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Application of cold plasma technology in the food industry and its combination with other emerging technologies

Yilmaz Ucar [a,b,*], Zafer Ceylan [c], Mustafa Durmus [b], Oktay Tomar [d], Turgay Cetinkaya [e]

[a] Fatsa Faculty of Marine Sciences, Ordu University, Ordu, Turkey
[b] Department of Seafood Processing Technology, Faculty Fisheries, Cukurova University, Adana, Turkey
[c] Department of Gastronomy and Culinary Arts, Faculty of Tourism, Van Yüzüncü Yıl University, Van, Turkey
[d] Faculty of Agriculture and Natural Science, Arslanbey Campus, Kocaeli University, Kocaeli, Turkey
[e] Food Processing Department, Armutlu Vocational School, Yalova University, Yalova, Turkey

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ABSTRACT

Background: The search for preservation methods that can be used as alternatives to heat treatment is a significant issue in food quality. Utilization of plasma technology, a useful nonthermal technique, is encouraged in the food industry because of its effectiveness in preserving the natural aroma and flavor and antimicrobial activity.
Scope and approach: The cold plasma (CP) technique is used for food processing for enhancing antimicrobial activity, structural modification, decontamination of surfaces, and disinfection of food-processing instruments. Currently, a combination of CP with other promising approaches, such as nanotechnology applications, including nanofiber, nanoemulsion, nanoparticles, and nanoencapsulation, and emerging nonthermal technologies, including pulsed electric field (PEF), pulsed light (PL), and ultrasound, is gaining increased attention. In addition to its many advantages, CP is a low-cost method that can be an alternative to heat-based techniques used for the processing of food products. Therefore, application of CP technology in the food industry has been described in this review.
Key findings and conclusions: Demand for raw or non-heat-treated foods is increasing due to factors, such as the preference of consumers for healthy foods and the development of consumer awareness. However, plasma technology can be used to improve microbial quality and prevent rapid physical, chemical, and sensory changes. Studies have shown that CP application is effective in offering higher-quality products for consumption by extending the shelf life of foods. Positive results have been achieved in terms of both quality and microbial activity in different food groups with plasma technology. In addition to recently published articles, the combined hurdle effect of CP with other emerging novel technologies such as nanotechnology, pulsed electric field (PEF), pulsed light (PL), and ultrasound processing on food or food packaging materials could be further studied and used to ensure food safety. However, the high initial investment costs for CP need to be considered.

1. Introduction

Food preservation and food safety concerns among food producers and consumers are becoming increasingly important globally. The use of alternative techniques for food processing instead of heat treatment have recently been reported in the food industry (Ekezie, Sung, and Cheng 2017; Sonawane and Patil 2020; Zhao, de Alba, Sun, & Tiwari, 2019). In addition, consumer demand for raw or unprocessed food is increasing with the rising interest in healthy lifestyles. However, problems such as the lack of microbiological safety can result in foodborne diseases. Therefore, the search for alternative sterilization techniques is necessary. Non-thermal techniques preserve the natural aroma and flavor, and increase microbiological food safety without causing loss of quality, which is observed in heat treatment. These advantages have resulted in increased interest in alternative techniques for food processing. One of these alternative new generation methods is plasma technology (C. M.G. Charoux et al., 2021; Clémentine M.G. Charoux et al., 2020; P. Y. Lee, Lusk, Mirosa, & Oey, 2016; Mir et al., 2020).

Plasma technology is nonthermal technique applied to foods in recent years. It is actually a technique developed for bonding and curing polymers, it is also used in many other fields. Plasma technology is the use of ionized gas in nonthermal sterilization technology (Fernández,

* Corresponding author. Department of Seafood Processing Technology, Faculty of Fisheries, Cukurova University, 01330, Balcalı, Adana, Turkey.
E-mail address: yucar@cu.edu.tr (Y. Ucar).

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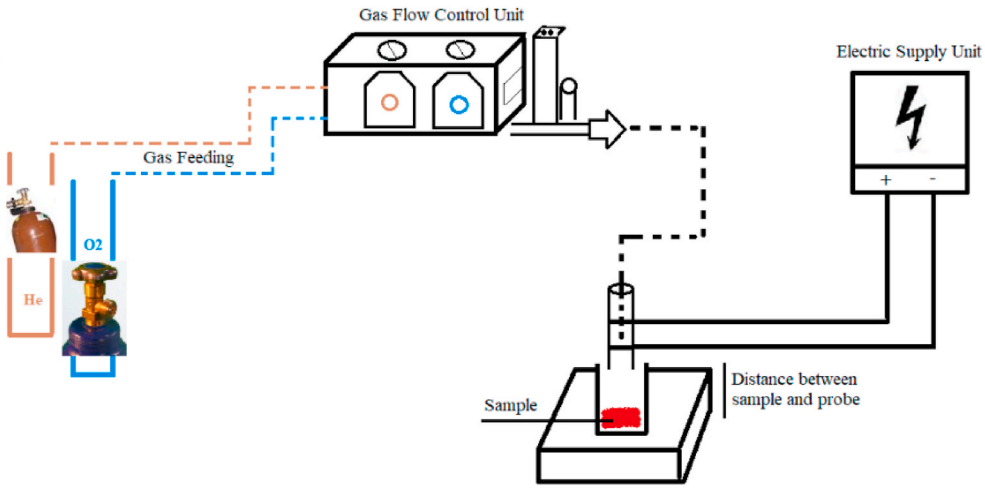

Fig. 1. A sample DBD plasma system.

Noriega, & Thompson, 2013). The principle of plasma technology is based on the partial ionization of positive and negative ions, free radicals, charged particles in the form of electrons and photons, and gas-containing molecules. Plasma can interact with bacterial cells and inactivate microorganisms, as well as spores and viruses (Mendes-Oliveira, Jensen, Keener, & Campanella, 2019; Misra, Tiwari, Raghavarao, & Cullen, 2011; Umair et al., 2021).

Plasma technology used especially for microorganism inactivation is considered advantageous because it is environmentally safe, does not contain a large amount of hazardous or toxic substances, and does not lead to the generation of persistent toxic compounds, and its process is sterile and reproducible (Yang, Chen, & Gao, 2009). However, there are disadvantages such as the cost of initial installation, security measures, process-specific equipment requirements, and the need for trained personnel (Kruk et al., 2011; Yun et al., 2010). Thus, the determination of plasma properties and principles with potential disadvantages and advantages to food components, and enzyme degradation, and the role of sanitation in food processing equipment is important for the scientific community. In contrats, CP technology can be applied to nanomaterials, such as nanofibers, and nanoparticles, or electrospinning solution solid matter to modify final product structures and increase antimicrobial activity. Furthermore, pretreatment, post-treatment, or simultaneous application of CP with other emerging technologies, such as nanotechnology, PEF, PL, and ultrasound processing, could guide food producers and open up of research. Thus, review describes the current knowledge on different views regarding this technology in the food industry.

2. Principles of CP

CP is used in fields such as decontamination technology, surface treatment, sterilization of medical instruments, and food safety. Lacombe et al. (2015) have reported that this technique can be applied to air, water, and surface disinfection of food, and it processes materials without causing any damage to living tissues. CP is divided into two classes based on the pressure of the working environment: low-pressure plasma and atmospheric-pressure plasma. The main principle of low-pressure plasma is that it is generated at low pressures or even in a vacuum. The other plasma method is a CP system that operates at radio-frequency. It creates ionization using fast electrical stimulations at periodic intervals and by operating the gases in the system at different voltages and powers (Niemira, 2012).

Owing to the low temperature in CP applications, the energy cost is lower than that of other plasma types. This situation is preferred in the food industry. Indirect CP is applied to collective food samples. It is applied with an integrated system placed on food processing belts (Toyokawa, Yagyu, Misawa, & Sakudo, 2017). In indirect application, the sample is placed away from the plasma and exposed only to reagents. This application is known as “afterglow”. This technique, which is applied to packaged foods during washing, or in the form of fog, or a spray, is used for the inactivation of microorganisms in packaged food products and the prevention of contamination that may occur after packaging. In addition, although plasma interacts with the components of the food, it does not penetrate the food, and only causes changes on the surface of the food (Schnabel et al., 2016; Shen et al., 2016).

CP, which is created under vacuum and at room temperature, is an economical, and reliable method that does not harm the environment, sterilizes cleaning materials, and inactivates/damages bacteria that may pose a risk to human health. Among the CP methods generally used in food processing, vacuum ultraviolet radiation is effective against organic components of contaminating elements on the surface. This causes contaminants with a high molecular weight to be detached from the surface (Donegan, Milosavljević, & Dowling, 2013). In the second stage, the oxygen types (O_2^+, O_2^-, O_3, O, O^+, O^-, ionized ozone, steadily excited oxygen, and free electrons) created in the plasma are effectively used in decontamination. These oxygen types react with organic contaminants with lower molecular weight hydrocarbons in the form of H_2O, CO_2, and CO. The process results in the sterilization of the treated surface. It has been reported that the atoms and ions activated during plasma generation can cause etching while breaking down organic contaminants (Pankaj et al., 2014).

In the decontamination process performed using the CP technique, harmful gases, including CO_2, NOx, water vapor with traces of carbon-monoxide, and other hydrocarbons, are produced although in small amounts. Moreover, it has been reported that the amount of harmful gas produced by the plasma process in 1 year is equal to the amount of gas exiting the exhaust of an automobile in 10 min (Prysiazhnyi, Zaporojchenko, Kersten, & Černák, 2012).

This technology generates varieties of reactive oxygen species (ROS) that are adequate for the total bacterial load within the semi-neutral plasma system, including bacterial spores and spoilage/pathogenic microorganisms. This is the biggest advantage of this system in terms of food decontamination (Butscher, Zimmermann, Schuppler, & Rudolf von Rohr, 2016; Choi, Puligundla, & Mok, 2017a; Sohbatzadeh, Mirzanejhad, Shokri, & Nikpour, 2016; Umair et al., 2021).

The effect of plasma treatment on microbial cells changes depending on plasma ions and cell interactions. Reagents in the plasma structure directly exert an oxidative effect on the outer surfaces of microbial cells. The effect of plasma also depends on the amount of water in the structure of the organism. The generally accepted hypothesis is that plasma damages the DNA of organisms. According to previous studies, plasma

Table 1
Antimicrobial effect of cold plasma application on some food products.

Food Type	Microorganisms	Plasma Source	Treatment Conditions	Observation	References
Smoked Salmon	*Photobacterium phosphoreum* *Listeria monocytogenes*, *Lactobacillus sakei*	DBD	A: 93% Ar + 7% CO_2 B: 100% Ar C: 93% Ar + 7% CO_2 + 100% Ar	A: Reduction, 3 log CFU/g for 60 s B: Reduction, 3 log CFU/g for 120 s C: No difference	Chiper, Chen, Mejlholm, Dalgaard, and Stamate (2011)
Dried Laver	Aerobic bacteria	Corona discharge plasma jet	Air atmosphere; 0–20 min at 20 kV, 58 kHz	Reduction: 2.0≥ x ≥ 1.5 log CFU/g after 20 min treatment	(J. W. Kim, Puligundla, & Mok, 2015)
Breast Chicken Fillets	Infected with *Escherichia coli* and *Staphylococcus aureus*	Atmospheric cold plasma	Argon with 99.9% purity at the fixed flow rate of 6 L/min; 10 min at 32 kHz	Reduction: *S. aureus* cell number by at least 3 log CFU/g Reduction: *E. coli* pretreated with essential oils considerably decreased by approximately 4 log CFU/g	Sahebkar, Hosseini, and Sharifan (2020)
Blueberries	Inoculated with Tulane virus (TV) and Murine Norovirus (MNV)	Atmospheric pressure plasma jet	CP alone or with ambient-temperature air 0–2 min; 47 kHz	Reduction: TV 1.5 PFU/g compared to the control after 45s treatment ($p < 0.05$), 3.5 log PFU/g after 120s (7 cfm ambient air) Reduction: MNV by 0.5 log PFU/g compared to the control at 15s, >5 log PFU/g at 90 s	Lacombe et al. (2017)
Fresh Mackerel Fillets	Psychrotrophic bacteria, Lactic acid bacteria, *Pseudomonas*	DBD	Air; 1, 3 and 5 min; 70 kV, 80 kV; 50 Hz	Reduction: ≤1.3 log CFU/g 80 kV 5 min was most effective	Albertos et al. (2017)
Dried Alaska Pollock Shreds	Aerobic bacteria, marine bacteria, *S. aureus,* yeasts, and molds	Corona discharge plasma jet	Air; 0, 1, 2, and 3 min	Reduction: 2.5 ≥ x ≥ 1 log CFU/g after 3 min treatment	Choi, Puligundla, and Mok (2016)
Dried Squid Shreds	Aerobic bacteria, marine bacteria, *S. aureus*	Corona discharge plasma jet	Air 2 L/s; 0, 1, 2, and 3 min; 20 kV; 58 kHz; 25 mm distance	Reduction: 2.0≥ x ≥ 0.9 log CFU/g	Choi et al. (2017a)
Shrimp	Total viable count	DBD-atmospheric cold plasma functionalized water	Ice, pH: 3.04, ORP: 485 mV, EC: 427 ms/cm, H_2O_2: 2.15 mg/L, Ozone: 8.60 mg/L, NO_3: 78.2 mg/L 30 W	Reduction: 2.1 log CFU/g	Liao et al. (2018)
Kumquat fruits	Aerobic bacteria, and yeasts, and mold	Corona discharge plasma jet	Air; 8 kV DC; 20 kHz; current levels of 2.0, 3.0, and 4.0 A	Reduction: 0.77–1.04 log CFU/g at 2.0 A current 1.08–1.57 log CFU/g at 3.0 A current	Puligundla, Lee, and Mok (2018)
Lettuce in Wash Water	Pseudomonas. fluorescens and Listeria innocua inoculated on lettuce	Atmospheric CP submerged DBD	Air; 20 kV for 0–10 min; 25.8 kHz; ~7.45 W	Reduction: *P. fluorescens* below the detection limit within 3 min Reduction: *L. innocua* by ~2.4 log CFU/g after 5 min	Patange, Lu, Boehm, Cullen, and Bourke (2019)
Salmon Nigiri and Hosomaki	Aerobic bacteria	DBD	Air; 5 min; 70 and 80 Kv; 50 kHz	Reduction: 1–1.5 log CFU/g (Not a significant antimicrobial effect)	Kulawik et al. (2018)
Duck Eggshell	*Salmonella* contaminated	Arc atmospheric pressure plasma	Air; Pressure of 101 kPa; Voltage of 12,000 V; 0, 10, 20, 30, and 40 s; Temperature of 20–49 °C	Reduction: 4.09 log cycle when plasma was applied for 40 s	Gavahian, Peng, and Chu (2019)
Korean Rice Cake	*E. coli, S. typhimurium, Listeria monocytogenes,* and *Penicillium chrysogenum* inoculated	Plasma activated water (PAW) using surface DBD	Air; 20 min; 8 kV, 14.4 kHz, and a power of 51.7 W	Reduction: *E. coli* 2.01–2.03 log CFU/g *S. Typhimurium* 2.08–2.12 log CFU/g, *Listeria monocytogenes* 1.98–2.17 log CFU/g *Penicillium chrysogenum* ~2 log CFU/g	Han et al. (2020)
Corn	Aflatoxin B_1	DBD	Air and MA65; 0, 1, 2, 5, 10, 20, and 30 min; 5, 40, 80% relative humidity (RH)	Reduction: 62% and 82% in 1 and 10 min, respectively at RH of 40% air	Shi, Ileleji, Stroshine, Keener, and Jensen (2017)
MAP Packaged Ready-to-Eat Ham	*L. monocytogenes*	DBD	0–30 kV under atmospheric pressure; 3.5 kHz; 23 ± 2 °C; 2.5 cm diameter	Initial cell population on ham surfaces was 8 log CFU/cm^2 Reduction: MAP1 (20% O_2 + 40% CO_2 + 40% N_2) higher log reduction (>2 log reduction) in comparison with MAP2 (50% CO_2 + 50% N_2) and MAP3 (100% CO_2), irrespective of ham formulation	Yadav et al. (2020)

affects the cell through the formation of ROS around the DNA. ROS including hydroxyl radicals, hydrogen peroxide, and superoxide anions are formed by the plasma technique. Therefore, malondialdehyde is formed in the microbial cells owing to plasma application and the DNA structure is damaged by malondialdehyde (Dobrynin et al., 2009; Thirumdas, Sarangapani, & Annapure, 2015). Fig. 1 shows a sample dielectric barrier discharge (DBD) system.

3. Advantages and disadvantages of using CP

CP treatment is an environmentally friendly process that does not generate toxic waste. It can allow decontamination at low temperatures with little energy expenditure and low cost. In addition, one of the most important properties of CP is that it can inhibit microorganisms adhering to the surfaces in a short time. Moreover, the process enables rapid sterilization without exposure to residues in the final products such as plastic bottles, caps, and packaged food (Niemira, 2012; Pankaj et al., 2014).

The use of CP for the processing of high-fat food products may be result in a rapid increase in the thiobarbituric acid reactive substances (TBARS) value because of the production of ROS, such as ozone, singlet oxygen, and peroxide (Albertos et al, 2017, 2019; Ganesan, Tiwari, Ezhilarasi, & Rajauria, 2021; Olatunde, Shiekh, & Benjakul, 2021). For instance, plasma treatment of squids before drying has been reported to increase the production of primary oxidation products, making the lipids more vulnerable to oxidation during storage (Choi et al, 2017a, 2017b; Gavahian, Chu, Mousavi Khaneghah, Barba, & Misra, 2018). In addition, lipid oxidation may cause the loss of nutrients and sensory properties of food and may change organoleptic properties (Olatunde et al., 2019, 2021). Modified atmospheres have been suggested to overcome lipid oxidation issues. Therefore, modified gas mixtures can be used to reduce oxygen levels and inhibit microbial growth and quality deterioration. Vacuum packaging plasma treatment may also prevent oxidative rancidity in food products (Albertos et al, 2017, 2019; Choi et al., 2017b; Zhao et al., 2019). The optimization of process parameters, such as input power, carrier gas composition, process time, and temperature, is another way to minimize lipid oxidation (Gavahian, Chu, & Jo, 2019; Gavahian et al., 2018; Olatunde et al., 2021). CP treatment may result in lower water holding capacity of fish fillets and water leaks during storage (Kulawik & Kumar Tiwari, 2019). Taken together, more research is needed to understand the chemical reaction and mechanism of plasma in food (Ganesan et al., 2021; K.; Zhang, Wang, & Zhuang, 2019). In addition, based on the previous literature, there is still limited knowledge on the effect of CP treatment on the toxicity, lethality, and biosecurity of foods.

4. Antimicrobial treatment with CP technology in the food industry

Table 1 shows the antimicrobial effects of CP application on some food products. In recent years, in line with a healthy lifestyle and consumer demand, more food diversity and an increase in fresh product consumption have led to the applicability of alternative technologies in the food industry (Thirumdas et al., 2015). However, this increase has also elevated the risk of foodborne disease outbreak due to fresh or low-processed foods. Consuming raw, non-heat-treated, or unprocessed food is often considered a microbial risk. Therefore, alternative techniques are needed for heat-sensitive products to prevent this situation and to provide safe food. In addition, the desire to minimize the changes that occur during the processes applied to the food ingredients restriction of microbial load by state regulations, and demand for high-quality and long-shelf-life food have led to the investigation of different applications other than heat treatment (Fernández et al., 2013).

For consumption of minimally processed foods, non-preserved foods are required to undergo antibacterial processes that do not alter product properties. In particular, this refers to fresh produce a typical example being raspberries. In addition, some ready-to-eat foods such as packed ham and deli foods, benefit from a postprocessing antibacterial treatment.

Bacterial inactivation using nonthermal plasma is a complex process and its mechanism of action is a subject of interest that is still not completely understood (Lu, Patil, Keener, Cullen, & Bourke, 2014). However, CP efficacy is directly correlated with the bacterial cell wall thickness in several species. CP is hypothesized to have different targets within the cell, including the cell membrane, cell wall, DNA, and intracellular proteins. Plasma species can break important bonds in the cell wall (peptidoglycan) structure in gram-positive bacteria and lead to membrane lipid peroxidation in gram-negative bacteria. This disruption of the outer shell of the cell will lead to leakage of cellular components, including potassium, nucleic acid, and proteins. After the cell wall is broken, reactive species can penetrate into the interior of the cell leads and further damage DNA and intracellular proteins with oxidative or nitrosative species. Plasma discharge results in the generation of a wide range of reactive species responsible for the antimicrobial effects. Depending on differences in the cell envelope, different inactivation responses have been observed in plasma sterilization studies, wherein gram-positive bacteria were found to be more resistant than gram-negative bacteria (Ermolaeva et al., 2011; Liao, Liu, Chen, Ye, & Ding, 2021). In contrast, other studies indicated no significant differences in the effect of plasma treatment between gram-positive and gram-negative bacteria (Kayes et al., 2007; Venezia et al., 2008). The differences in physical damage caused by plasma in gram-negative and gram-positive bacteria imply a difference in the cellular damage pattern, which may be because of differences in cell structure and composition. Antimicrobial particles in plasma react directly with the outer membranes of gram-negative bacteria and eventually kill them; however, ROS produced from plasma first penetrate the cell wall and membrane of gram-positive bacteria before reacting with internal cellular components and eventually killing the bacteria (Huang et al., 2020).

Milk is a naturally nutritious food that can be consumed daily. However, a major problem is that if contaminated milk is consumed, pathogenic and spoilage bacteria can cause serious health problems (Tiozzo et al., 2011; Todd & Notermans, 2011). Therefore, thermal processes such as pasteurization and high-temperature heat treatment are applied to prevent the consumption of raw milk. However, these applications cause changes in the physicochemical properties of the milk. Studies have shown that milk is not suitable for many new thermal techniques because of its complex structure (Segat, Misra, Cullen, & Innocente, 2015). Plasma technology is a new technology in the dairy industry. Factors such as the ability to apply the plasma technology at low temperatures and maintaining a stable temperature during application make it a promising technology in the dairy industry (Korachi et al., 2015). Yong, Kim, Park, Alahakoon, et al. (2015) reported the effects of the CP technique on sliced cheese contaminated with *Listeria monocytogenes;* the microbial load increased in proportion to the input power and plasma exposure, and a significant decrease was observed in the bacterial load.

Gurol, Ekinci, Aslan, and Korachi (2012) has investigated the inhibition of *Escherichia coli* by plasma technology applied at low temperatures in raw milk containing different fat ratios (full fat, semi-skimmed, and skimmed). They reported that the plasma technique applied at different times caused a 0.3 log CFU/g reduction in the total count of *E. coli* and that the technique did not cause a significant change in parameters such as color and pH of the raw milk. Although there has been increasing interest in the use of plasma as a sterilization technique, this was the first study to test the use of plasma technology (low temperature) as a decontamination technique in milk. Further experiments are needed to be carried out in order to demonstrate the full effects of this system on milk, including studies on other microorganisms and the effects of low-temperature plasma on the chemical, physical, and compositional properties of milk.

It has also been found that plasma is effective against bacteria and some viruses on meat and meat products (Bae, Park, Choe, & Ha, 2015; Gavahian, Chu, & Jo, 2019; Gök, Aktop, Özkan, & Tomar, 2019; Puligundla & Mok, 2016).

Kim, Lee, Cho, and Kim (2013) investigated the inactivation of *Campylobacter jejuni* in chicken ham using the atmospheric-pressure plasma method operating at radiofrequency and using argon gas. They reported a decrease in the bacterial growth up to 3 log and 1.5 log CFU/cm^2 after 6 and 10 min of treatment, respectively (Ulbin-Figlewicz, Brychcy, & Jarmoluk, 2015). investigated the effect of CP on the inactivation of microorganisms on meat surface, meat quality, and pH value using helium, argon, and nitrogen gases. After 10 min of plasma application using helium and argon, there was a 3 and 2 log CFU/cm^2 decrease in the proportion of psychrotrophic and total bacteria, respectively. Although no interaction was observed in these bacterial groups with nitrogen application, the amount of yeasts and molds decreased by 1 log CFU/cm^2 after 10 min of treatment. It has been determined that the CP technique does not have any negative effects on the quality, color, and pH of meat. Noriega, Shama, Laca, Díaz, and Kong

Table 2
Effect of CP on the quality attributes of some food products and their treatment conditions.

Type of Food Material	Process Parameters	Source and Carrier Gas	Effect on Quality Attribute	Reference
Beef Jerky	15 kHz for 0 (control), 2.5, 5, and 10 min treatments	Flexible thin-layer plasma system, Ambient air	No significant changes were observed in shear force, and myofibrillar fragmentation index. Peroxide content and color parameters changed. Flavor, off-odor, and overall acceptance were negatively affected after 10 min treatment.	Yong et al. (2017)
Wolfberry	3 L/min; 20 kHz, and 750 W with a distance of 6 cm for 15, 30, 45, and 60 s	Atmospheric plasma, Air	Total phenolic content and total flavonoids content decreased with the various treatment times ($p < 0.05$). The color parameters (L*, a*, b*, and ΔE) decreased. 30–60 s processing resulted in a better color appearance than 15 s. Etched micro-holes on the surface observed. The rehydration ratio increased by 7–16%.	Zhou et al. (2020)
Chicken Breast	100 kV; 233 ± 5 W power; 0, 1, 3, and 5 min duration	DBD, Atmospheric CP	CP had minimal effect on the color, pH and water holding capacity of poultry meat. Shelf life extended by 6 days at 4 °C. From the 12th day onward the pH was lower ($p < 0.05$) compared to the control. Differences in mean malonaldehyde content and L*, a*, b* values were insignificant ($p > 0.05$).	Moutiq, Misra, Mendonça, and Keener (2020)
Tofu in PAW	10 L/min; a voltage difference of 2 kV between electrodes; 1 kHz; 1 Watt output power; 0–15 min	Plasma jet, Air at atmospheric pressure (<40 °C)	Up to 80% of the initial content of total polyphenols retained. Fresh-like texture and color properties maintained. 4, 8 and 15 min treatments did not cause significant ($p > 0.05$) effect on hardness and gumminess. An immediate softening (of between 16 and 26%) and loss of gumminess (of between 18 and 32%) occurred for <4 min.	Frías et al. (2020)
Dried Filefish Fillets	3.0 ppm ozone at a distance of 9.5 cm; UV light with a radiation spectrum between 180 and 270 nm); continuous temperature <32.5 °C; 0, 3, 5, 10 and 20 min	Air subjected to high-energy deep-ultraviolet (UV) light, and ozone	20 min application increased oxidation rate. 20 min treatment significantly reduced flavor and overall acceptability scores (from 6.82 to 5.82) Significant increase in TBARS after treatment, increasing with treatment time. 10 min application was most appropriate.	Park and Ha (2015)
Semi Dried Squid Shreds	20 kV DC voltage at 58 kHz; 1.5 A; 0–10 min	Corona discharge plasma jet	10 min did not exert significant changes ($p > 0.05$) in TVBN and the TMA content compared to controls. Significant changes ($p < 0.05$) in moisture content, water activity, pH, and color were observed. TBARS levels increased with increasing exposure time. Better sensory properties than those in the controls in terms of appearance, visual color, and flavor.	Choi et al. (2017b)
Barley Grain Cheddar Cheese	1 A current; 300 W; 3500 Hz; duty cycle was 70%; 0, 2, 4, 6, 8, and 10 min	DBD atmospheric CP system, Air	Protein, β-glucan and moisture content were not significantly affected. Germination parameters of barley grains was plasma time-dependent, and 6 min treatment showed the best results.	Feizollahi, Iqdiam, Vasanthan, Thilakarathna, and Roopesh (2020)
	15 kHz; the inner electrode at 100-W peak power and 2-W average power; 0, 2.5, 5, and 10 min.	DBD plasma within the food package, atmospheric gas containing nitrogen and O_2.	The pH and L* values decreased whereas TBA reactive substances values and b* values increased significantly. No significant changes in color and sensory appearance. Flavor and taste scores were significantly reduced in 5 and 10-min treated samples, respectively. Off-odor increased.	(Yong, Kim, Park, Kim, et al., 2015)
Rapeseed Seed	Air (2 L/min); 20 kV; 1.5 A; 58 kHz; 25 mm distance; 0–3 min	Corona discharge plasma jet generation under atmospheric pressure, Air	Sensory characteristics (appearance, color, flavor, taste, texture, overall acceptance were unaffected up to 2 min. >3 min negatively affected sensory characteristics (except color and texture).	Puligundla, Kim, and Mok (2017) Xiang et al. (2019)

(*continued on next page*)

Table 2 (*continued*)

Type of Food Material	Process Parameters	Source and Carrier Gas	Effect on Quality Attribute	Reference
Mung Bean Sprouts in PAW	5 kV; 40 kHz; 750 W, and flow rate of 30 L/min; Each 200 mL of sterile distilled water was exposed to plasma for 30 s 10 g of samples were immersed in PAW, incubated 10–30 min.	Atmospheric pressure plasma jet system based on gliding arc discharge in air	No significant difference in the total phenolic, flavonoid contents. No adverse change in appearance, color, flavor, and texture properties.	
Atlantic Herring	70 and 80 kV; 50 Hz; 1, 3, and 5 min	DBD system, Air	Significant reduction at 80 kV. 11 days of storage: Significant reduction in L* and a*, while a significant increase in b*. 8 days of storage: Significant initial reduction in pH and the lower pH were maintained. No differences in TBARS.	Albertos et al. (2019)
Pacific White Shrimp	220 V; 282 W; 50 Hz, and 1.9 A; 45, 90, and 150 s	Plasma jet, Air	Lower rate of increase in pH, TVB-N content, TBARS, free fatty acid, peroxide value, and fluorescent compounds ($p < 0.05$). No undesirable effects on sensory quality. 90 s was the most efficient.	Zouelm, Abhari, Hosseini, and Khani (2019)
Cherry Tomato	220 kV power, 8 kV output; 20 kHz; 2.0, 3.0, and 4.0 A, 0–120 s	Intermittent corona discharge plasma jet, Air at atmospheric pressure	Sensory properties (taste, flavor, color, and texture) of cherry tomatoes remained in an acceptable level. Treatment extended the shelf life.	(T. Lee, Puligundla, & Mok, 2018)
Fresh Cut Pear	65 kV for 1 min	In-package atmospheric CP	Respiration retarded and organoleptic properties and other quality attributes maintained. Peroxidase and pectin methylesterase activities were decreased.	(Y. Zhang et al., 2021)

(2011) reported that the CP technique applied at various time frequencies for the sterilization of chicken meat and skin contaminated *Listeria innocua* achieved 3 log reductions. They also recommended that the CP technique should be integrated with commercial applications in foods as well as used for *L. innocua* sterilization.

Fungal diseases seriously affect agricultural production and the food industry. Crop protection is usually achieved using synthetic fungicides; therefore, more sustainable, and innovative technologies are increasingly required. Atmospheric-pressure low-temperature plasma is a novel and suitable technique. Ambrico et al. (2020) reported that plasma treatment of phytopathogenic fungi causes quantitative and qualitative losses of products both in the field and postharvest. In vivo experiments on artificially inoculated cherry fruits demonstrated that the inactivation of fungal spores by the direct inhibitory effect of plasma extended their shelf life. Pretreatment of fruits before inoculation improves resistance to infections by activating defense responses in plant tissues. The inactivation effects of CP treatment on *Candida albicans* biofilms were assessed by He et al. (2020) in vitro and in vivo. The in vitro studies indicated that *C. albicans* in suspension and *C. albicans* biofilm were significantly inactivated by plasma treatment. The in vivo studies indicated that plasma treatment achieves the best antifungal effect at optimal dose (4 min in this case), because excessive plasma treatment damages the normal tissues and thus induces aggravation of infection compared with that in the 4-min treatment group.

Fungal diseases are one of the most important problems in hard-shelled fruits. In studies on inhibition of these microorganisms, the effect of sulfur hexane fluoride (SF_6), and air gas on hazelnut samples have been investigated (Basaran, Basaran-Akgul, & Oksuz, 2008). The antifungal effect of CP on *Aspergillus parasiticus* was investigated using the low-pressure CP technique. A 1 log decrease was observed at the end of 5 min of air gas application whereas 1 log decrease was observed when air gas was applied for 5 more minutes and temperature optimization was performed. However, when SF_6 gas was used, an effective decrease of approximately 5 log was observed. Sterilization has also been applied to apple surfaces and fresh fruits contaminated with *E. coli* O157: H7 and *Salmonella* Stanley (Niemira & Sites, 2008). It has been reported that a decrease in the number of bacteria was observed in all CP applications. When SF_6 and air gas were applied to legumes and wheat seeds contaminated with to *Aspergillus* spp. and *Penicilium* spp. using the low-pressure CP method, a 3-log reduction was observed in the samples (Selcuk, Oksuz, & Basaran, 2008). Park and Ha (2015) reported the effect of CP on dried filefish filet surfaces inoculated with *Cladosporium cladosporioides* and *Penicillium citrinum* and observed that the microbial loads decreased with increasing oxygen plasma treatment duration from 3 to 20 min. Increasing the duration of exposure to plasma to 20 min also significantly increased oxidation the rate and significantly reduced flavor and sensory scores. However, 10 min treatment was selected as the most acceptable application to inhibit mold growth while causing fewer changes to the physicochemical and sensory qualities. Albertos et al. (2017) effectively used DBD plasma for microbial inactivation and studies its effect on other quality parameters of fresh mackerel fillets. A significant reduction in the proportion of psychrotrophic bacteria, *Pseudomonas,* and lactic acid bacteria was observed. Furthermore, treatment time of 1–5 min and voltage of 70–80 kV influenced the CP effect. CP also resulted in low TBARS and pH values of fillets and preserved the color of the samples. However, a significant increase in lipid oxidation was observed and immobilized water within myofibrillar proteins was reduced. The peroxide value and conjugated dienes increased with longer treatments. Kulawik et al. (2018) investigated the effect of in-package DBD plasma on salmon and cooked rice sushi products (nigiri and hosomaki) to retard the growth of total aerobic bacteria during storage. A moderate effect was reported for the total aerobic counts. The TBARS value increased by up to 1.5 mg/kg, resulting in a slightly higher oxidation rate with the treatment, but there was no significant difference in fatty acid composition, moisture, and protein content. Liao et al. (2018) functionalized water using CP for 10 min and froze it at −20 °C to delay microbial growth in shrimp samples. In its ice form, plasma-functionalized water reduced the total viable count by 2 log CFU/g after 24 h. This result is attributed to the ample stable reactive species of H_2O_2, nitrite, nitrate, and O_3 in plasma-functionalized water. Furthermore, treatment delayed the progression of melanosis in the shrimp. The effects of CP on other quality attributes of some food products are presented in Table 2.

5. Relationship between CP treatment and food components

Cold atmospheric plasma is composed of abundant reactive species such as photons, ions, and electrons. These molecules strongly interact with food components, leading to a rich source of reaction chemistry, such as dimerization, oxidation, deamidation, nitration, sulfoxidation, dehydrogenation, and/or hydroxylation of amino acids (Pérez-Andrés, Álvarez, Cullen, & Tiwari, 2019; Takai et al., 2014). Therefore, CP can affect the structure and composition of biomolecules, which makes it a good alternative to traditional methods to enhance the functional properties of proteins (Sharma & Singh, 2020). In other words, CP treatment alters the functionality of food proteins via structural and conformational changes (Ekezie, Sun, & Cheng, 2017). Bußler, Steins, Ehlbeck, and Schlüter (2015) reported that CP technology can modify pea protein isolate by inducing compositional changes and could also affect the solubility of proteins.

Ekezie, Cheng, and Sun (2018b) extracted actomyosin from king prawn (*Litopenaeus vannamei*) and subjected it to an atmospheric-pressure plasma jet generated in argon gas. Actomyosin exhibited a 2% decrease in pH and a 5.4% increase in solubility within the first few minutes of plasma exposure. An approximately 37.5% and 50% increase in emulsifying activity and foaming capacity, respectively, were noted after 5 min of plasma exposure. In a similar study, Ekezie, Cheng, and Sun (2019) investigated the effect of atmospheric pressure plasma jet treatment (0–10 min) on the structural and physicochemical properties of myofibrillar proteins extracted from king prawn (*L. vannamei*). The surface hydrophobicity and particle size of myofibrillar proteins increased with the treatment. They also reported that plasma applications have an effect on protein properties and may cause partial denaturation.

These studies showed that under optimal conditions, the effect of CP treatment on protein or polysaccharide properties appears promising for the food industry and modification-based novel applications still need to be investigated.

6. Role of CP in sanitation and decontamination

6.1. Food processing equipment

The other effects of CP on food and its constituents are presented in Table 3. Direct contact of food products with unhygienic surfaces can be considered a means of contamination in the food industry. However, traditional sanitation methods may not completely dissipate microorganisms from food-processing surfaces. Therefore, the CP technique has been suggested as a potential application for disinfection of processing equipment against pathogens (Yepez, Misra, & Keener, 2020, pp. 607–628). Moreover, stainless steel and aluminum surfaces have rough and sponge-like surfaces that enable easier attachment of microorganisms to these surfaces. In this context, CP has been successfully used to reduce the adhesion of *Enterobacter sakazakii* and *E. coli* to food-contact surfaces, including stainless steel, aluminum, and glass surfaces (Sen & Mutlu, 2013; Şen, Bağci, Güleç, & Mutlu, 2012).

It is known that pathogens, such as *L. monocytogenes* are commonly introduced into meat-based products through contact with contaminated food-processing surfaces (Katsigiannis, Bayliss, & Walsh, 2020). Knives and cutting tools used in the processing of meat products are critical points of contamination by such pathogens during operation. Among CP sources, DBDs are successfully used for pathogen decontamination, and they offer uniform treatment over large surface areas (Pan, Zhang, Cheng, & Sun, 2020). Leipold, Kusano, Hansen, and Jacobsen (2010) used CP for the decontamination of a deli meat-slicing machine. After the application of a direct-mode DBD on the surface of an industrial rotating cutting tool, a reduction in microbial contamination (log 5) was observed. Katsigiannis et al. (2020) also observed that CP exposure on stainless steel resulted in a reduction in the proportion of *L. monocytogenes* and *S. typhimurium,* as described above.

These studies demonstrated that CP is effective for reducing microbial load on surfaces composed of stainless steel or other industrial materials that may have close contact with the food product. Therefore, CP application can be considered for the decontamination of food-processing equipment.

6.2. Decontamination and/or modification of packaging material

Cold plasma systems are used more effectively in the decontamination of vegetative gram-negative and gram-positive bacteria, yeasts, molds, viruses, and endospores. The mode of action of CP varies according to the method applied and the type of bacteria involved (Misra et al., 2011; Rød, Hansen, Leipold, & Knøchel, 2012).

Most polymers used as packaging materials, such as polyethylene terephthalate (PET), do not withstand high temperatures. In addition, some undesirable chemical agents have maximum limits and can generate toxic waste substances, or their residues may cause environmental hazards (Mandal, Singh, & Pratap Singh, 2018). Considering the abovementioned factor, CP treatment offers a potential alternative approach for the decontamination of packaged food, as it can reduce biofilm formation on polymeric food packaging materials (Bourke, Ziuzina, Han, Cullen, & Gilmore, 2017; Sen & Mutlu, 2013; Sen, Mutlu, & Bagci, 2011). For the sterilization of food packaging materials, the use of CP technology can be categorized as direct or indirect. The relevant materials are placed within the plasma discharge region and sterilized by exposure to the active species produced within the plasma region, as well as high-energy photons such as UV light during direct treatment (Peng et al., 2019, pp. 269–286).

Surface decontamination using CP successfully inactivates microorganisms, including bacterial and fungal spores and viruses, on food contact surfaces (Kart, Gurel, & Kayaardi, 2018; Misra et al., 2011; Umair et al., 2021). H.J. Kim, Puligundla, and Mok (2015) observed a 3–4 log CFU/cm^2 in biofilms of *E. coli* O157:H7, *S. typhimurium,* and *L. monocytogenes* present on collagen casing, polypropylene, and PET surfaces with 10-min plasma jet treatment (Bauer et al., 2017). applied atmospheric-pressure CP on vacuum-packaged beef loin with polyamide-polyethylene-based films. The treatment reduced *Staphyloccus. aureus*, *L. monocytogenes* and *E. coli* counts by more than 2 log units on films without affecting the integrity of the vacuum packaging matrix. Furthermore, oxidation was delayed over a period of 10 days. Lei et al. (2014) investigated the antimicrobial activity of plasma-treated PET/polypropylene films (assembled with chitosan and preservatives) against *S. aureus*, *Bacillus subtilis,* and *E. coli*. The films showed higher antimicrobial activity against *E. coli* and *B. subtilis* than against *S. aureus*.

Another field of CP application is its use in the sterilization of packaging materials such as plastic bottles, caps, and films, without causing any corrosion in these packaging materials and without damaging its structure (Muranyi, Wunderlich, & Heise, 2007). Studies in this field revealed that more extensive future research could be conducted on the treatment of food products for packed food and packaging materials using CP disinfection. Many functional groups can be generated on the surface of a polymeric material when exposed to plasma. The active plasma species break the covalent bonds, leading to hydrogen abstraction and the formation of surface radicals; the latter can then react with gas-phase species to form chemically active functional groups on the material surface (Almasi, Jahanbakhsh Oskouie, & Saleh, 2020). In this respect, functionalization may change the physical, mechanical, or chemical properties such as glazing, metal adhesion, sealing,

Table 3
Other effects of CP on food and its constituents.

Application Type	Target	Plasma Source and Gas	Process Parameters	Observation	References
Modification of Food Packaging Material	Defatted soybean meal films	Glow discharge; Air, Helium, Oxygen, Ar and N_2	1 L/min 2.45 GHz 400–900 W power Samples with 16.1 cm diameter	Effect on films: 24.4%, 13.4%, and 6.8% increase in moisture barrier property, elongation, and tensile strength, respectively using Ar gas. L* of the film was increased using N2 and Ar. Roughness improved the printability and biodegradability of films. Effect of films on food: Higher effectiveness in maintaining hardness ($p < 0.05$) and lipid oxidation retarded.	Oh et al. (2016)
Modification of Food Packaging Material	Fish protein films	Glow discharge with alternating current; Dry air	Distance of 13 cm Pressure at 2 Pa 2 or 5 min The high voltage input of 4.4 kV 60 Hz	Opacity increased ($p < 0.05$) compared to the control films, meaning a decrease in transparency. An increase in oxygen content was observed. Higher elongation at break and water vapor permeability was observed for 2 min treatment.	Romani et al. (2019)
Modification of Food Packaging Material	Carnauba wax-coated fish protein films	Alternating current glow discharge; Dry air	4.4 kV 60 Hz Distance of 13 cm 10 Pa 11 and 5 W power 5 and 1 min	Better barrier and adhesion properties. Higher surface coverage of wax. 175% higher tensile strength and 65% lower water vapor permeability in optimal conditions. A decrease of glass transition and melting temperatures.	Romani et al. (2020)
Decontamination of Food Processing Surfaces	Bacteria inoculated stainless steel surface	DBD; Air	Copper sheet as a high voltage electrode (4 cm diameter), a circular quartz glass disk as a dielectric (5 cm diameter, 1 mm thick) and a hexagonal Stainless steel mesh Dissipated power was held constant at 15 W	Negligible effect on stainless steel surface morphology. >3.55 log CFU/mL and 2.06 log CFU/mL reduction in *L. monocytogenes* and *S.typhimurium*	Katsigiannis et al. (2020)
Decontamination of Food Package Surface	SARS-CoV-2 RNA extract contaminated fresh-cut apple packages	Surface DBD; Air	Two 5 μL drops of RNA extract were spread to polyethylene terephthalate and polypropylene films 5 and 10 min 1–20 kV with a frequency in the 1–20 kHz range	10 min of exposure was sufficient to almost eliminate the viral RNA from the package surface. Plasma treatment did not produce any significant variation in packaging material performance or the shelf-life of fresh-cut apples.	Capelli et al. (2021)
Allergen Degradation	Peanut and dry defatted peanut flour	DBD; Air	RH: 80% Primary winding received input at 230 V, 50 Hz 80 kV for 0–60 min	The IgG-binding capacity of allergen in both whole peanut and dry defatted peanut flour reduced. A decrease of 43% and 9.3% in antigenicity was observed for DPF and WP, respectively.	Venkataratnam, Sarangapani, Cahill, and Ryan (2019)
Allergen Degradation	King prawn (*Litopenaeus Vannamei*) tropomyosin	Plasma jet; 98% Ar and 2% O_2	Gases were blown through a quartz tube at 20 standard liters per min (slm) 2 mg/mL of the TM solutions exposed for 3, 6, 9, 12, and 15 min	15 min treatment: 17.6% and 26.87% reduction recorded for IgE- and IgG binding capacities, respectively.	Ekezie, Sun, and Cheng (2019)
Enzyme Degradation	Alkaline phosphatase (ALP) in raw milk	DBD; Atmospheric Air	15 mL of ALP enzyme solution was placed in a Petri dish and treated 40, 50, and 60 kV 15 s to 5 min at room temperature	90% inactivation achieved at 180 s. Both voltage and duration had a significant effect ($p < 0.05$) on the inactivation. The interaction between time and voltage was also found to be significant ($p \leq 0.05$).	Segat, Misra, Cullen, and Innocente (2016)
Enzyme Degradation	Peroxidase in fresh-cut tomato slices	DBD; Helium, Air Gliding arc plasma system; Air	DBD: Gas flux rate in the was set at 3 lit/min at 30 °C Gliding arc; the distance between two electrodes was 6 mm and the voltage was set at 14 kV, 20 kHz	Helium: <90% deactivation even at 5 min Air: 90% reduction at 1 min No significant change in color of the product. The residual enzyme activity was reduced to 7.32% using gliding arc plasma treatment for 7 min.	Khani, Shokri, and Khajeh (2017)
Enzyme Degradation	Polyphenol oxidase in Pacific White Shrimp (*Litopenaeus vannamei*)	Corona discharge plasma jet; Air	220 V, 282 W, 50 Hz, and 1.9 A with 45–150 s	Polyphenol oxidase inhibited by 50% at 150 s exposure.	Zouelm et al. (2019)
Enzyme Degradation		DBD; Argon			

(*continued on next page*)

Table 3 (*continued*)

Application Type	Target	Plasma Source and Gas	Process Parameters	Observation	References
	Lipoxygenase enzyme in extra virgin olive oil		A source that creates plasma through 50 kHz voltage pulses Ar stream of 2 slm Energy varying between 5 W and 15 W at 25 °C	Enzyme activity was inhibited up to 42.9%. No significant changes in color, volatiles, phenolic profiles, antioxidant activity and peroxide value.	Amanpour et al. (2019)
Improvement in Membrane Properties for Insecticide Detection	Insecticides in *Pampus argenteus* fish	Argon	60 s under a 30 Pa Ar atmosphere, delivering 45 W to generate radicals on the surface for molecularly imprinted membrane	Molecularly imprinted membranes produced using CP-induced grafting polymerization. Five pyrethroid insecticides (fenvalerate, deltamethrin, cypermethrin, cyfluthrin and bifenthrin) residues successfully recognized.	(R. Zhang et al., 2014)
Effect on Food Components	Actomyosin extracted from king prawn (*Litopenaeus vannamei*)	Atmospheric pressure plasma jet; 98% Ar and 2% O_2	Gas flowing at a speed of 20 slm 50 kHz 1, 2, 3, 4, and 5 min	~37% increase in emulsifying activity index ($p < 0.05$) and ~50% increase in foaming capacity after 5 min. ~3.82% decrease in pH ($p < 0.05$) after 5 min.	Ekezie et al. (2018b)
Effect on Food Components	The amino acid content of wine pickled Bullacta exarate	Atmospheric CP; Air	40–60 kV 36 kHz 20 ± 2 °C and 50 ± 5% RH	Serine, glutamine, aspartic acid, glycine, threonine, and leucine content increased significantly while histidine, and tyrosine decreased.	(H. M. Lin, Zhang, Zheng, Miao, & Deng, 2020)
Effect on Food Components	Myofibrillar protein isolated from Alaska pollock (*Theragra chalcogramma*) muscle	DBD; Air	Samples were placed in Petri dishes and treated at 0, 20, 30, 40, 50, and 60 kV for 10 min. After, treated samples were diluted to 30 mg/mL as diluted using buffer solution to a final concentration of 30 mg mL	Increased water-holding capacity, textural properties, color properties ($p < 0.05$) and thermal stability. By increasing treatment voltage, free sulfhydryl content decreased significantly, while the turbidity and surface hydrophobicity increased.	Miao et al. (2020)
Effect on Food Components	Banana starch	Corona electrical discharge; Air	60 A at 30 kV/cm, 40 kV/cm, and 50 kV/cm for 3 min	No change in the resistance of starch and the amylose content. Crystallinity, gelatinization temperature and roughness at the surface increased. Reduction in gelatinization enthalpy (30%) and pasting properties (peak viscosity, breakdown, final viscosity, setback).	Wu, Sun, and Chau (2018)
Effect on Food Components	Thai rat-tailed radish microgreens	High voltage direct current; Air	21 kV with an average supplied current of 0.53 mA	Higher total phenolic content, antioxidant activity, ferric reducing antioxidant power assay, cytotoxicity, antiproliferative activity, and antimigratory activity were observed.	Luang-In et al. (2021)
Effect on Food Components	Pumpkin seed coat	CP jet; Helium/Ar	Both gases were flown at a rate of 2 L/min 8 kV pulse amplitude, 6 kHz pulse frequency, 1 μs pulse width, and ~70 ns pulse rise and fall time	Seed coats surface properties modified. Strong corrugation of pumpkin seed coats, water uptake enhances, seed germination accelerated, and seed growth increased.	Volkov, Hairston, Patel, Gott, and Xu (2019)
Effect on Food Components	Maize (*Zea mays* L.) Narrow-leaved lupine (*Lupinus angustifolius* L.) Winter wheat (*Triticum aestivum* L.)	Low-pressure radio frequency plasma	A pressure of 200 Pa 5.28 MHz The distance between electrodes is 20 mm. 2, 4, 5, and 7 min	Decrease in the level of seed infection. Increase in maize yield by 1.7%, narrow-leaved lupine by 26.8%, wheat by 2.3% An increase in proline, anthocyanins, and total phenolic content in roots of maize observed.	Filatova et al. (2020)
Lipid Oxidation Estimation	Fish oil	DBD-plasma jet; Ar doped with 0.6% O_2	50 kHz voltage input was fixed at 6.00 kV a current of 128 mA a gas flow rate of 2.00 slm	The oxidation of fish oil was accelerated by plasma. The typical lipid oxidation markers detected. Antioxidant effect of alpha-tocopherol (1000 μg/g) in fish oil successfully predicted.	Vandamme et al. (2015)
Lipid Oxidation Acceleration	β-carotene loaded nanoemulsions	Radio-frequency power source; Atmospheric air	500 kHz and 10 kV Different powers (0, 15, 30, and 60 W) and contact times (0, 15, and 30 min)	CP had a negligible effect on the physical, chemical, bioaccessibility, in vitro digestion and β-carotene stability. Discharge significantly influenced the degradation, of β-carotene in nanoemulsion ($p < 0.05$).	Chaijan, Srirattanachot, Nisoa, Cheong, and Panpipat (2021)

dyeability, hardness, and wettability of the packaging material (Ekezie et al., 2017; Pankaj et al., 2014; Şen et al., 2012).

Various applications have been proposed to improve the packaging material properties using CP treatment. Sen and Mutlu (2013) reported that plasma generated in a vacuum environment influences the surface of polyethylene (PE). Oh, Roh, and Min (2016) investigated the effect of CP application on edible films made from defatted soybean meal to cover smoked salmon. The film subjected to argon showed an increase in the moisture barrier properties, elongation, and tensile strength and reduction in lipid oxidation.

Romani et al. (2019) observed changes in fish protein film properties (mechanical, thermal, barrier, and color) through glow-discharge plasma application. The tensile strength and solubility in water increased after 5 min of plasma treatment, which was explained by the etching effects. In addition, the film surfaces were slightly rougher after plasma application. In a similar study, the same research group used glow-discharge plasma and carnauba wax coating to modify the properties of fish protein films. Tensile strength and adhesion properties increased, and a higher barrier performance was observed which was confirmed through the analysis of the microstructure, glass transition, and melting temperatures (Romani et al., 2020). Increases in surface roughness, ink adhesion, contact angle, and biodegradability of protein-based films with CP application have also been reported in the literature (Moosavi et al., 2020). Chen et al. (2020) evaluated the effect of CP pretreatment on zein films with porous polylactic acid coatings. The surface hydrophobicity, fracture resistance, the water vapor barrier, thermal stability, and UV barrier properties of the zein films were improved.

Sealing properties could also be affected by CP treatment. Heise, Neff, Franken, Muranyi, and Wunderlich (2004) stated that the sealing properties of polymer foils or laminates can be maintained by DBD. Furthermore, Ekezie et al. (2017) noted that CP technology can be used to deposit coatings on the surface of polymers by employing layers of a deposition barrier. Thus, the permeation of oxygen and carbon dioxide into food packaging materials could be reduced.

In recent years, limited studies have been published on the effects of CP on both antimicrobial packaging and package modification. Honarvar et al. (2017) utilized CP on carboxymethyl cellulose-coated polypropylene films containing essential oils. The plasma-treated PP/CMC films showed lower water vapor permeability and higher tensile strength than those of the untreated films. Furthermore, plasma-treated PP had rougher surfaces and reduced contact angle, indicating increased surface hydrophilicity. A minor inhibitory effect was also observed against *S. aureus*, *Bacillus cereus*, *E. coli*, and *S. typhimurium* using 1% Zataria essential oil. Wong et al. (2020) prepared a gallic acid-coated polyethylene film using capacitively coupled plasma treatment at 30 W for 60s. The growth of *E. coli* and *S. aureus* was inhibited (0.5–0.6 log CFU/mL) when the gallic acid concentration was 1% or above. Structural characterization results showed that the surface roughness increased, which facilitated the GA coating and the surface became smoother after GA coating. These studies revealed that CP is a promising candidate for synergistic approaches in the food packaging industry and requires further investigation.

6.3. Elimination of insects and detection of insecticides

Insecticides are commonly used in modern agriculture to control crop infestation to reduce crop losses by eliminating insects. However, their usage may have a negative effect on both human health and ecosystems. Therefore, the use of insecticides must be controlled by alternative techniques. For this purpose, recently published articles related to CP have revealed that CP technology can be considered a promising approach to protect food products by diminishing insecticidal effects (Paul and Mahendran, 2020; Ratish Ramanan, Sarumathi, & Mahendran, 2018; Sarangapani et al., 2016). Ratish Ramanan et al. (2018) reported that 2500 V, 15 min, and 3.7 cm were defined as the optimum CP parameters to eliminate *Tribolium castaneum*, the red flour beetle, in packed refined wheat flour. (Paul and Mahendran, 2020) revealed that 100% elimination of *T. castaneum* was achieved after 24 h exposure of brown rice to CP at 200 V. Similarly, the potential effect of CP treatment on wheat grain infested with red flour beetles was observed at 800 V for 4 min (Afsheen et al., 2019). Abotaleb, Badr, and Rashed (2021) investigated the efficacy of atmospheric-pressure plasma produced with DBD and microwave energy to control *T. castaneum* and *Trogoderma granarium* in wheat seeds. This treatment resulted in 50% mortality at 15.9 W power after 24 h treatment. For the detection of insecticides, Zhang et al. (2014) developed molecularly imprinted membranes (MIM) with the help of CP to improve grafting polymerization. In this regard, five pyrethroid insecticide residues (fenvalerate, deltamethrin, cypermethrin, cyfluthrin, and bifenthrin) were detected in *Pampus argenteus* fish samples. Above mentioned recently published studies could reveal CP as an alternative approach for the elimination of insects and detection of insecticides in some foods.

7. Allergen or enzyme degradation approach

Among seafoods, fish, crustaceans (shellfish), and mollusks (shellfish) are considered the most important food products that cause allergic reactions (Gavahian & Khaneghah, 2020; Kamath, Rahman, Komoda, & Lopata, 2013). Food allergens are usually water-soluble glycoproteins (Alves Filho, de Brito, & Rodrigues, 2019, pp. 253–268). Tropomyosin (a myofibrillar protein) is a major allergen in most shellfish. Researchers have been investigating approaches to mitigate the allergenicity of seafood, and heat treatment is one such approach. However, owing due to the heat-stable nature of tropomyosin, simple heat treatment does not sufficiently reduce allergenicity (Ekezie, Sun, & Cheng, 2019).

Ekezie, Sun, and Cheng (2019) examined the allergic response of tropomyosin in fresh king prawns (*L. vannamei)* exposed to a cold argon plasma jet. After 15 min of plasma treatment, IgE- and IgG-binding capacities were reduced by 17.6% and 26.87%, respectively. Furthermore, surface hydrophobicity and total free sulfhydryl group contents were altered after more than 9 min of treatment. This is attributed to alteration of amino acids in the IgE-binding region, which influences the antibody-binding capacity of tropomyosin with a possible modification in α-helix and β-sheet structures. Another mechanism involved in protein denaturation is the reduction in protein solubility due to aggregate formation. Crosslinking can also decrease food allergen content (Alves Filho et al., 2019, pp. 253–268; Ekezie, Cheng, & Sun, 2018a).

CP also has the potential to inactivate enzymes and provide enzymatic stability while preserving the original food quality (Misra, Pankaj, Segat, & Ishikawa, 2016; Pan, Cheng, & Sun, 2019; Umair et al., 2021) Therefore, the effect of CP on the main seafood spoilage enzyme histidine decarboxylase needs to be investigated. The recent studies mentioned above imply that plasma treatments may be potentially useful in commercial applications for reducing the allergenicity or enzyme activity of seafood products. Furthermore, CP can be combined with other nonthermal technologies (nanotechnology, pulsed light, and ultrasound) to achieve better results.

8. Combination of CP with other emerging technologies

Table 4 presents some combinations of CP treatment with other

Table 4
Combination of CP with other technologies.

Application Type	Target	Combination Method	Process Conditions	Observation	Reference
Nanotechnology for Structure Modification	Starch nanoparticle (SNP)	A vacuum CP system with a working pressure of 30–50 Pa and 1 kW power was treated to SNPs	3, 5, or 7 min, by three times repetition O_2 and NH_3 with a flow rate of 300 mL min^{-1}	O_2 showed a better dispersibility than NH_3. The relative crystallinity decreased from 44.13 to 33.80%. High absorption of tea polyphenols was observed. Better diameter (75.94–159.72 nm) without much aggregation.	Chang et al. (2020)
Nanotechnology for Active Packaging	Phlorotannin/ *Momordica charantia* polysaccharide-based nanofiber	Nanofiber membranes were processed in a CP reaction chamber with 350 W power	30 s Nitrogen at a flow rate of 100 (standard cubic centimeters)/min (sccm)	The surface structure of nanofibers was improved. The release efficiency of phlorotannin from nanofibers was promoted by 23.5% (4 °C) and 25% (25 °C). Free radical scavenging capacity was increased from 80.64 to 91.74%. Antibacterial and antioxidative activities were enhanced.	Cui et al. (2020)
Nanotechnology for Antimicrobial Packaging	Thyme essential oil/silk fibroin (TO/SF) nanofibers against *S. Typhimurium* in poultry	Nanofiber membrane obtained from TO/SF was exposed to plasma at 400 W	4 min Nitrogen at flow rate of 100 sccm	Decline: ~6 log CFU/g (*S. Typhimurium*) in chicken and duck meat at 25 °C.	(L. Lin, Liao, & Cui, 2019)
Nanotechnology for Antimicrobial Packaging	Polypropylene/low density polyethylene (BOPP/LDPE) laminates	80 × 120 mm films (5 cm separation distance between electrodes) pretreated with CP at 84 W by DBD systemThen nanofibrillated cellulose/nisin coating solution was applied onto a CP treated BOPP/LDPE	2 min Sub-atmospheric pressure (1600Pa) using an O_2/Air mixture at a flow rate of 200 mL/min for O_2 and 500 mL/min for air	Surface hydrophilicity of CP-treated films provided for better attachment of the coatings. Increasing the nisin concentration to 5 mg/g resulted in a 94% reduction in *L. monocytogenes* counts ($p < 0.05$).	(P. Lu et al., 2018)
Nanotechnology for the Inhibition of the Biofilm Formation	Chitosan electrospun nanofibers	Chitosan powders pretreated in free rotation pyrex glass chamber (internal diameter: 5 cm; length: 30 cm). Then powders were dissolved in an acetic acid solution and electrospun with polyvinyl alcohol	30 min 13.56 MHz 5–6 × 10^{-2} Torr 50 W	Biofilm formation of *P. aeruginosa* PA01 on electrode surface coated with chitosan-furan nanofiber was significantly prevented. The highest prevention value was observed for 30 mg polyvinyl alcohol/chitosan-furan nanofiber (80.4%).	Maslakci et al. (2017)
Nanotechnology for Structure Modification	Grass pea (Lathyrus sativus L.) protein nanoparticles (GPPINPs)	A thin layer of GPPI (0.3 g) was equally spread over the surface of the ground electrode and directly exposed to the plasma using the DBD system.	5 min and 10 min Air (RH 42 ± 5%) 25 ± 2 °C 0–20 kV 20 kHz	The size of NPs decreased, morphology became more nonuniform, the surface hydrophobicity increased while their solubility decreased by increasing voltage and time. More complex tertiary structure and higher disulfide bonds formed stronger interfacial layer.	Mahdavian Mehr and Koocheki (2021)
Ultrasound for Quality Improvement	Sea asparagus *Salicornia neei* extract applied to Italian salami	Dried Salicornia neei samples (400 mg) were pretreated using alternating current glow discharge plasma Then ultrasound-assisted extraction was performed	5 and 60 min Atmospheric air 0–15 kV 60 Hz 2 × 10^{-2} mbar 14 W	No higher lipid oxidation and texture deterioration. No negative impact on sensory quality Inhibition against *E. coli.*	Faria et al. (2020)
Pulsed Light for Quality Improvement	Red Pepper powder (Capsicum annuum L.)	Simultaneously CP and intense PL treatment	Plasma system; 0–10 kV 6.4–40.0 kHz He PL system; Input 220 V AC supply source at 25 30 kV 0.38 μF capacitor	Aerobic bacteria reduction: Only plasma, 1, 3, and 5 min by 0.2, 0.4, and 0.9 log CFU/g ($p < 0.05$) (initial bacterial counts: 4.8 log CFU/g) respectively. Aerobic bacteria reduction: Plasma + PL, 1.9–2.9 log CFU/g for 1–5 min ($p < 0.05$). No negative effect on color, capsaicin, vitamin C, and antioxidant activity.	(H. S. Lee et al., 2020)
PEF for quality improvement	Shrimp (*Litopenaeus vannamei*)	*S*amples pretreated with PEF (15 kV/cm, 800 pulses, 697 kJ/kg) and immersed in 1% or 2% Chamuang leaf extract (CLE) solutions for 30 min. Samples were packaged under MAP with Ar/Air 80/20 mixture. Then high voltage cold atmospheric plasma (HVCAP) was applied which related to the DBD system.	10 min Transformer (230 V input voltage 0–120 kV output voltage 50 Hz Electrodes 15-cm 2 cm distance	Shelf-life extension by 9 days The lowest microbial load and spoilage bacteria count (≤5 log CFU/g meat) were attained in PEF treated sample with 2% CLE followed by plasma ($p < 0.05$).	Shiekh, Zhou, and Benjakul (2021)

(*continued on next page*)

Table 4 (*continued*)

Application Type	Target	Combination Method	Process Conditions	Observation	Reference
PEF and Vacuum Impregnation (VI) for Quality Improvement	Pacific white shrimp (PWS)	Samples were pretreated with PEF and were immersed in CLE solutions. VI process was conducted for 15 min using a vacuum pressure of 5 kPa. Then vacuum was released, and samples MAP packaged. They were subjected to HVCAP using the DBD system.	10 min 2 cm 16 kV Atmospheric pressure	The combined process delayed the rapid microbial spoilage (TVC, Enterobacteriaceae, H_2S-producing bacteria, *Pseudomonas*, LAB).	Shiekh, Benjakul, Qi, Zhang, and Deng (2021)
Ultrasound for quality improvement	*E. coli* and *S. aureus* in chicken muscle, rough skin, and smooth skin.	The tissue samples were soaked in PAW. The device is set up to discharge PAW beneath the water surface at a distance of 5 mm between the electrode and ground. Then the samples were ultrasonicated at 4, 25, and 40 °C for 30, 45, and 60 min.	6.5 min Ar underwater plasma jet at a flow rate of 3 slm. Ultrasonication operation: 40Hz and an output power of 220W.	Combination inactivated *E. coli* 1.33 log CFU/mL and *S. aureus* 0.83 log CFU/mL, at 40 °C for 60 min at a sample thickness of 4 mm. PAW reduction of *E. coli* is 0.46 log CFU/mL and *S. aureus* is 0.33 log CFU/mL. Hardness, protein, and lipid values were maintained.	Royintarat et al. (2020)
Intense Pulsed light (IPL)-ultraviolet for quality improvement	Rice germ (Oryzae sativa L.)	i: Atmospheric pressure plasma ii: IPL iii: UV-C	APPJ: Air compressor (7.4 kW, 0.80 MPa, 840 L/min air production) IPL: 3 kV, 2 Hz. UV-C: 5 lamps, 8 W each, 253.7 nm, 5 cm distance	Reduction in bacteria and yeast and mold by 1.0 and 2.0 log CFU/g.	(S. Y. Lee et al., 2021)
Ultrasound for quality improvement	Cuminaldehyde/ β-cyclodextrin inclusion complex (CUM/βCD-IC) in vegetable juice	CUM/βCD-IC was prepared using the ultrasound method. Then its powder was treated with cold nitrogen plasma	6 min 50 0W Nitrogen flow rate of 100 sccm	This combination showed antibacterial effect against *E. coli* O157:H7 in cucumber juice (2.51 Log CFU/mL) and tomato juice (2.58 Log CFU/mL) at 4 °C for 3 days. No negative effect on the color of the vegetable juices.	(L. Lin et al., 2021)

emerging technologies. As can be seen from the table designed for different food products, CP can be combined with other methods for stronger microbial inactivation. In this respect, the combined application of novel technologies with CP treatment, such as, nanoscience (Chang et al., 2020; Cui, Yang, Abdel-Samie, & Lin, 2020; P.; Lu, Guo, Xu, & Wu, 2018; Mahdavian Mehr & Koocheki, 2021; Maslakci, Ulusoy, & Oksuz, 2017; Uygun, Kiristi, Oksuz, Manolache, & Ulusoy, 2011; J.; Zhang, Wang, & Zhuang, 2019), PEF (Shiekh, Benjakul, Qi, Zhang, & Deng, 2021; Shiekh, Zhou, & Benjakul, 2021), PL (H. S. Lee, Park, & Min, 2020; S. Y. Lee et al., 2021), and ultrasound processing (Faria et al., 2020; L.; Lin et al., 2021; Pan et al., 2020; Royintarat, Choi, Boonyawan, Seesuriyachan, & Wattanutchariya, 2020), is a promising approach. Simultaneous or sequential pretreatment and post-treatment of these novel technologies could show a synergistic effect with better microbial safety and sensory quality than those with single usage to improve overall effectiveness.

Nanomaterials might be potential candidates in synergy with CP to develop novel hurdle technologies (Bermudez-Aguirre, 2019, pp. 49–91; Dufay, Jimenez, & Degoutin, 2020; Ostrikov, Neyts, & Meyyappan, 2013). Zhang et al, (2019) noted that plasma treatment of packages, combined with bacteriostatic nanophotocatalysts (e.g. Fe_2O_3+ ZnO) on food packing films, limited adverse effects on the sensory quality parameters of fish. As stated by Borra, Jidenko, Hou, and Weber (2015), DBD at atmospheric pressure can generate tailored nanoparticles with the same composition as that of metal electrodes. CP produces metal nanoparticles using Au, Ag, and Cu metal electrodes through DBD. Nanoparticles significantly inactivate foodborne microorganisms in food products and food packages. In another study, Bae et al. (2015), reported that Au nanoparticles (AuNPs) exhibited a synergistic cytotoxic effect in the treatment with CP. The combination of CP with AuNPs significantly improved the accumulation of AuNPs inside cells through the stimulation of ATP-independent endocytosis pathways. In contrast, AuNPs can help trap the CP–generated reactive species, prolong their half-life, and deliver them into target cells. In this respect, a sample potential application based on the combined treatment of nanotechnology and CP is presented in Fig. 2.

Studies have revealed that CP application can be combined with ultrasound pretreatment. The effects of ultrasound pretreatment combined with DBD on the inactivation of *L. monocytogenes* were also investigated (Cui, Bai, & Lin, 2018). For instance, cellulose nanofibers (CNFs) were extracted via air plasma treatment combined with ultrasonication. After modifying the surface of the cellulose fibers (CFs) by air plasma treatment, the CNFs were extracted using an ultrasonic bath. Tensile test results and Scanning Electron Microscopy images of the fracture surfaces showed significant improvement in adhesion between the CNF and TPS matrix compared with composites reinforced by neat CF (Fazeli & Simão, 2019). Moreover, plasma can effectively inactivate some viruses and show protein-denaturing potential (Zhao et al., 2019). In this sense, the treatment of nanomaterials with CP might be a potential intervention to achieve synergism against infectious diseases such as Coronavirus disease 2019 (COVID-19) and other possible future outbreaks (Ceylan, Meral, & Cetinkaya, 2020). CP may be combined with other nano-based materials, such as nanofibers, nanoparticles, and nanoemulsions obtained from different types of bioactive materials (Ceylan, Yaman, Sağdıç, Karabulut, & Yilmaz, 2018), probiotic bacteria, (Ceylan et al., 2019), biopolymers (Cetinkaya et al., 2021; Ceylan, Unal Sengor, Sağdıç, & Yilmaz, 2017), agro-waste products (Ceylan, Meral, & Cetinkaya, 2020), and edible oils (Durmus et al., 2019). With this promising combination, a larger contact area on the surface of food products and food packaging materials can be provided for antimicrobial, antioxidative, and antifungal materials.

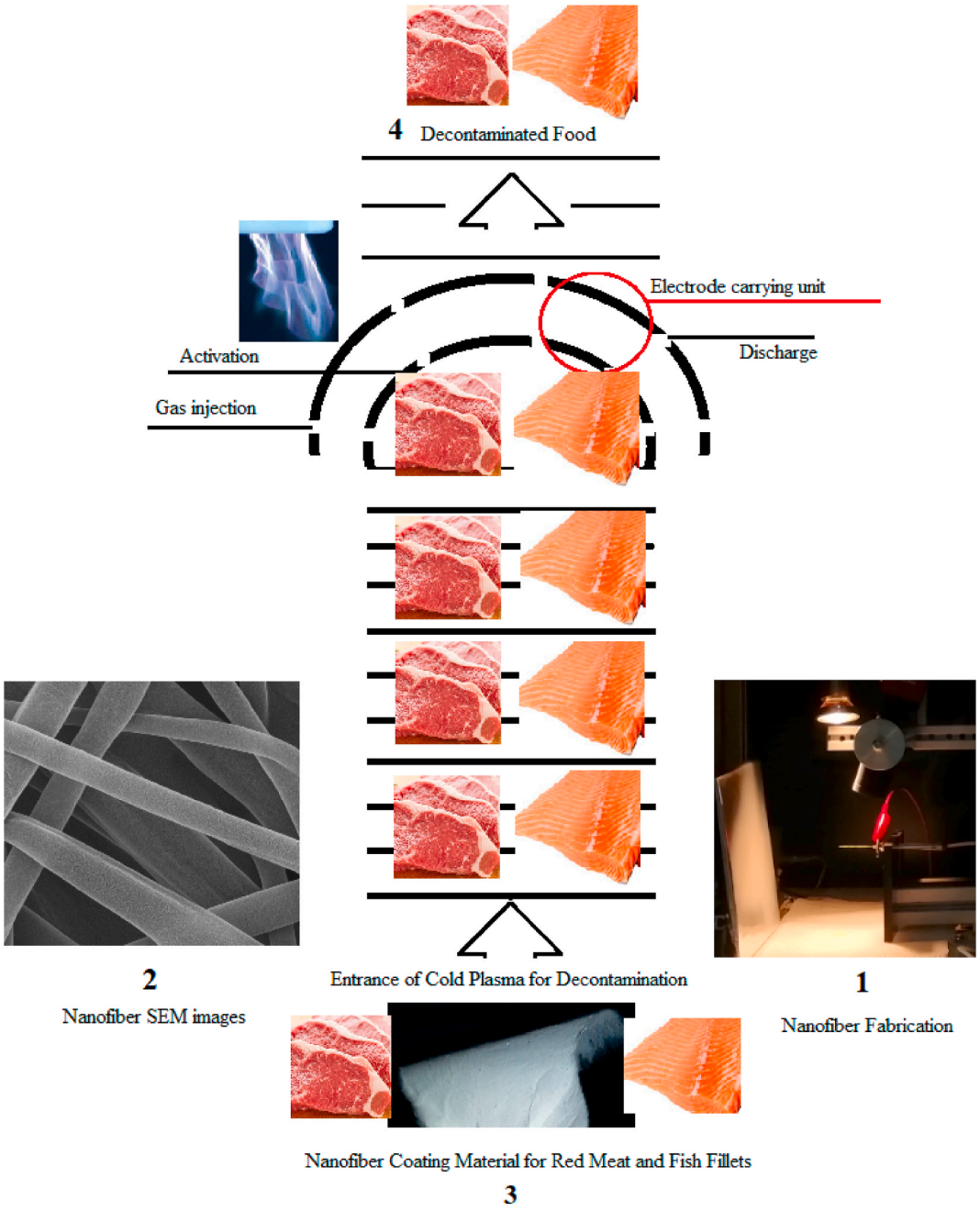

Fig. 2. Potential combination of cold plasma and nanofiber coating for food samples.

9. Conclusion and future directions

Demand for raw or non-heat-treated foods is increasing because of factors such as the preference of consumers for healthy foods and the development of consumer awareness. The use of plasma technology can prevent some sensory, chemical, and physical changes in addition to improving the microbiological quality of food. It can be concluded that CP application is effective in offering higher-quality products for consumption by extending the shelf life of the foods. Positive results have been achieved in terms of both quality and microbial activity in different food groups with plasma technology. In addition to recently published articles, the synergistic hurdle effect of CP with other novel technologies such as nanotechnology on food or food packaging materials could be further studied and used more extensively to ensure food safety. However, the high initial investment costs of CP need to be considered.

Credit author statement

Yilmaz Ucar: Original draft preparation, conceptualization, writing. Zafer Ceylan: Review, writing, and visualization. Mustafa Durmus: Resources, editing. Oktay Tomar: Editing. Turgay Cetinkaya: Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abotaleb, A. O., Badr, N. F., & Rashed, U. M. (2021). Assessment of the potential of non-thermal atmospheric pressure plasma discharge and microwave energy against

Tribolium castaneum and Trogoderma granarium. *Bulletin of Entomological Research*, 1–16. https://doi.org/10.1017/S0007485321000225
Afsheen, S., Fatima, U., Iqbal, T., Abrar, M., Muhammad, S., Saeed, A., et al. (2019). Influence of cold plasma treatment on insecticidal properties of wheat seeds against red flour beetles. *Plasma Science and Technology, 21*(8), Article 085506. https://doi.org/10.1088/2058-6272/ab19ee
Albertos, I., Martín-Diana, A. B., Cullen, P. J., Tiwari, B. K., Ojha, S. K., Bourke, P., et al. (2017). Effects of dielectric barrier discharge (DBD) generated plasma on microbial reduction and quality parameters of fresh mackerel (*Scomber scombrus*) fillets. *Innovative Food Science & Emerging Technologies, 44*, 117–122. https://doi.org/10.1016/j.ifset.2017.07.006
Albertos, I., Martin-Diana, A. B., Cullen, P. J., Tiwari, B. K., Ojha, S. K., Bourke, P., et al. (2019). Shelf-life extension of herring (*Clupea harengus*) using in-package atmospheric plasma technology. *Innovative Food Science & Emerging Technologies, 53*, 85–91. https://doi.org/10.1016/j.ifset.2017.09.010
Almasi, H., Jahanbakhsh Oskouie, M., & Saleh, A. (2020). A review on techniques utilized for design of controlled release food active packaging. *Critical Reviews in Food Science and Nutrition*, 1–21. https://doi.org/10.1080/10408398.2020.1783199
Alves Filho, E. G., de Brito, E. S., & Rodrigues, S. (2019). Effects of cold plasma processing in food components. *Advances in cold plasma applications for food safety and preservation*. https://doi.org/10.1016/B978-0-12-814921-8.00008-6. Elsevier.
Amanpour, A., Vandamme, J., Polat, S., Kelebek, H., van Durme, J., & Selli, S. (2019). Non-thermal plasma effects on the lipoxygenase enzyme activity, aroma and phenolic profiles of olive oil. *Innovative Food Science & Emerging Technologies, 54*, 123–131. https://doi.org/10.1016/j.ifset.2019.04.004
Ambrico, P. F., Šimek, M., Rotolo, C., Morano, M., Minafra, A., Ambrico, M., et al. (2020). Surface dielectric barrier discharge plasma: A suitable measure against fungal plant pathogens. *Scientific Reports, 10*(1), 1–17. https://doi.org/10.1038/s41598-020-60461-0
Bae, S. C., Park, S. Y., Choe, W., & Ha, S. do (2015). Inactivation of murine norovirus-1 and hepatitis A virus on fresh meats by atmospheric pressure plasma jets. *Food Research International, 76*, 342–347. https://doi.org/10.1016/j.foodres.2015.06.039
Basaran, P., Basaran-Akgul, N., & Oksuz, L. (2008). Elimination of Aspergillus parasiticus from nut surface with low pressure cold plasma (LPCP) treatment. *Food Microbiology, 25*(4), 626–632. https://doi.org/10.1016/j.fm.2007.12.005
Bauer, A., Ni, Y., Bauer, S., Paulsen, P., Modic, M., Walsh, J. L., et al. (2017). The effects of atmospheric pressure cold plasma treatment on microbiological, physical-chemical and sensory characteristics of vacuum packaged beef loin. *Meat Science, 128*, 77–87. https://doi.org/10.1016/j.meatsci.2017.02.003
Bermudez-Aguirre, D. (2019). Advances in the inactivation of microorganisms and viruses in food and model systems using cold plasma. *Advances in cold plasma applications for food safety and preservation*. https://doi.org/10.1016/B978-0-12-814921-8.00002-5. Elsevier.
Borra, J. P., Jidenko, N., Hou, J., & Weber, A. (2015). Vaporization of bulk metals into single-digit nanoparticles by non-thermal plasma filaments in atmospheric pressure dielectric barrier discharges. *Journal of Aerosol Science, 79*. https://doi.org/10.1016/j.jaerosci.2014.09.002
Bourke, P., Ziuzina, D., Han, L., Cullen, P. J., & Gilmore, B. F. (2017). Microbiological interactions with cold plasma. *Journal of Applied Microbiology, 123*(2), 308–324. https://doi.org/10.1111/jam.13429
Butscher, D., Zimmermann, D., Schuppler, M., & Rudolf von Rohr, P. (2016). Plasma inactivation of bacterial endospores on wheat grains and polymeric model substrates in a dielectric barrier discharge. *Food Control, 60*, 636–645. https://doi.org/10.1016/j.foodcont.2015.09.003
Bußler, S., Steins, V., Ehlbeck, J., & Schlüter, O. (2015). Impact of thermal treatment versus cold atmospheric plasma processing on the techno-functional protein properties from Pisum sativum "Salamanca. *Journal of Food Engineering, 167*, 166–174. https://doi.org/10.1016/j.jfoodeng.2015.05.036
Capelli, F., Tappi, S., Gritti, T., de Aguiar Saldanha Pinheiro, A. C., Laurita, R., Tylewicz, U., et al. (2021). Decontamination of food packages from SARS-CoV-2 RNA with a cold plasma-assisted system. *Applied Sciences, 11*(9). https://doi.org/10.3390/app11094177
Cetinkaya, T., Mendes, A. C., Jacobsen, C., Ceylan, Z., Chronakis, I. S., Bean, S. R., et al. (2021). Development of kafirin-based nanocapsules by electrospraying for encapsulation of fish oil. *Lebensmittel-Wissenschaft und -Technologie, 136*, 110297. https://doi.org/10.1016/j.lwt.2020.110297
Ceylan, Z., Meral, R., & Cetinkaya, T. (2020). Relevance of SARS-CoV-2 in food safety and food hygiene: Potential preventive measures, suggestions and nanotechnological approaches. *VirusDisease, 31*(2), 154–160. https://doi.org/10.1007/s13337-020-00611-0
Ceylan, Z., Meral, R., Kose, Y. E., & Cavidoglu, I. (2020). Wheat germ oil nanoemulsion for oil stability of the cooked fish fillets stored at 4 °C. *Journal of Food Science & Technology, 57*(5), 1798–1806. https://doi.org/10.1007/s13197-019-04213-7
Ceylan, Z., Unal Sengor, G. F., Sağdıç, O., & Yilmaz, M. T. (2017). A novel approach to extend microbiological stability of sea bass (*Dicentrarchus labrax*) fillets coated with electrospun chitosan nanofibers. *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology, 79*, 367–375. https://doi.org/10.1016/j.lwt.2017.01.062
Ceylan, Z., Uslu, E., İspirli, H., Meral, R., Gavgalı, M., 'Yilmaz, M. T., et al. (2019). A novel perspective for Lactobacillus reuteri: Nanoencapsulation to obtain functional fish fillets. *Lebensmittel-Wissenschaft und -Technologie, 115*, 108427. https://doi.org/10.1016/j.lwt.2019.108427
Ceylan, Z., Yaman, M., Sağdıç, O., Karabulut, E., & Yilmaz, M. T. (2018). Effect of electrospun thymol-loaded nanofiber coating on vitamin B profile of gilthead sea bream fillets (*Sparus aurata*). *Lebensmittel-Wissenschaft und -Technologie, 98*, 162–169. https://doi.org/10.1016/j.lwt.2018.08.027
Chaijan, M., Srirattanachot, K., Nisoa, M., Cheong, L. Z., & Panpipat, W. (2021). Role of antioxidants on physicochemical properties and in vitro bioaccessibility of β-carotene loaded nanoemulsion under thermal and cold plasma discharge accelerated tests. *Food Chemistry, 339*, 128157. https://doi.org/10.1016/j.foodchem.2020.128157
Chang, R., Lu, H., Tian, Y., Li, H., Wang, J., & Jin, Z. (2020). Structural modification and functional improvement of starch nanoparticles using vacuum cold plasma. *International Journal of Biological Macromolecules, 145*, 197–206. https://doi.org/10.1016/j.ijbiomac.2019.12.167
Charoux, C. M. G., Free, L., Hinds, L. M., Vijayaraghavan, R. K., Daniels, S., O'Donnell, C. P., et al. (2020). Effect of non-thermal plasma technology on microbial inactivation and total phenolic content of a model liquid food system and black pepper grains. *Lebensmittel-Wissenschaft und -Technologie, 118*, 108716. https://doi.org/10.1016/j.lwt.2019.108716
Charoux, C. M. G., Patange, A., Lamba, S., O'Donnell, C. P., Tiwari, B. K., & Scannell, A. G. M. (2021). Applications of nonthermal plasma technology on safety and quality of dried food ingredients. *Journal of Applied Microbiology, 130*(2), 325–340. https://doi.org/10.1111/jam.14823
Chen, G., Chen, Y., Jin, N., Li, J., Dong, S., Li, S., et al. (2020). Zein films with porous polylactic acid coatings via cold plasma pre-treatment. *Industrial Crops and Products, 150*, 112382. https://doi.org/10.1016/j.indcrop.2020.112382
Chiper, A. S., Chen, W., Mejlholm, O., Dalgaard, P., & Stamate, E. (2011). Atmospheric pressure plasma produced inside a closed package by a dielectric barrier discharge in Ar/CO2 for bacterial inactivation of biological samples. *Plasma Sources Science and Technology, 20*(2), Article 025008. https://doi.org/10.1088/0963-0252/20/2/025008
Choi, S., Puligundla, P., & Mok, C. (2016). Microbial decontamination of dried Alaska pollock shreds using corona discharge plasma jet: Effects on physicochemical and sensory characteristics. *Journal of Food Science, 81*(4), M952–M957. https://doi.org/10.1111/1750-3841.13261
Choi, S., Puligundla, P., & Mok, C. (2017a). Effect of corona discharge plasma on microbial decontamination of dried squid shreds including physico-chemical and sensory evaluation. *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology, 75*, 323–328. https://doi.org/10.1016/j.lwt.2016.08.063
Choi, S., Puligundla, P., & Mok, C. (2017b). Impact of corona discharge plasma treatment on microbial load and physicochemical and sensory characteristics of semi-dried squid (Todarodes pacificus). *Food Science and Biotechnology, 26*(4), 1137–1144. https://doi.org/10.1007/s10068-017-0137-8
Cui, H., Bai, M., & Lin, L. (2018). Plasma-treated poly(ethylene oxide) nanofibers containing tea tree oil/beta-cyclodextrin inclusion complex for antibacterial packaging. *Carbohydrate Polymers, 179*, 360–369. https://doi.org/10.1016/j.carbpol.2017.10.011
Cui, H., Yang, X., Abdel-Samie, M. A., & Lin, L. (2020). Cold plasma treated phlorotannin/Momordica charantia polysaccharide nanofiber for active food packaging. *Carbohydrate Polymers, 239*, 116214. https://doi.org/10.1016/j.carbpol.2020.116214
Dobrynin, D., Kalghatgi, S., Fridman, G., Wu, A., Podolsky, E., Barbee, K., et al. (2009). *Toxicity of low temperature plasma treatment of living tissue*. Drexel IEEE Graduate Forum, Technical Poster Symposium, Philadelphia, USA.
Donegan, M., Milosavljević, V., & Dowling, D. P. (2013). Activation of PET using an RF atmospheric plasma system. *Plasma Chemistry and Plasma Processing, 33*(5), 941–957. https://doi.org/10.1007/s11090-013-9474-4
Dufay, M., Jimenez, M., & Degoutin, S. (2020). Effect of cold plasma treatment on electrospun nanofibers properties: A review. *ACS Applied Bio Materials, acsabm.* , Article 0c00154. https://doi.org/10.1021/acsabm.0c00154
Durmus, M., Ozogul, Y., Küley Boga, E., Uçar, Y., Kosker, A. R., Balikci, E., et al. (2019). The effects of edible oil nanoemulsions on the chemical, sensory, and microbiological changes of vacuum packed and refrigerated sea bass fillets during storage period at 2 ± 2°C. *Journal of Food Processing and Preservation, 43*(12), Article e14282. https://doi.org/10.1111/jfpp.14282
Ekezie, F. G. C., Cheng, J. H., & Sun, D. W. (2018a). Effects of nonthermal food processing technologies on food allergens: A review of recent research advances. *Trends in Food Science & Technology, 74*, 12–25. https://doi.org/10.1016/j.tifs.2018.01.007
Ekezie, F. G. C., Cheng, J. H., & Sun, D. W. (2018b). Effects of mild oxidative and structural modifications induced by argon plasma on physicochemical properties of actomyosin from king prawn (*Litopenaeus vannamei*). *ACS Publications, 66*(50), 13285–13294. https://doi.org/10.1021/acs.jafc.8b05178
Ekezie, F. G. C., Cheng, J. H., & Sun, D. W. (2019). Effects of atmospheric pressure plasma jet on the conformation and physicochemical properties of myofibrillar proteins from king prawn (*Litopenaeus vannamei*). *Food Chemistry, 276*, 147–156. https://doi.org/10.1016/j.foodchem.2018.09.113
Ekezie, F. G. C., Sun, D. W., & Cheng, J. H. (2017). A review on recent advances in cold plasma technology for the food industry: Current applications and future trends. *Trends in Food Science & Technology, 69*, 46–58. https://doi.org/10.1016/j.tifs.2017.08.007
Ekezie, F. G. C., Sun, D. W., & Cheng, J. H. (2019). Altering the IgE binding capacity of king prawn (*Litopenaeus Vannamei*) tropomyosin through conformational changes induced by cold argon-plasma jet. *Food Chemistry, 300*, 125143. https://doi.org/10.1016/j.foodchem.2019.125143
Ermolaeva, S. A., Varfolomeev, A. F., Chernukha, M. Y., Yurov, D. S., Vasiliev, M. M., Kaminskaya, A. A., et al. (2011). Bactericidal effects of non-thermal argon plasma in vitro, in biofilms and in the animal model of infected wounds. *Journal of Medical Microbiology, 60*(1), 75–83. https://doi.org/10.1099/jmm.0.020263-0
Faria, G. Y. Y., Souza, M. M., Oliveira, J. R. M., Costa, C. S. B., Collares, M. P., & Prentice, C. (2020). Effect of ultrasound-assisted cold plasma pretreatment to obtain

sea asparagus extract and its application in Italian salami. *Food Research International, 137*, 109435. https://doi.org/10.1016/j.foodres.2020.109435
Fazeli, M., & Simão, R. A. (2019). Preparation and characterization of starch composites with cellulose nanofibers obtained by plasma treatment and ultrasonication. *Plasma Processes and Polymers, 16*(6), 1800167. https://doi.org/10.1002/ppap.201800167
Feizollahi, E., Iqdiam, B., Vasanthan, T., Thilakarathna, M. S., & Roopesh, M. S. (2020). Effects of atmospheric-pressure cold plasma treatment on deoxynivalenol degradation, quality parameters, and germination of barley grains. *Applied Sciences, 10*(10), 3530–undefined. https://doi.org/10.3390/app10103530
Fernández, A., Noriega, E., & Thompson, A. (2013). Inactivation of *Salmonella* enterica serovar Typhimurium on fresh produce by cold atmospheric gas plasma technology. *Food Microbiology, 33*(1), 24–29. https://doi.org/10.1016/j.fm.2012.08.007
Filatova, I., Lyushkevich, V., Goncharik, S., Zhukovsky, A., Krupenko, N., & Kalatskaja, J. (2020). The effect of low-pressure plasma treatment of seeds on the plant resistance to pathogens and crop yields. *Journal of Physics D: Applied Physics, 53*(24), 244001. https://doi.org/10.1088/1361-6463/ab7960
Frías, E., Iglesias, Y., Alvarez-Ordóñez, A., Prieto, M., González-Raurich, M., & López, M. (2020). Evaluation of Cold Atmospheric Pressure Plasma (CAPP) and plasma-activated water (PAW) as alternative non-thermal decontamination technologies for tofu: Impact on microbiological, sensorial and functional quality attributes. *Food Research International, 129*, 108859. https://doi.org/10.1016/j.foodres.2019.108859
Ganesan, A. R., Tiwari, U., Ezhilarasi, P. N., & Rajauria, G. (2021). Application of cold plasma on food matrices: A review on current and future prospects. *Journal of Food Processing and Preservation, 45*(1). https://doi.org/10.1111/jfpp.15070
Gavahian, M., Chu, Y., & Jo, C. (2019). Prospective applications of cold plasma for processing poultry products: Benefits, effects on quality attributes, and limitations. *Comprehensive Reviews in Food Science and Food Safety, 18*(4), 1292–1309. https://doi.org/10.1111/1541-4337.12460
Gavahian, M., Chu, Y. H., Mousavi Khaneghah, A., Barba, F. J., & Misra, N. N. (2018). A critical analysis of the cold plasma induced lipid oxidation in foods. *Trends in Food Science & Technology, 77*, 32–41. https://doi.org/10.1016/j.tifs.2018.04.009
Gavahian, M., & Khaneghah, A. M. (2020). Cold plasma as a tool for the elimination of food contaminants: Recent advances and future trends. *Critical Reviews in Food Science and Nutrition, 60*(9), 1581–1592. https://doi.org/10.1080/10408398.2019.1584600
Gavahian, M., Peng, H. J., & Chu, Y. H. (2019). Efficacy of cold plasma in producing salmonella-free duck eggs: Effects on physical characteristics, lipid oxidation, and fatty acid profile. *Journal of Food Science & Technology, 56*(12), 5271–5281. https://doi.org/10.1007/s13197-019-03996-z
Gök, V., Aktop, S., Özkan, M., & Tomar, O. (2019). The effects of atmospheric cold plasma on inactivation of *Listeria monocytogenes* and *Staphylococcus aureus* and some quality characteristics of pastırma—a dry-cured beef product. *Innovative Food Science & Emerging Technologies, 56*, 102188. https://doi.org/10.1016/j.ifset.2019.102188
Gurol, C., Ekinci, F. Y., Aslan, N., & Korachi, M. (2012). Low temperature plasma for decontamination of E. coli in milk. *International Journal of Food Microbiology, 157*(1), 1–5. https://doi.org/10.1016/j.ijfoodmicro.2012.02.016
Han, J.-Y., Song, W.-J., Kang, J. H., Min, S. C., Eom, S., Hong, E. J., et al. (2020). Effect of cold atmospheric pressure plasma-activated water on the microbial safety of Korean rice cake. *Lebensmittel-Wissenschaft und -Technologie, 120*, 108918. https://doi.org/10.1016/j.lwt.2019.108918
He, M., Duan, J., Xu, J., Ma, M., Chai, B., He, G., et al. (2020). *Candida albicans* biofilm inactivated by cold plasma treatment in vitro and in vivo. *Plasma Processes and Polymers, 17*(4), 1900068. https://doi.org/10.1002/ppap.201900068
Heise, M., Neff, W., Franken, O., Muranyi, P., & Wunderlich, J. (2004). Sterilization of polymer foils with dielectric barrier discharges at atmospheric pressure. *Plasmas and Polymers, 9*(1), 23–33. https://doi.org/10.1023/B:PAPO.0000039814.70172.c0
Honarvar, Z., Farhoodi, M., Khani, M. R., Mohammadi, A., Shokri, B., Ferdowsi, R., et al. (2017). Application of cold plasma to develop carboxymethyl cellulose-coated polypropylene films containing essential oil. *Carbohydrate Polymers, 176*, 1–10. https://doi.org/10.1016/j.carbpol.2017.08.054
Huang, M., Zhuang, H., Zhao, J., Wang, J., Yan, W., & Zhang, J. (2020). Differences in cellular damage induced by dielectric barrier discharge plasma between *Salmonella Typhimurium* and *Staphylococcus aureus*. *Bioelectrochemistry, 132*, 107445.
Kamath, S. D., Rahman, A. M. A., Komoda, T., & Lopata, A. L. (2013). Impact of heat processing on the detection of the major shellfish allergen tropomyosin in crustaceans and molluscs using specific monoclonal antibodies. *Food Chemistry, 141*(4), 4031–4039. https://doi.org/10.1016/j.foodchem.2013.06.105
Kart, D., Gurel, D. B., & Kayaardi, S. (2018). Cold plasma and ultrasound applications in cleaning of food contact surfaces. *International Journal of Scientific and Technological Research, 4*(8), 17–27.
Katsigiannis, A. S., Bayliss, D. L., & Walsh, J. L. (2020). Cold plasma decontamination of stainless steel food processing surfaces assessed using an industrial disinfection protocol. *Food Control.* , Article 107543. https://doi.org/10.1016/j.foodcont.2020.107543
Kayes, M. M., Critzer, F. J., Kelly-Wintenberg, K., Roth, J. R., Montie, T. C., & Golden, D. A. (2007). Inactivation of foodborne pathogens using a one atmosphere uniform glow discharge plasma. *Foodborne Pathogens and Disease, 4*(1), 50–59. https://doi.org/10.1089/fpd.2006.62
Khani, M. R., Shokri, B., & Khajeh, K. (2017). Studying the performance of dielectric barrier discharge and gliding arc plasma reactors in tomato peroxidase inactivation. *Journal of Food Engineering, 197*, 107–112. https://doi.org/10.1016/j.jfoodeng.2016.11.012
Kim, H. J., Jayasena, D. D., Yong, H. I., Alahakoon, A. U., Park, S., Park, J., et al. (2015). Effect of atmospheric pressure plasma jet on the foodborne pathogens attached to commercial food containers. *Journal of Food Science & Technology, 52*(12), 8410–8415. https://doi.org/10.1007/s13197-015-2003-0
Kim, J. S., Lee, E. J., Cho, E. A., & Kim, Y. J. (2013). Inactivation of Campylobacter jejuni using radio-frequency atmospheric pressure plasma on agar plates and chicken hams. *Korean Journal for Food Science of Animal Resources, 33*(3), 317–324. https://doi.org/10.5851/kosfa.2013.33.3.317
Kim, J. W., Puligundla, P., & Mok, C. (2015). Microbial decontamination of dried laver using corona discharge plasma jet (CDPJ). *Journal of Food Engineering, 161*, 24–32. https://doi.org/10.1016/j.jfoodeng.2015.03.034
Korachi, M., Ozen, F., Aslan, N., Vannini, L., Guerzoni, M. E., Gottardi, D., et al. (2015). Biochemical changes to milk following treatment by a novel, cold atmospheric plasma system. *International Dairy Journal, 42*, 64–69. https://doi.org/10.1016/j.idairyj.2014.10.006
Kruk, Z. A., Yun, H., Rutley, D. L., Lee, E. J., Kim, Y. J., & Jo, C. (2011). The effect of high pressure on microbial population, meat quality and sensory characteristics of chicken breast fillet. *Food Control, 22*(1), 6–12. https://doi.org/10.1016/j.foodcont.2010.06.003
Kulawik, P., Alvarez, C., Cullen, P. J., Aznar-Roca, R., Mullen, A. M., & Tiwari, B. (2018). The effect of non-thermal plasma on the lipid oxidation and microbiological quality of sushi. *Innovative Food Science & Emerging Technologies, 45*, 412–417. https://doi.org/10.1016/j.ifset.2017.12.011
Kulawik, P., & Kumar Tiwari, B. (2019). Recent advancements in the application of non-thermal plasma technology for the seafood industry. *Critical Reviews in Food Science and Nutrition, 59*(19), 3199–3210. https://doi.org/10.1080/10408398.2018.1510827
Lacombe, A., Niemira, B. A., Gurtler, J. B., Fan, X., Sites, J., Boyd, G., et al. (2015). Atmospheric cold plasma inactivation of aerobic microorganisms on blueberries and effects on quality attributes. *Food Microbiology, 46*, 479–484. https://doi.org/10.1016/j.fm.2014.09.010
Lacombe, A., Niemira, B. A., Gurtler, J. B., Sites, J., Boyd, G., Kingsley, D. H., et al. (2017). Nonthermal inactivation of norovirus surrogates on blueberries using atmospheric cold plasma. *Food Microbiology, 63*, 1–5. https://doi.org/10.1016/j.fm.2016.10.030
Lee, S. Y., Lee, W. K., Lee, J. W., Chung, M.-S., Oh, S.-W., Shin, J.-K., et al. (2021). Microbial decontamination of rice germ using a large-scale plasma jet-pulsed light-ultraviolet-C integrated treatment system. *Food and Bioprocess Technology, 14*(3). https://doi.org/10.1007/s11947-021-02590-6
Lee, P. Y., Lusk, K., Mirosa, M., & Oey, I. (2016). Effect of information on Chinese consumers' acceptance of thermal and non-thermal treated apple juices: A study of young Chinese immigrants in New Zealand. *Food Quality and Preference, 48*, 118–129. https://doi.org/10.1016/j.foodqual.2015.09.002
Lee, H. S., Park, H. H., & Min, S. C. (2020). Microbial decontamination of red pepper powder using pulsed light plasma. *Journal of Food Engineering, 284*, 110075. https://doi.org/10.1016/j.jfoodeng.2020.110075
Lee, T., Puligundla, P., & Mok, C. (2018). Intermittent corona discharge plasma jet for improving tomato quality. *Journal of Food Engineering, 223*, 168–174. https://doi.org/10.1016/j.jfoodeng.2017.11.004
Leipold, F., Kusano, Y., Hansen, F., & Jacobsen, T. (2010). Decontamination of a rotating cutting tool during operation by means of atmospheric pressure plasmas. *Food Control, 21*(8). https://doi.org/10.1016/j.foodcont.2010.02.006
Lei, J., Yang, L., Zhan, Y., Wang, Y., Ye, T., Li, Y., et al. (2014). Plasma treated polyethylene terephthalate/polypropylene films assembled with chitosan and various preservatives for antimicrobial food packaging. *Colloids and Surfaces B: Biointerfaces, 114*, 60–66. https://doi.org/10.1016/j.colsurfb.2013.09.052
Liao, X., Liu, D., Chen, S., Ye, X., & Ding, T. (2021). Degradation of antibiotic resistance contaminants in wastewater by atmospheric cold plasma: Kinetics and mechanisms. *Environmental Technology, 42*(1), 58–71. https://doi.org/10.1080/09593330.2019.1620866
Liao, X., Su, Y., Liu, D., Chen, S., Hu, Y., Ye, X., et al. (2018). Application of atmospheric cold plasma-activated water (PAW) ice for preservation of shrimps (*Metapenaeus ensis*). *Food Control, 94*, 307–314. https://doi.org/10.1016/j.foodcont.2018.07.026
Lin, L., Liao, X., & Cui, H. (2019). Cold plasma treated thyme essential oil/silk fibroin nanofibers against *Salmonella Typhimurium* in poultry meat. *Food Packaging and Shelf Life, 21*, 100337. https://doi.org/10.1016/j.fpsl.2019.100337
Lin, L., Liao, X., Li, C., Abdel-Samie, M. A., Siva, S., & Cui, H. (2021). Cold nitrogen plasma modified cuminaldehyde/β-cyclodextrin inclusion complex and its application in vegetable juices preservation. *Food Research International, 141*, 110132. https://doi.org/10.1016/j.foodres.2021.110132
Lin, H. M., Zhang, S., Zheng, R. S., Miao, J. Y., & Deng, S. G. (2020). Effect of atmospheric cold plasma treatment on ready-to-eat wine-pickled Bullacta exarata. *Lebensmittel-Wissenschaft und -Technologie, 120*, 108953. https://doi.org/10.1016/j.lwt.2019.108953
Luang-In, V., Saengha, W., Karirat, T., Buranrat, B., Matra, K., Deeseenthum, S., et al. (2021). Effect of cold plasma and elicitors on bioactive contents, antioxidant activity and cytotoxicity of Thai rat-tailed radish microgreens. *Journal of the Science of Food and Agriculture, 101*(4), 1685–1698. https://doi.org/10.1002/jsfa.10985
Lu, P., Guo, M., Xu, Z., & Wu, M. (2018). Application of nanofibrillated cellulose on BOPP/LDPE film as oxygen barrier and antimicrobial coating based on cold plasma treatment. *Coatings, 8*(6), 207. https://doi.org/10.3390/coatings8060207
Lu, H., Patil, S., Keener, K. M., Cullen, P. J., & Bourke, P. (2014). Bacterial inactivation by high-voltage atmospheric cold plasma: Influence of process parameters and effects on cell leakage and DNA. *Journal of Applied Microbiology, 116*(4), 784–794. https://doi.org/10.1111/jam.12426
Mahdavian Mehr, H., & Koocheki, A. (2021). Physicochemical properties of Grass pea (*Lathyrus sativus L.*) protein nanoparticles fabricated by cold atmospheric-pressure

plasma. *Food Hydrocolloids, 112*, 106328. https://doi.org/10.1016/j.foodhyd.2020.106328
Mandal, R., Singh, A., & Pratap Singh, A. (2018). Recent developments in cold plasma decontamination technology in the food industry. In *Trends in food science and technology* (Vol. 80, pp. 93–103). https://doi.org/10.1016/j.tifs.2018.07.014. Elsevier Ltd.
Maslakci, N. N., Ulusoy, S., & Oksuz, A. U. (2017). Investigation of the effects of plasma-treated chitosan electrospun fibers onto biofilm formation. *Sensors and Actuators B: Chemical, 246*, 887–895. https://doi.org/10.1016/j.snb.2017.02.089
Mendes-Oliveira, G., Jensen, J. L., Keener, K. M., & Campanella, O. H. (2019). Modeling the inactivation of Bacillus subtilis spores during cold plasma sterilization. *Innovative Food Science & Emerging Technologies, 52*, 334–342. https://doi.org/10.1016/j.ifset.2018.12.011
Miao, W., Nyaisaba, B. M., Koddy, J. K., Chen, M., Hatab, S., & Deng, S. (2020). Effect of cold atmospheric plasma on the physicochemical and functional properties of myofibrillar protein from Alaska pollock (*Theragra chalcogramma*). *International Journal of Food Science and Technology, 55*(2), 517–525. https://doi.org/10.1111/ijfs.14295
Mir, S. A., Siddiqui, M. W., Dar, B. N., Shah, M. A., Wani, M. H., Roohinejad, S., et al. (2020). Promising applications of cold plasma for microbial safety, chemical decontamination and quality enhancement in fruits. *Journal of Applied Microbiology, 129*(3), 474–485. https://doi.org/10.1111/jam.14541
Misra, N., Pankaj, S., Segat, A., & Ishikawa, K. (2016). Cold plasma interactions with enzymes in foods and model systems. *Trends in Food Science & Technology, 55*, 39–47. https://doi.org/10.1016/j.tifs.2016.07.001
Misra, N., Tiwari, B., Raghavarao, K., & Cullen, P. (2011). Nonthermal plasma inactivation of food-borne pathogens. *Food Engineering Reviews, 3*(4), 159–170. https://doi.org/10.1007/s12393-011-9041-9
Moosavi, M. H., Khani, M. R., Shokri, B., Hosseini, S. M., Shojaee-Aliabadi, S., & Mirmoghtadaie, L. (2020). Modifications of protein-based films using cold plasma. *International Journal of Biological Macromolecules, 142*, 769–777. https://doi.org/10.1016/j.ijbiomac.2019.10.017
Moutiq, R., Misra, N. N., Mendonça, A., & Keener, K. (2020). In-package decontamination of chicken breast using cold plasma technology: Microbial, quality and storage studies. *Meat Science, 159*, 107942. https://doi.org/10.1016/j.meatsci.2019.107942
Muranyi, P., Wunderlich, J., & Heise, M. (2007). Sterilization efficiency of a cascaded dielectric barrier discharge. *Journal of Applied Microbiology, 103*(5), 1535–1544. https://doi.org/10.1111/j.1365-2672.2007.03385.x
Niemira, B. A. (2012). Cold plasma decontamination of foods. *Annual Review of Food Science and Technology, 3*(1), 125–142. https://doi.org/10.1146/annurev-food-022811-101132
Niemira, B. A., & Sites, J. (2008). Cold plasma inactivates Salmonella Stanley and Escherichia coli O157:H7 inoculated on golden delicious apples. *Journal of Food Protection, 71*(7), 1357–1365. https://doi.org/10.4315/0362-028X-71.7.1357
Noriega, E., Shama, G., Laca, A., Díaz, M., & Kong, M. G. (2011). Cold atmospheric gas plasma disinfection of chicken meat and chicken skin contaminated with Listeria innocua. *Food Microbiology, 28*(7), 1293–1300. https://doi.org/10.1016/j.fm.2011.05.007
Oh, Y. A., Roh, S. H., & Min, S. C. (2016). Cold plasma treatments for improvement of the applicability of defatted soybean meal-based edible film in food packaging. *Food Hydrocolloids, 58*, 150–159. https://doi.org/10.1016/j.foodhyd.2016.02.022
Olatunde, O. O., Benjakul, S., & Vongkamjan, K. (2019). Combined effects of high voltage cold atmospheric plasma and antioxidants on the qualities and shelf-life of Asian sea bass slices. *Innovative Food Science & Emerging Technologies, 54*, 113–122. https://doi.org/10.1016/j.ifset.2019.03.012
Olatunde, O. O., Shiekh, K. A., & Benjakul, S. (2021). Pros and cons of cold plasma technology as an alternative non-thermal processing technology in seafood industry. *Trends in Food Science & Technology, 111*. https://doi.org/10.1016/j.tifs.2021.03.026
Ostrikov, K., Neyts, E. C., & Meyyappan, M. (2013). Plasma nanoscience: From nano-solids in plasmas to nano-plasmas in solids. *Advances in Physics, 62*(2), 113–224. https://doi.org/10.1080/00018732.2013.808047
Pan, Y., Cheng, J., & Sun, D. (2019). Cold plasma-mediated treatments for shelf life extension of fresh produce: A review of recent research developments. *Comprehensive Reviews in Food Science and Food Safety, 18*(5), 1312–1326. https://doi.org/10.1111/1541-4337.12474
Pankaj, S. K., Bueno-Ferrer, C., Misra, N. N., Milosavljević, V., O'Donnell, C. P., Bourke, P., et al. (2014). Applications of cold plasma technology in food packaging. *Trends in Food Science & Technology, 35*(1). https://doi.org/10.1016/j.tifs.2013.10.009
Pan, Y., Zhang, Y., Cheng, J. H., & Sun, D. W. (2020). Inactivation of *Listeria Monocytogenes* at various growth temperatures by ultrasound pretreatment and cold plasma. *Lebensmittel-Wissenschaft und -Technologie, 118*, 108635. https://doi.org/10.1016/j.lwt.2019.108635
Park, S. Y., & Ha, S.-D. (2015). Application of cold oxygen plasma for the reduction of Cladosporium cladosporioides and Penicillium citrinum on the surface of dried filefish (*Stephanolepis cirrhifer*) fillets. *International Journal of Food Science and Technology, 50*(4), 966–973. https://doi.org/10.1111/ijfs.12730
Patange, A., Lu, P., Boehm, D., Cullen, P. J., & Bourke, P. (2019). Efficacy of cold plasma functionalised water for improving microbiological safety of fresh produce and wash water recycling. *Food Microbiology, 84*, 103226. https://doi.org/10.1016/j.fm.2019.05.010
Paul, A., & R, M. (2020). Mortality of *Tribolium castaneum* and quality changes in *Oryza sativa* by indirect exposure to Non-Thermal Plasma. *Frontiers in Advanced Materials Research, 2*(2), 26–40. https://doi.org/10.34256/famr2024
Peng, P., Chen, P., Zhou, N., Schiappacasse, C., Cheng, Y., Chen, D., et al. (2019). Packed food and packaging materials disinfected by cold plasma. *Advances in cold plasma applications for food safety and preservation*. https://doi.org/10.1016/B978-0-12-814921-8.00009-8. Elsevier.
Pérez-Andrés, J. M., Álvarez, C., Cullen, P. J., & Tiwari, B. K. (2019). Effect of cold plasma on the techno-functional properties of animal protein food ingredients. *Innovative Food Science & Emerging Technologies, 58*, 102205. https://doi.org/10.1016/j.ifset.2019.102205
Prysiazhnyi, V., Zaporojchenko, V., Kersten, H., & Černák, M. (2012). Influence of humidity on atmospheric pressure air plasma treatment of aluminium surfaces. *Applied Surface Science, 258*(14), 5467–5471. https://doi.org/10.1016/j.apsusc.2012.02.040
Puligundla, P., Kim, J.-W., & Mok, C. (2017). Effect of corona discharge plasma jet treatment on decontamination and sprouting of rapeseed (*Brassica napus L.*) seeds. *Food Control, 71*, 376–382. https://doi.org/10.1016/j.foodcont.2016.07.021
Puligundla, P., Lee, T., & Mok, C. (2018). Effect of intermittent corona discharge plasma treatment for improving microbial quality and shelf life of kumquat (*Citrus japonica*) fruits. *Lebensmittel-Wissenschaft und -Technologie, 91*, 8–13. https://doi.org/10.1016/j.lwt.2018.01.019
Puligundla, P., & Mok, C. (2016). Non-thermal plasmas (NTPs) for inactivation of viruses in abiotic environment. *Research Journal of Biotechnology, 11*(6), 91–96.
Ratish Ramanan, K., Sarumathi, R., & Mahendran, R. (2018). Influence of cold plasma on mortality rate of different life stages of *Tribolium castaneum* on refined wheat flour. *Journal of Stored Products Research, 77*, 126–134. https://doi.org/10.1016/j.jspr.2018.04.006
Rød, S. K., Hansen, F., Leipold, F., & Knøchel, S. (2012). Cold atmospheric pressure plasma treatment of ready-to-eat meat: Inactivation of Listeria innocua and changes in product quality. *Food Microbiology, 30*(1), 233–238. https://doi.org/10.1016/j.fm.2011.12.018
Romani, V. P., Olsen, B., Pinto Collares, M., Meireles Oliveira, J. R., Prentice-Hernández, C., & Guimarães Martins, V. (2019). Improvement of fish protein films properties for food packaging through glow discharge plasma application. *Food Hydrocolloids, 87*, 970–976. https://doi.org/10.1016/j.foodhyd.2018.09.022
Romani, V. P., Olsen, B., Pinto Collares, M., Meireles Oliveira, J. R., Prentice, C., & Martins, V. G. (2020). Cold plasma and carnauba wax as strategies to produce improved bi-layer films for sustainable food packaging. *Food Hydrocolloids, 108*, 106087. https://doi.org/10.1016/j.foodhyd.2020.106087
Royintarat, T., Choi, E. H., Boonyawan, D., Seesuriyachan, P., & Wattanutchariya, W. (2020). Chemical-free and synergistic interaction of ultrasound combined with plasma-activated water (PAW) to enhance microbial inactivation in chicken meat and skin. *Scientific Reports, 10*(1). https://doi.org/10.1038/s41598-020-58199-w
Sahebkar, A., Hosseini, M., & Sharifan, A. (2020). Plasma-assisted preservation of breast chicken fillets in essential oils-containing marinades. *Lebensmittel-Wissenschaft und -Technologie, 131*, 109759. https://doi.org/10.1016/j.lwt.2020.109759
Sarangapani, C., Misra, N. N., Milosavljevic, V., Bourke, P., O'Regan, F., & Cullen, P. J. (2016). Pesticide degradation in water using atmospheric air cold plasma. *Journal of Water Process Engineering, 9*, 225–232. https://doi.org/10.1016/j.jwpe.2016.01.003
Schnabel, U., Schmidt, C., Schlüter, O., Bundeswehr, M. A., Niquet, R., Stachowiak, J., et al. (2016). Antimicrobial efficiency of non-thermal atmospheric pressure plasma processed water (PPW) against agricultural relevant bacteria suspensions. *International Journal of Environmental & Agriculture Research (IJOEAR) ISSN, 2*(5), 212–224. https://www.researchgate.net/publication/303812694.
Segat, A., Misra, N. N., Cullen, P. J., & Innocente, N. (2015). Atmospheric pressure cold plasma (ACP) treatment of whey protein isolate model solution. *Innovative Food Science & Emerging Technologies, 29*, 247–254. https://doi.org/10.1016/j.ifset.2015.03.014
Segat, A., Misra, N. N., Cullen, P. J., & Innocente, N. (2016). Effect of atmospheric pressure cold plasma (ACP) on activity and structure of alkaline phosphatase. *Food and Bioproducts Processing, 98*, 181–188. https://doi.org/10.1016/j.fbp.2016.01.010
Selcuk, M., Oksuz, L., & Basaran, P. (2008). Decontamination of grains and legumes infected with *Aspergillus spp.* and *Penicillum spp.* by cold plasma treatment. *Bioresource Technology, 99*(11), 5104–5109. https://doi.org/10.1016/j.biortech.2007.09.076
Şen, Y., Bağci, U., Güleç, H. A., & Mutlu, M. (2012). Modification of food-contacting surfaces by plasma polymerization technique: Reducing the biofouling of microorganisms on stainless steel surface. *Food and Bioprocess Technology, 5*(1), 166–175. https://doi.org/10.1007/s11947-009-0248-1
Sen, Y., & Mutlu, M. (2013). Sterilization of food contacting surfaces via non-thermal plasma treatment: A model study with Escherichia coli-contaminated stainless steel and polyethylene surfaces. *Food and Bioprocess Technology, 6*(12), 3295–3304. https://doi.org/10.1007/s11947-012-1007-2
Sen, Y., Mutlu, M., & Bagci, U. (2011). April). *Sterilization of food contacting polymer surfaces via non-thermal plasma treatment by using different precursor gas composition. 6th international CIGR technical symposium - towards a sustainable food chain: Food process* (Bioprocessing and Food Quality Management).
Sharma, S., & Singh, R.k. (2020). Cold plasma treatment of dairy proteins in relation to functionality enhancement. *Trends in Food Science & Technology, 102*, 30–36. https://doi.org/10.1016/j.tifs.2020.05.013
Shen, J., Tian, Y., Li, Y., Ma, R., Zhang, Q., Zhang, J., et al. (2016). Bactericidal effects against S. aureus and physicochemical properties of plasma activated water stored at different temperatures. *Scientific Reports, 6*(1), 1–10. https://doi.org/10.1038/srep28505
Shiekh, K. A., Benjakul, S., Qi, H., Zhang, B., & Deng, S. (2021). Combined hurdle effects of pulsed electric field and vacuum impregnation of Chamuang leaf extract on quality and shelf-life of Pacific white shrimp subjected to high voltage cold

atmospheric plasma. *Food Packaging and Shelf Life, 28*. https://doi.org/10.1016/j.fpsl.2021.100660
Shiekh, K. A., Zhou, P., & Benjakul, S. (2021). Combined effects of pulsed electric field, Chamuang leaf extract and cold plasma on quality and shelf-life of *Litopenaeus vannamei. Food Bioscience, 41*. https://doi.org/10.1016/j.fbio.2021.100975
Shi, H., Ileleji, K., Stroshine, R. L., Keener, K., & Jensen, J. L. (2017). Reduction of aflatoxin in corn by high voltage atmospheric cold plasma. *Food and Bioprocess Technology, 10*(6), 1042–1052. https://doi.org/10.1007/s11947-017-1873-8
Sohbatzadeh, F., Mirzanejhad, S., Shokri, H., & Nikpour, M. (2016). Inactivation of Aspergillus flavus spores in a sealed package by cold plasma streamers. *Journal of Theoretical and Applied Physics, 10*(2), 99–106. https://doi.org/10.1007/s40094-016-0206-z
Sonawane, S. K., T, M., & Patil, S. (2020). Non-thermal plasma: An advanced technology for food industry. *Food Science and Technology International, 26*(8). https://doi.org/10.1177/1082013220929474
Takai, E., Kitamura, T., Kuwabara, J., Ikawa, S., Yoshizawa, S., Shiraki, K., et al. (2014). Chemical modification of amino acids by atmospheric-pressure cold plasma in aqueous solution. *Journal of Physics D: Applied Physics, 47*(28), 285403. https://doi.org/10.1088/0022-3727/47/28/285403
Thirumdas, R., Sarangapani, C., & Annapure, U. S. (2015). Cold plasma: A novel non-thermal technology for food processing. *Food Biophysics, 10*(1), 1–11. https://doi.org/10.1007/s11483-014-9382-z
Tiozzo, B., Mari, S., Magaudda, P., Arzenton, V., Capozza, D., Neresini, F., et al. (2011). Development and evaluation of a risk-communication campaign on salmonellosis. *Food Control, 22*(1), 109–117. https://doi.org/10.1016/j.foodcont.2010.04.030
Todd, E. C. D., & Notermans, S. (2011). Surveillance of listeriosis and its causative pathogen, *Listeria monocytogenes*. *Food Control, 22*(9), 1484–1490. https://doi.org/10.1016/j.foodcont.2010.07.021
Toyokawa, Y., Yagyu, Y., Misawa, T., & Sakudo, A. (2017). A new roller conveyer system of non-thermal gas plasma as a potential control measure of plant pathogenic bacteria in primary food production. *Food Control, 72*, 62–72. https://doi.org/10.1016/j.foodcont.2016.07.031
Ulbin-Figlewicz, N., Brychcy, E., & Jarmoluk, A. (2015). Effect of low-pressure cold plasma on surface microflora of meat and quality attributes. *Journal of Food Science & Technology, 52*(2), 1228–1232. https://doi.org/10.1007/s13197-013-1108-6
Umair, M., Jabbar, S., Ayub, Z., Muhammad Aadil, R., Abid, M., Zhang, J., et al. (2021). Recent advances in plasma technology: Influence of atmospheric cold plasma on spore inactivation. *Food Reviews International*. https://doi.org/10.1080/87559129.2021.1888972
Uygun, A., Kiristi, M., Oksuz, L., Manolache, S., & Ulusoy, S. (2011). RF hydrazine plasma modification of chitosan for antibacterial activity and nanofiber applications. *Carbohydrate Research, 346*(2), 259–265. https://doi.org/10.1016/j.carres.2010.11.020
Vandamme, J., Nikiforov, A., Dujardin, K., Leys, C., de Cooman, L., & van Durme, J. (2015). Critical evaluation of non-thermal plasma as an innovative accelerated lipid oxidation technique in fish oil. *Food Research International, 72*, 115–125. https://doi.org/10.1016/j.foodres.2015.03.037
Venezia, R. A., Orrico, M., Houston, E., Yin, S.-M., Naumova, Y. Y., & Jersey, N. (2008). Lethal activity of nonthermal plasma sterilization against microorganisms. *Infection Control and Hospital Epidemiology, 29*(5). https://doi.org/10.1086/588003
Venkataratnam, H., Sarangapani, C., Cahill, O., & Ryan, C. B. (2019). *Effect of cold plasma treatment on the antigenicity of peanut allergen Ara h 1. 52*. Innovative Food Science & Emerging Technologies. https://doi.org/10.1016/j.ifset.2019.02.001
Volkov, A. G., Hairston, J. S., Patel, D., Gott, R. P., & Xu, K. G. (2019). Cold plasma poration and corrugation of pumpkin seed coats. *Bioelectrochemistry, 128*, 175–185. https://doi.org/10.1016/j.bioelechem.2019.04.012
Wong, L. W., Hou, C. Y., Hsieh, C. C., Chang, C. K., Wu, Y. S., & Hsieh, C. W. (2020). Preparation of antimicrobial active packaging film by capacitively coupled plasma treatment. *Lebensmittel-Wissenschaft und -Technologie, 117*, 108612. https://doi.org/10.1016/j.lwt.2019.108612
Wu, T. Y., Sun, N. N., & Chau, C. F. (2018). Application of corona electrical discharge plasma on modifying the physicochemical properties of banana starch indigenous to Taiwan. *Journal of Food and Drug Analysis, 26*(1), 244–251. https://doi.org/10.1016/j.jfda.2017.03.005
Xiang, Q., Liu, X., Liu, S., Ma, Y., Xu, C., & Bai, Y. (2019). Effect of plasma-activated water on microbial quality and physicochemical characteristics of mung bean sprouts. *Innovative Food Science & Emerging Technologies, 52*, 49–56. https://doi.org/10.1016/j.ifset.2018.11.012
Yadav, B., Spinelli, A. C., Misra, N. N., Tsui, Y. Y., McMullen, L. M., & Roopesh, M. S. (2020). Effect of in-package atmospheric cold plasma discharge on microbial safety and quality of ready-to-eat ham in modified atmospheric packaging during storage. *Journal of Food Science, 85*(4), 1203–1212. https://doi.org/10.1111/1750-3841.15072
Yang, L., Chen, J., & Gao, J. (2009). Low temperature argon plasma sterilization effect on *Pseudomonas aeruginosa* and its mechanisms. *Journal of Electrostatics, 67*(4), 646–651. https://doi.org/10.1016/j.elstat.2009.01.060
Yepez, X.v., Misra, N. N., & Keener, K. M. (2020). Nonthermal plasma technology. *Food engineering series*. Springer. https://doi.org/10.1007/978-3-030-42660-6_23
Yong, H. I., Kim, H. J., Park, S., Alahakoon, A. U., Kim, K., Choe, W., et al. (2015). Evaluation of pathogen inactivation on sliced cheese induced by encapsulated atmospheric pressure dielectric barrier discharge plasma. *Food Microbiology, 46*, 46–50. https://doi.org/10.1016/j.fm.2014.07.010
Yong, H. I., Kim, H.-J., Park, S., Kim, K., Choe, W., Yoo, S. J., et al. (2015). Pathogen inactivation and quality changes in sliced cheddar cheese treated using flexible thin-layer dielectric barrier discharge plasma. *Food Research International, 69*, 57–63. https://doi.org/10.1016/j.foodres.2014.12.008
Yong, H. I., Lee, H., Park, S., Park, J., Choe, W., Jung, S., et al. (2017). Flexible thin-layer plasma inactivation of bacteria and mold survival in beef jerky packaging and its effects on the meat's physicochemical properties. *Meat Science, 123*, 151–156. https://doi.org/10.1016/j.meatsci.2016.09.016
Yun, H., Kim, B., Jung, S., Kruk, Z. A., Kim, D. B., Choe, W., et al. (2010). Inactivation of Listeria monocytogenes inoculated on disposable plastic tray, aluminum foil, and paper cup by atmospheric pressure plasma. *Food Control, 21*(8), 1182–1186. https://doi.org/10.1016/j.foodcont.2010.02.002
Zhang, R., Guo, X., Shi, X., Sun, A., Wang, L., Xiao, T., et al. (2014). Highly permselective membrane surface modification by cold plasma-induced grafting polymerization of molecularly imprinted polymer for recognition of pyrethroid insecticides in fish. *Analytical Chemistry, 86*(23), 11705–11713. https://doi.org/10.1021/ac503049s
Zhang, K., Perussello, C. A., Milosavljević, V., Cullen, P. J., Sun, D.-W., & Tiwari, B. K. (2019). Diagnostics of plasma reactive species and induced chemistry of plasma treated foods. *Critical Reviews in Food Science and Nutrition, 59*(5). https://doi.org/10.1080/10408398.2018.1564731
Zhang, J., Wang, J., & Zhuang, H. (2019). *Synergistic sterilizing and preserving method for fresh meat with high voltage electric field plasma and nano photocatalysis*. Patent No. US20170043895A1).
Zhang, Y., Zhang, J., Zhang, Y., Hu, H., Luo, S., Zhang, L., et al. (2021). Effects of in-package atmospheric cold plasma treatment on the qualitative, metabolic and microbial stability of fresh-cut pears. *Journal of the Science of Food and Agriculture*. https://doi.org/10.1002/jsfa.11085. jsfa.11085.
Zhao, Y. M., de Alba, M., Sun, D. W., & Tiwari, B. (2019). Principles and recent applications of novel non-thermal processing technologies for the fish industry—a review. *Critical Reviews in Food Science and Nutrition, 59*(5), 728–742. https://doi.org/10.1080/10408398.2018.1495613
Zhou, Y.-H., Vidyarthi, S. K., Zhong, C.-S., Zheng, Z.-A., An, Y., Wang, J., et al. (2020). Cold plasma enhances drying and color, rehydration ratio and polyphenols of wolfberry via microstructure and ultrastructure alteration. *Lebensmittel-Wissenschaft und -Technologie, 134*, 110173. https://doi.org/10.1016/j.lwt.2020.110173
Zouelm, F., Abhari, K., Hosseini, H., & Khani, M. (2019). The effects of cold plasma application on quality and chemical spoilage of pacific white shrimp (*Litopenaeus vannamei*) during refrigerated storage. *Journal of Aquatic Food Product Technology, 28*(6), 624–636. https://doi.org/10.1080/10498850.2019.1627452