldt et al., 2023; Zhang et al., 2022). Therefore, the temperature, treatment duration, gas type, and power of cold plasma treatment should be optimized, considering the food composition, fat content, fatty acid profile, and presence of antioxidants (Saremnezhad et al., 2021). Methods such as preferring lower power ranges, shortening application duration, and adding antioxidant substances to the food composition are effective preventive measures against observed lipid oxidation due to cold plasma (Zhang et al., 2022). One of the most illustrative examples of this is the study conducted by Chen et al. (2019c). In the survey, dielectric barrier discharge (DBD) cold plasma was applied to chub mackerel (*Scomber japonicus*) samples, investigating their chemical, microbial, and sensory effects. The results indicated that an optimal power level of 60 kV with a treatment time of 60 seconds delayed lipid oxidation in the processed products, as specified by low peroxide value (PV) and thiobarbituric acid (TBA) amounts.

Pérez-Andrés et al. (2020) studied protein and lipid oxidation in mackerel fillets after a cold atmospheric plasma process and investigated the stability of the product's shelf life. In this study, samples were subjected to in-bag plasma treatment at 80 kV power for 5 minutes. The samples obtained after treatment did not exhibit significant alterations in lipid oxidation and fatty acid composition compared to control samples. However, carbonyl formation accelerated in the samples treated with plasma after storage at 4°C and 8°C. The acceleration of carbonyl formation adversely affects the sensory quality of foods by causing deterioration in taste, aroma, and color. It also reduces nutritional value and shortens shelf life. Therefore, oxidative stability is of critical importance for maintaining food quality. Accordingly, the cold plasma parameters applied to minimize such adverse effects should be carefully optimized.

3.2.4. Vitamins

Vitamins are organic compounds necessary for people to maintain their daily lives and metabolic events. As the human body lacks the capability to endogenously synthesize vitamins, these essential micronutrients must be acquired through external sources, where they fulfill critical functions in growth and development. Vitamins are an important parameter for the nutritional value of foods and the quality of food. Several studies in the literature have investigated the vitamin content of foods treated with cold plasma technology and how it is affected throughout their shelf life. The type of food used in the studies is generally fresh products. Moreover, many studies have specifically examined vitamin C, as it is a widely present but highly unstable vitamin in foods. Cold plasma treatment, when applied under appropriate processing parameters, can contribute to the preservation and in some cases, even the enhancement of vitamin content. As a non-thermal technology, it minimizes vitamin loss and largely preserves the overall nutritional value of the food (Zhang et al., 2022).

In a study conducted on blueberries, dielectric barrier discharge (DBD) treatment was applied for specific durations, and the samples were subsequently stored for 0, 4, 8, 12, 16, and 20 days. Vitamin C value initially increased after treatment and decreased during storage. As a result of the study, the vitamin C value in the samples applied for 2 and 8 minutes of treatment and 16 and 20 days of storage was higher than the control group. The vitamin C content calculated after 4 minutes of treatment and 16 days of storage is 1.5 times that of the control group. This is the highest vitamin C content in the study (Dong & Yang, 2019). 6, 8, 10 kV plasma-activated water (PAW) treatment was applied to fresh-cut pears for 5 minutes and the vitamin C content was checked in the samples stored for 12 days. No significant change in ascorbic acid content was observed after treatment, but a reduction in ascorbic acid content was observed in the first 4 days of storage for treated and untreated samples. Between 2 and 4 days of storage, the ascorbic acid content dropped significantly, especially in the samples treated with 6 and 8 kV. There was no discernible difference between the samples treated with PAW treatment and the control after the 6th day of storage. The parameters that gave the best results in this study were the samples with 10 kV PAW treatment. From the 2nd day to the 6th day of storage, the ascorbic acid value in the treated samples was observed to be higher than the control, meaning that 10 kV treatment helped to significantly delay the rapid decrease in the ascorbic acid content. As a general result of the study, the decrease in ascorbic acid value increased from 52.90% to 63.52% on the 12th day of storage (Chen et al., 2019a). In another study, cold plasma treatment was applied to fresh tomato juices for 2, 3, and 5 minutes and stored for 5 days. A small loss in vitamin C value was observed after treatment and storage. A maximum of 5% vitamin C loss was calculated as a result of 5 minutes of treatment and storage. In comparison to the control group, these differences were not statistically significant (Starek et al., 2019). The samples from a study using fresh-cut strawberries applied at 45 kV DBD were kept at 4 °C for five days. The treated samples have a higher vitamin C value than the control group, but as storage time increases, the vitamin C value decreases (Li et al., 2019).

Cold plasma application can generally cause a very small loss of the vitamin C content of fresh products. In addition, it helps to reduce losses during the storage process compared to samples that are not treated. Some studies even observed an increase. The reason for these increases and decreases may be that vitamin C is affected by the renewal rate of ascorbic acid (Dong & Yang, 2019). In addition, the reason for the decrease in vitamin C content after plasma application may be due to the oxidative effect of the plasma or the UV radiation occurring during treatment (Starek et al., 2019).

3.2.5. Bioactive Compounds

Bioactive compounds are compounds that are biologically and physiologically active and have multiple health benefits. Food quality, nutritional value, and antioxidant content are just a few of the many aspects that are impacted by these compounds. The anti-inflammatory, anticancer, antiviral, antidiabetic, and antitumor properties of bioactive compounds make them extremely significant. Anthocyanin and phenolic compounds can be given as examples of these compounds (Banwo et al., 2021). Several studies have examined the impact of cold plasma treatment on bioactive compounds in foods and its subsequent effect on shelf life.

In the literature, the bioactive compounds of fresh products have generally been examined. In addition, there are also studies conducted on juice and fresh/dried oilseeds. In three different studies conducted on blueberries, fresh-cut strawberries, and strawberries, DBD treatment was applied, the samples were stored and their bioactive contents were examined after storage. A similar increase in bioactive compound content was observed in these three studies (Dong & Yang, 2019; Li et al., 2019; Rana et al., 2020). The anthocyanin content increased by 2.2 times in the blueberry study, but it decreased in the fresh-cut strawberry study after the treated samples' anthocyanin value initially exceeded that of the control during the first 3 days of storage (Dong & Yang, 2019; Li et al., 2019). At the end of storage, total flavonoid content increased by 31.39% and 43.58% in control and treated samples, compared to day 0. DPPH value increased compared to the control in the first 3 days of storage. It then decreased with storage time. The DPPH value is a significant parameter indicating the antioxidant capacity of a food product. An increase in this value reflects a greater ability of the food to neutralize free radicals, thereby enhancing its resistance to oxidative degradation. High antioxidant capacity is directly associated with extended shelf life, preservation of nutritional value, and improvement of sensory qualities such as taste, aroma, and color. Therefore, the observed increase in DPPH levels following cold plasma treatment is highly important in terms of both food quality and shelf life (Li et al., 2019). In a similar study, strawberries treated with DBD for 15 minutes had higher total phenolic content (TPC) and antioxidant activity; however, overexposure for 30 minutes resulted in lower TPC (Rana et al., 2020). Similar to the results in these studies, treated samples produced a higher phenolic content from 10 to 15% compared to untreated ones in tomato juices, orange, apple, and sour cherry nectar juices and foods stored following the application of Atmospheric Pressure Plasma Jet (APPJ) (Dasan & Boyaci, 2018). In a study conducted with cloudy apple juice, total phenolic content increased by 69 and 64% in 4 and 5-minute treatments after storage with spark discharge plasma treatment. Following 3, 4, and 5 minutes of treatment, there was an increase in DPPH % inhibition from 79.4 ± 0.8% to roughly 93% (Illera et al., 2019). Unlike the results in this study, a decrease in total phenolic content (TPC) over time was observed in both the control and PAW-treated fresh-cut pears; however, the extent of this reduction varied depending on the treatment applied. The control group exhibited the highest retention of TPC, with only a 15.26% loss after 12 days of storage. In contrast, treatments with NaClO, 6-kV, 8-kV, and 10-kV PAW resulted in TPC reductions of 22.52%, 24.18%, 24.45%, and 16.08%, respectively (Chen et al., 2019a). In a study conducted on fresh and dried walnuts, plasma jet treatment was applied and stored. The 11-minute application did not have any effect on total phenolic content and antioxidant activity. An increase in these values was observed after 15 and 30 days of storage (Amini & Ghoranneviss, 2016).

In general, cold plasma treatment has a positive effect on phenolic stability in foods. In addition, cold plasma treatment type, duration, and storage time may affect the bioactive compound content. In some studies, the initial decrease of phenolic substance in the treatment may be due to the antioxidative capacity of phenolic compounds in scavenging free radicals produced in plasma. Later, the reason for the increase in TPC may be due to the plasma reagents produced during processing with cold plasma with sufficient energy (Herceg et al., 2016).

3.3. Microbial Changes during Storage of the Foods

Cold plasma, which is known to have a high antibacterial effect, has been proven by studies to have a synergistic sterilization effect of the ultraviolet photons and charged particles it contains, and it is known to inactivate bacteria, fungi, viruses, even cancer cells, spores and phages (Kandemir et al., 2021). Recently researchers have been performing surface sterilization and microbial inactivation of fruits, various seeds and vegetables with cold plasma technology. Reactive species formed by cold plasma technology, which cause lesions on cell surfaces by chemical interaction with microorganisms and can pass through the cell membrane of microorganisms, react with membrane macromolecules during this transition. Thus, DNA modifications and faulty cell replication occur due to disruption of cell integrity. The damage caused by reactive species, the damage caused by UV photons to cell membranes and cellular components inactivates microorganisms. Shelf-life studies on various fruits, vegetables, meat products, and seafood indicate that cold plasma extends shelf life by reducing the initial microbial load of foods (Kim et al., 2014).

Dong & Yang (2019) subjected blueberries, which are susceptible to post-harvest microbial growth, to cold plasma treatment to extend shelf life and improve quality. For this purpose, the fruits were treated with dielectric barrier discharge (DBD) cold plasma at 36 V, 1.8 A, and atmospheric pressure for durations of 0, 2, 4, 6, 8, and 10 minutes. Following the treatment, they were stored under controlled laboratory conditions at 25°C and 50% relative humidity for 0, 4, 8, 12, 16, and 20 days. After 10 minutes of cold plasma application, a 93% decrease in the bacterial count and a 25.8% decrease in the fungal count were determined, and also after 20 days of storage, 6, 8, and 10 minutes of cold plasma treatment resulted in 17.7%, 14.3%, and 5.2% decreasing decay rates, respectively. In the study conducted by Chen et al. (2019a), 6, 8, 10 kV plasma-activated water (PAW) treatment was applied to fresh-cut pears for 5 minutes and the shelf life of fresh-cut pears stored at 4°C for 12 days was checked. According to the results obtained, at the end of 12 days, total aerobic bacteria count (log CFU/g) was 5.11 ± 0.01 in the control group and 4.46 ± 0.05 in the treated sample, yeast count (log CFU/g) was 5.29 ± 0.02 in the control group and 4.25 ± 0.02 in the treated sample and mold count (log CFU/g) was 2.48 ± 0.06 in the control group and 1.71 ± 0.13 in the treated sample, proving that cold plasma treatment significantly affected microbial growth.

In another study, strawberries were quartered and subsequently subjected to dielectric barrier discharge (DBD) plasma treatment at 45 kV for 1 minute, followed by storage at 4 °C for one week. The total aerobic bacterial count of strawberries with cold plasma treated at the end of 7 days was 3.98 log CFU/g in the sample with treated compared to 5.39 log CFU/g for the control group (Li et al., 2019). Similarly, in another study, dielectric barrier discharge (DBD) was applied to strawberries at 60 kV for treatment durations of 10, 15, and 30 minutes. A 15-minute atmospheric cold plasma (ACP) treatment resulted in an approximately 2-log reduction in the microbial load of strawberries, indicating a significant enhancement in microbial safety and a reduced risk of spoilage. It was found that while untreated strawberries degraded in 2 days, cold plasma treated strawberries' shelf life was extended to 5 days at 25°C and 9 days at 4°C due to microbial inactivation (Rana et al., 2020).

In a study conducted on ready-to-eat rocket leafy salad, surface dielectric barrier discharge (SDBD) cold plasma was applied at 6 kV to evaluate its effects on product quality and shelf life. The salad samples were exposed to plasma treatment for 5, 10, 15, and 20 minutes. Following the treatment, the samples were stored at three different temperatures (2 °C, 5 °C, and 9 °C) for a period of 5 days to assess the impact of both treatment duration and storage conditions on product stability and microbial safety. It was found that the initial numbers of yeast/molds and lactic acid bacteria decreased by 0.493 and 0.996 log CFU/g after treatment of cold plasma of rocket leaves. Treatment of cold plasma for 10 minutes was found to be sufficient for microbial inactivation and leafy rocket salad's shelf life was checked at 2, 5, and 9°C after treatment. According to the study, the salad's shelf life was estimated as 63, 57, and 37 hours for the control samples, while the treated salad's shelf life was achieved as 116, 84, and 55 hours, respectively (Giannoglou et al., 2020).

Tappi et al. (2016) conducted a study on freshly cut melons, applying dielectric barrier discharge (DBD) at 15 kV power for 15 + 15 and 30 + 30 minutes. The cold plasma treatment resulted in a significant microbial reduction on melons. Specifically, a 3.4 log reduction was observed for mesophilic bacteria, while lactic acid bacteria exhibited a 2-log reduction. In contrast, psychrotrophic bacteria were less affected by the treatment, with reductions not exceeding 1 log CFU/g. These findings indicate that the effectiveness of plasma treatment varies depending on the microbial group, with mesophilic and lactic acid bacteria being more susceptible compared to psychrotrophs. Also, according to the results of study, the shelf life of melons was prolonged in the 4-day shelf-life control. In a study involving fresh tomato juice, atmospheric cold plasma treatment was applied using nitrogen gas at a power of 40 W and a voltage of 3.8 kV. The exposure durations ranged from 0.5 to 5 minutes to assess the treatment's impact on microbial inactivation and quality parameters. Following plasma application, the treated tomato juice samples were stored at 4 °C for 5 days. Total aerobic mesophilic bacterial colonies, yeasts, and molds decreased by 3.45 log CFU/ml, 3.55 log CFU/ml, and 3.32 log CFU/ml, respectively, and were found to extend shelf life compared to 5 days of shelf-life monitoring (Starek et al., 2019).

In a study carried by Mol et al. (2023), fresh sea bass samples were subjected to atmospheric cold plasma treatment at 30 kV for varying exposure times of 0.5, 1, 3, 5, 7, and 10 minutes. Following treatment, the samples were stored under refrigerated conditions at 2 ± 1 °C for a period of 5 days. Significant reductions in mesophilic aerobic bacterial counts were observed after 7 and 10 minutes of treatment, with levels decreasing from 4.66 log CFU/g to 3.37 log CFU/g. In the study of Olatunde et al. (2020), in-bag dielectric barrier discharge (IB-DBD) cold plasma treatment (0–120 kV) was applied to Asian sea bass slices. A reduction in microbial load ranging from 0.73 to 0.81 log CFU/g was achieved. Also, according to the shelf-life follow-up lasting 18 days at 4°C, it was determined that the shelf life of the sea bass was extended by 3 days. Chicken breast samples were treated using dielectric barrier discharge (DBD) cold plasma at a power of 233 ± 5 W and a voltage of 100 kV for 1, 3, and 5 minutes. Following treatment, the samples were stored for 24 days to assess the effects of plasma exposure time on shelf-life extension and quality preservation. The mesophiles, psychrotrophs, and Enterobacteriaceae population of chicken breasts with cold plasma treatment were 1.5, 1.4 and 0.5 log lower than those of chicken breasts without cold plasma treatment at 24 days, hence the shelf life was 6 days longer (Moutiq et al., 2020).

Food contamination by fungi and mycotoxins is a major global issue that presents a significant challenge to the food industry. Some mycotoxins have harmful effects that can be mutagenic, carcinogenic, cytotoxic, or genotoxic to humans. Mycotoxins can be transmitted and reproduced during pre-harvest, post-harvest, processing, and storage. In addition to harming human health, it causes annual food loss and economic losses. Mycotoxins must fall below the maximum acceptable limits. Different approaches are being tried for this, one of them is cold plasma technology. The food industry has become interested in cold plasma, a non-thermal technology that can degrade inactivated microorganisms including mycotoxin (Neuenfeldt et al., 2023). There are studies aiming to reduce mycotoxins found in foods to acceptable levels by applying cold plasma treatment and examining shelf life.

In one of these studies, maize samples were subjected to pulsed dielectric barrier discharge (DBD) plasma treatment at 6 kV for 10 minutes. A reduction of up to 66% in aflatoxin B1 and fumonisin B1 levels was achieved (Wielogorska et al., 2019). The shelf life of samples treated with PAW treatment was increased by 4–8 hours in comparison to tap water in fresh shrimp treated with conventional tap water ice and PAW ice treatment. In addition, treatment did not affect the protein and there has been a study showing that it can be used in the preservation of fresh produce (Liao et al., 2018). Furthermore, the elimination of mycotoxin and inactivation of microorganisms typically occur concurrently with other possible advantageous effects of cold plasma, like the inactivation of enzymes and the extension of shelf life (Gavahian & Cullen, 2020). Cold plasma treatment is a promising technology to help reduce mycotoxin levels, but more studies are needed for shelf life, nutrition, and safety.

4. Conclusion

The growing interest in non-thermal food processing technologies arises from the detrimental effects of conventional thermal treatments on the nutritional and sensory quality of foods. Among these alternatives, cold plasma has emerged as a promising novel technology due to its effective microbial inactivation capability without compromising food quality. Numerous studies have demonstrated that cold plasma treatment not only preserves but can also enhance the sensorial and nutritional properties of various food products throughout storage. Furthermore, it has been shown to significantly extend shelf life by reducing microbial load. However, the interaction mechanisms between cold plasma and specific food components such as proteins, lipids, vitamins, and bioactive compounds remain complex and require further in-depth investigation. For cold plasma to transition from laboratory-scale applications to industrial food processing, research must go beyond efficacy data and address critical gaps related to process standardization and scalability. Specifically, future studies should focus on the reproducibility of plasma dosage, the uniformity of treatment across irregular food surfaces, and the influence of processing parameters on both safety and quality outcomes. In addition, energy consumption, equipment cost, and the compatibility of plasma systems with different packaging materials must be systematically evaluated to ensure economic feasibility. Regulatory approval processes also require long-term toxicological assessments and the development of internationally accepted validation protocols. Addressing these challenges will require interdisciplinary collaboration between food technologists, engineers, material scientists, and regulatory experts. By targeting these research needs with concrete, application-oriented studies, cold plasma technology can be advanced from a promising laboratory method to a safe, standardized, and commercially viable food processing solution.

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6. Conflicts of Interest

The authors declare no conflict of interest.

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Data availability statement

Data associated with this manuscript are available from the corresponding author, upon reasonable request.

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