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Cold plasma as an emerging nonthermal technology for food processing: A comprehensive review

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A B S T R A C T

Cold plasma, a partially ionized gas maintained at low temperatures, has emerged as a promising nonthermal food processing technique with various applications, including food sterilization and improved agricultural output. By generating reactive species such as ions, radicals, and photons, cold plasma interacts with and modifies the surfaces of materials or living cells. This comprehensive review focuses on the microbial decontamination capabilities of cold plasma and its impact on a wide range of food products, including cereals, milk, fruits, vegetables, and meat. Cold plasma treatment offers distinct advantages over traditional methods such as heat treatment, chemical treatment, and irradiation. It effectively eliminates pathogenic microbes from food surfaces while preserving the quality, flavor, and nutritional content of the food. By sterilizing food surfaces and packaging materials, cold plasma significantly reduces the risk of harmful microorganism contamination. Moreover, it extends the shelf life of food products by eliminating germs, viruses, and other hazardous microbes. This review critically assesses the qualitative impact of plasma treatment, emphasizing the importance of selecting the appropriate cold plasma technology for various food products. To ensure the safety and effectiveness of cold plasma technology for commercial implementation, this review investigates the properties of cold plasma treatment for different food products. It examines the molecular connections between dietary components and cold plasma species, highlighting potential avenues for future research.

1. Introduction

Foods that have undergone non-thermal processing can potentially be kept fresh for a longer period and delivered to consumers with ease without adversely affecting the nutritional value or shelf life. Consumer comprehension of a healthy diet could help in the prevention of nutrition-related ailments. Furthermore, individuals are eager to shift their eating habits to healthier ones in this new era since immunity is now an important consideration [1]. Recent reports from the food sector employ methods apart from heat treatment for preparing food [2,3]. As a result of thermal food preservation, there is a significant loss in food quality, such as overcooking, textural deterioration, flavor, sensory attribute modifications, a drop in nutritional content due to heat exposure, and so on. [4]; Singh et al., 2017; [5]. Thermal food processing is being in use for more than two centuries and is still one of the important food processing techniques used in food processing industries [6]. The use of high heat treatment can result in undesirable effects such as change in color, texture, loss of nutrients etc., motivating researchers to explore more non-thermal alternatives for food processing [7]. Researchers are concentrating on creating new processing methods that retain most of the quality attributes; a few of them are dielectric heating (microwave heating and radiofrequency), infrared heating, ultrasound, ohmic heating, pulsed electric field, high-pressure processing, ozone processing, pulsed light, and cold plasma. These emerging techniques offer minimum treatment, preservation of sensory attributes of food with subsequent protection of food bioactive compounds and their functionality for extend period of time. Emerging techniques possess numerous applications in the food sector, promising reduced heating and residence time, improved food quality, energetic yield, control of maillard and other chemical reaction, and environmental stresses protection [8,9]. Emerging technologies are not based on high temperature but on the heat generation through internal energy transmission (such as

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adiabatic and resistive during high hydrostatic pressure, and pulsed electric fields respectively) which reduces sensory deterioration, nutritional, and functional and nutritional profile of foods [1].

Cold plasma (CP) is a recent technical intervention for maintaining food quality and safety [43]. Primarily it is a technology created for curing and bonding polymers, additionally utilized in a variety of industries [44]. Cold plasma technique has demonstrated itself as a successful technology in the food industry for removing sporulating and harmful organisms from food items. In recent years, this innovative technique has been declared as a disinfectant of foods and food contact surfaces. The innovation of this method lies in its versatility of production and potential applications such as direct or indirect plasma, its non-thermal effect, functional coatings as well as plasma treated water, and, as food quality characteristics are not been affected negatively [45]. Cold plasma can be used to decontaminate objects that have microorganisms on their surface. Unlike light (for example, UV light decontaminating), plasma travels around things, eliminating shadow effects and guaranteeing that all product portions are cleaned. Surfaces might be cleaned with cold plasma before packing or as part of the packaging procedure. Even with the added requirement for carrier gas, plasma technologies' electronics and longevity are equivalent to UV-C systems regarding energy usage and profitability for treating food. Cold plasma with potent antibacterial properties could reduce the time needed for treatment and benefit from low working temperatures (30-50 °C) to keep foods nutritional and sensory qualities [46]. Low-temperature (or so-called "cold") plasmas are quasineutral particle systems of semi-gas and semi-fluid mixtures of high active moieties. Cold plasma is generated by electric discharges implemented at various levels of pressure in high-moisture foods, as a vacuum is boosting liquid conversion to gaseous phase. This novel method also results in microbial inactivation of foods [47].

Cold plasma has a number of benefits over existing food safety systems, including being easily adapted to a food processing environment, requiring short treatment times, utilizing little energy, and quickly reverting active gas species to their initial gas after treatment. After the reactive compounds have been removed from the power source, plasma is ecologically safe. This method is appropriate for sensitive raw and also fresh food products. It does not impact both the nutritional and sensory characteristics of food ingredients. Low-cost noble gases are employed for processing, which reduces equipment costs, at low temperatures, microbial inactivation efficiency can be obtained; it also requires less electricity to operate (Keener and Misra, 2016; [48–51]. Based on this, the review focuses on the effects of cold plasma technology on food items such as cereals, milk, fruits, vegetables, and meat as well as microbiological decontamination. Moreover, insightful analyses of the qualitative effects of plasma treatment are presented, highlighting the significance of choosing the cold plasma technique for various food products. The assessment examines the characteristics of cold plasma treatment for various kinds of food to guarantee the technology's efficacy and safety for commercial use.

2. Principle of cold plasma

Plasma is the fourth matter state that exists, following solids, liquids, and gases, as shown in Fig. (1). It is frequently shown as a brilliant fluorescent light discharge or arc. Physically, it is a gaseous mixture that is partially or completely ionized [52,53]. Irving Langmuir coined the name "plasma" in the year 1928 and described this 4th state of matter, He discovered plasma oscillations in the ionized gas, which is an entirely as well as partially ionized condition of gas [54]. As we raise the energy input, solids change into liquids, which subsequently turn into gases. Increasing the energy supply above a particular extent in the gaseous phase induces the ionization of molecules, which results in the plasma phase.

Plasma consists of activated molecules, free radicals, positive ions, negative ions, and neutral atoms. Cold plasma utilizes atmospheric temperature to generate plasma [55]. Many gases (H_2, O_2, He, N_2, Ar, Ne, CF_4, CH_4, NH_3) can be converted into plasma by subjecting them to electric fields such as alternating current (higher frequency), direct current, thermal, microwave, and radio frequency, magnetic field. It produces plasma particles such as ions, free radicals, and electrons that collide with greater kinetic energies [54]. There is no net charge in the plasma system. Plasma changes are influenced by factors such as supply gas proportion, surrounding phase, power, humidity as well as voltage levels [46,56].

In the context of microbial inactivation, when contamination of the food surface is subjected to plasma-created reactive species, electrostatic forces accumulate at the point where the energy is at its highest. The flow of energy results in far more radical bombardment activity, which results in cell lysis. The effects of heavy bombardment produce surface injuries, leaving the pathogenic bacteria cell incapable of swiftly repairing itself, culminating in cell death. This is referred to as "plasma etching". Plasma etching denatures DNA as well as chemical bonds, providing the cell with an antimicrobial effect [57].

3. Classification of plasma

Plasma can be categorized into two kinds based on the method of creation: Non-equilibrium or low-temperature plasma and equilibrium or thermal plasma. At temperatures around 20,000 K, thermal plasma is made up of electrons, ions, and gas molecules, maintaining thermodynamic equilibrium. Once more, quasi-equilibrium plasma (100–150 °C)

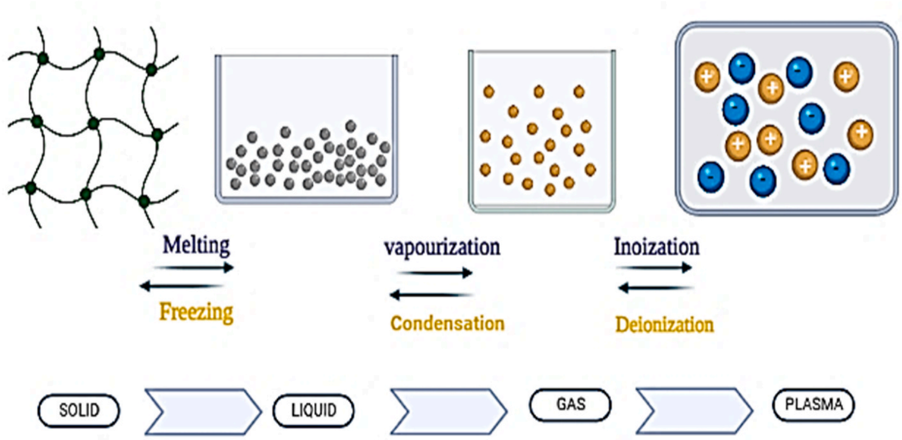

Fig. 1. States of matter solid, liquid, gas and plasma and Freezing, condensation and ionization method.

and non-equilibrium plasma (30–50 °C) are used to categorize low-temperature plasma. Species, including gas molecules and electrons are in local thermodynamic equilibrium within the quasi-equilibrium plasma. Gas molecules and electrons in a non-equilibrium plasma experience different temperature. Since there is no local thermodynamic equilibrium, which causes a decreased overall system temperature, non-equilibrium plasma is often known as atmospheric cold plasma (ACP), cold plasma (CP), nonthermal plasma (NTP), and cold atmospheric plasma (CAP).

Rather than heating the entire gas flow, the majority of the supplied energy is centered on electrons in nonthermal plasma generation. As a consequence of this, the temperature of gases remains essentially constant. Because of that cold plasma is also referred to as "cold plasma" or "nonthermal approach" [58].

The three main categories of the cold atmospheric plasma system are electrode contact, direct exposure, and remote exposure [59]. The remote exposure approach involves placing food in a faraway location before being exposed to a plasma producing source, which creates subsequent chemical compounds from the atmosphere and acts on the desirable product by sterilizing it. Those food components employed with the direct exposure approach are put right up against the active plasma, a source of plasma formation that generates both transient and persistent chemical species. The food substance is put on the electrode field that produces plasma, which results in ion bombardment and chemical species emission in the electrode contact technique. Additionally, surface modification using cold atmospheric pressure plasma is one of the efficient and cost-effective technique for various materials and of growing interests in food sector, as it is quite difficult to form granular and powdered products fulfilling both needs, adequate bulk properties and particular treatment to alter the surface characteristics [60]. The surface-effects, such as etching and plasma sputtering, induced by applying cold atmospheric pressure plasma to food products improves techno-functional and surface properties selectively while the material bulk properties remain unaltered [61]. Due to its higher potential of being energy saving and environment friendly, its capability and flexibility results in the development of various atmospheric plasma sources for numerous applications in food and non-industries [62].

3.1. Methods of generation of cold plasma

The energy distribution among the component particles in the cold plasma treatment is distinctively non-uniform (a non-equilibrium), where the electrons are more susceptible to transferring heat through a collision with heavier particles, and so determines the particular matrix's electron component. Furthermore, the medium's temperature (35 °C) does not change, which is a distinctive aspect appropriate for thermal-sensitive products. Several nonthermal plasma discharge techniques are used depending on the mechanism and desired target response.

3.1.1. Dielectric barrier discharge

This approach employs a dielectric substance wrapped around two flat metal electrodes which block electric currents and keeps sparks from forming. In a closed target chamber, any inert gas combination or neutral gas travels involving two electrodes and is ionized to produce plasma products. A high-voltage circuit is connected to one electrode, while the ground is connected to the other. It is a non-equilibrium alternating or direct current discharge that typically works across a wide variety of gas pressures (often around 10^4 to 10^6 Pa), about 0.05–500 kHz [63], and its operational energy requirements range from 10 to 100 W [64]. Various parameters impact dielectric barrier discharge's efficiency, including the operating voltage, the gas used, and the spacing between the electrodes. For large surfaces, dielectric barrier discharge is the best plasma source [65].

3.1.2. Corona discharge plasma

A changing electric field strength at atmospheric pressure creates plasma in this process. Corona discharge can be seen on sharp edges and along thin wires. When gases surpass their breakdown strength in a very non-uniform electric field, they generate weakly ionized plasma with some luminance. The corona system may be created in a simple device and does not need a complicated apparatus, saving money on setup and maintenance costs. Its primary drawback is that it only affects a small region and does so unevenly [66]. However, corona discharges are still regarded as the best choice for food sterilization applications [57].

3.1.3. Plasma jet discharge

There are two parallel electrodes in plasma jet systems through which the carrier gas flows at various speeds. Radio frequencies are commonly used to produce plasma jets or flames at atmospheric pressures. The excited species exit by a tiny valve or a hole approaching the electrode's terminal with the assistance of a carrier gas. Noble gases like helium or argon at an increased flow rate (>10 s/m) are frequently employed in the process. Plasma jets have the benefit of being directly applicable and may be employed between small areas. Although it is suitable for some biological applications, food processing cannot utilize this due to the high expense associated with the gas flow [67].

3.1.4. Microwave plasma discharge

Instead of employing electrodes with varying potentials, A high-frequency electromagnetic field drives microwave plasma discharges generated by a magnetron (usually takes place at 2.45 GHz) (Tolouie et al., 2018). Microwave radiation oscillates electrons, which form ions by interacting with gaseous atoms and molecules, resulting in an elevated ionization level in microwave plasma. The electrode-less setup of Microwave-driven discharges is their main benefit since it is user-friendly [65]. The drawback, though, is the space constraint. Large regions must be directly decontaminated using a variety of discharges. This approach is commonly used in high-temperature processing [68]. The plasma discharge techniques are shown in Fig. (2).

4. The impact of cold plasma on different foods

The use of high heat treatment over a longer period of time leads to undesirable changes such as change in texture, color, nutritional loss. Thus, non-thermal techniques such as cold plasma can be used to overcome these changes. In blueberries, cold plasma treatment can decrease firmness [69,26], which can be attributed to the mechanical damage due to high air-flow rates of plasma jet and the temperature rise during the treatment. In another study, the firmness retention of strawberries was found to be improved in high-oxygen environment than a nitrogen-rich environment, thus depicting that plasma gas is an essential factor affecting the firmness of treated foods. Similarly, increase in texture retention under higher oxygen atmosphere and ozone treatments have also been studied [70,71]. The enhanced firmness retention can be attributed due to the decrease in ripening rate as a stress response to high oxygen atmosphere [7]. Cold plasma treatment of legumes and grains can reduce chewiness and hardness [72]. There was decrease in cooking or soaking time for plasma-treated legumes and grains based food products, which can be considered desirable for the food industries [73]. In terms of nutrients, the mechanisms of protein denaturation by cold plasma treatment can be due to the interaction of plasma reactive species with amino acids [74], and secondary structure due to loss of α-helix and β-sheet [75]. The impact of cold plasma treatment in muscle protein in fresh mackerel resulted in reduction in immobilized water located in the protein-dense myofibrillar network [76]. In wheat flour, changes in protein structure were due to the formation of disulphide bonds and oxidation of sulfhydryl groups, affecting their functional and structural properties. In a study, cold plasma synergistic tartaric acid (CPA) treatment used to induce the interaction between pea protein isolate (PPI) and tartaric acid molecules to prepare

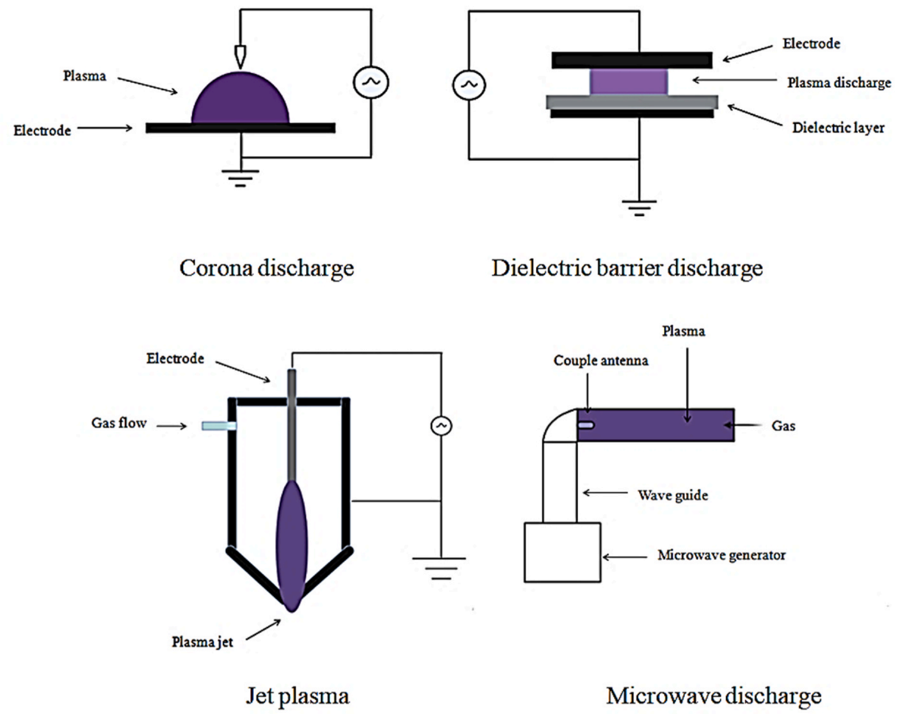

Fig. 2. Plasma discharge techniques such as corona discharge, dielectric barrier discharge, Jet plasma, and microwave discharge.

fibrous PPI and to enhance foamability, protein stability and foam stability. It was observed that PPI prepared by CPA treatment for 10 min shown enhanced foamability and foam stability. CPA treatment also resulted in destruction of protein subunit or disulfide bond to alter the primary structure and composition of PPI [77]. In cashew apple juice, cold plasma treatment caused degradation of all reducing and non-reducing sucrose [78]. It was also observed that there was increase in sucrose content after prolonged exposure to cold plasma, attributing to the degradation of the oligosaccharides with higher degree of polymerization. The similar increase in sucrose and decrease in fructose and degradation of oligosaccharides with higher degree of polymerization was also observed in prebiotic orange juice. The studies suggest ozonolysis to be the main cause of degradation resulting in breaking of glycoside bonds, causing de-polymerization of macromolecule and the oxidation of functional groups to produce carboxyl and carbonyl compounds, hydroperoxides CO_2 and lactones, [79].

4.1. Grains and derivative products

The impact of cold plasma on black gram was investigated by Ref. [72]. They concluded that a decrease in cooking time and enhancement of cooking could be seen when treated with cold plasma. The black gram cooking period decreased from 30.25 to 20.45 min, and the hardness value decreased from 22.50 to 12.36 N, it was observed that short amylopectin leaching was greater than amylose, which is what caused the decrease in hardness. And the reduction in cooking time was facilitated by the depolymerization of starch and the compromised surface integrity of cereal grains. According to one research [13], After 4 h of immersion, plasma therapy increased the ability to absorb water due to the production of simple carbohydrates. Furthermore, surface depolymerization and plasma etching can boost the activity of amylase and Brown rice's capacity to absorb water (up to 1.21 folds). In terms of intermediate grain products such as flour also shows significant change when treated with plasma; for example, in basmati rice flour, the water retaining capacity improves as exposure duration and plasma energy increase [11]. Parboiled rice on treatment using cold plasma led to a lower amylase content, flour wetting characteristics, and phenolic compound release improved by 30.34 to 27.89% [14]. Different legumes and grains were checked for Aspergillus species and Penicillium species before and after plasma therapy. A significant log drop was seen after 15 min of plasma treatment [33]. The impact of cold plasma treatment on grains and derivative products is presented in Table 1. Cold plasma treatment can be significantly used to reduce mold and mycotoxin count in rice grain. In a study, rice grains were artificially with molds were exposed to cold plasma treatment. The microbial activities of Rhizopus oryzae, Aspergillus niger, Fusarium graminearum and Penicillium verrucosum were significantly inhibited by cold plasma treatment. The electrical conductivity and malondialdehyde content in rice grain increased by 30.14% and 103.27%, respectively. The seed germination also was observed to be decreased with treatment time reached 8 min [80]. The exposure of cold plasma to pearl millet flour can modify its functional, proximate, antinutritional, thermal, rheological properties. It has been observed that the treatment can reduce the antinutritional factors such as phytic acid and tannin present in pearl millet flour. Cold plasma treated samples also showed shear thinning behavior and high storage modulus values (G'), indicating an elastic response of the flour. In addition to this, there was an increase in functional properties such as water and oil absorption capacity, emulsifying capacity and foaming capacity [81].

4.2. Dairy processing sector

The dairy business maintains milk's safety and storage life using thermal techniques like high-temperature-short-time (HTST). But, while the heating process ensures milk safety, excessive heat treatment for prolonged period can adversely affect milk quality by causing non-enzymatic browning, protein denaturation, vitamin deficiencies, as well as flavor changes. Milk can be pasteurized quickly and non-thermally using cold plasma, preserving the milk's quality while ensuring food safety [82].

Research findings by Refs. [49,16] indicate that cold plasma has previously been tried on a variety of milk products, including whole milk, skim milk, sliced cheese, and UHT milk, with research suggesting that it might be a workable substitute for conventional milk processing

Table 1
Cold plasma treatment's impact on grains and derivative products.

Food material	Source of plasma	Treatment	Findings	References
Parboiled rice	Radiofrequency	T = 5 min, P = 50 W.	Decreased cooking time and hardness, Increased water absorption capacity.	[10]
Brown rice	Radiofrequency	T = 10 min, P = 50 W.	The cooking duration is shortened to 21.1 min from 29.1 min, while water intake is increased.	[11]
Basmati rice	Radiofrequency	T = 5 min, P = 40 W.	Reduced contact angle, cooking duration and increased water absorption	[12]
Brown rice	DBD	T = 20 min, P = 250 W.	Substantial rise in -amylase activity, accompanied by a large decrease in hardness	[13]
Parboiled rice flour	Radiofrequency	T = 15 min, P = 50 W.	decline in broad endothermic enthalpy, crystallinity, as well as hardness and sickness	[14]
Basmati rice flour	Radiofrequency	T = 10 min, P = 40 W.	Increased hydration characteristics of flour and gel	[11]
Wheat germ	DBD atmospheric plasma	T = 25 min, V = 24Kv.	Wheat germ lipoxygenase and lipase activity were decreased to 25.03% and 49.98%, respectively. Wheat germ has a longer shelf life and is more stable.	Tolouie et al., 2018

T = exposure time, P = Power, V = Voltage, DBD = Dielectric barrier discharge.

methods. Being nonthermal in nature, cold plasma is less likely to have an impact on the color, pH, nutritional value, and flavor of milk and milk products, and it inactivates microorganisms and phosphatase enzymes in a few seconds. Some studies reported that Cold plasma treatment causes milk to become more acidic, which may result from several interactions between water and volatile substances produced by plasma like O, NOx, and O3 at the gas-water contact. The impact of cold plasma treatment on milk and milk products is shown in Table 2. It was observed that plasma bubbling can efficiently reduce microbial load (0.64 and 1.82 log reduction of bacteria and coliforms count), yet it resulted in increase in lipid oxidations and decrease in whiteness index. However, the reduction in oxalates, phytates and lipoxygenase activity was also observed with treatment, depicting that this technique can be used as efficient alternative technique in sesame milk processing [83]. In another study, cold plasma technique was efficiently used to prevent mold growth in Kashar cheese. It has been observed that cold plasma application with different gas compositions was effective to inactivate A. favus and P. crysogenum. It was reported that a reduction of 3–4 logs was achieved for both mold types and resulted in increase in textural properties and shelf life of Kashar cheese depending on the gas composition and application time used [84].

4.3. Meat and egg processing sector

Meat has significant moisture and plenty of nutrients, making it a

Table 2
Cold plasma treatment's impact on Milk and milk products.

Treatment	Findings	Reference
Nonfat powdered milk		
Nitrogen gas was used to make atmospheric cold plasma at 4.4 kV lasting 0–120 s. Samples were subjected to controlled humidity at 35% for 0–120 s.	Treatment duration and flow rate effectively rendered *Cronobacter sakazakii* inactive.	[15]
Cheese		
Helium gas powers an atmospheric pressure plasma operating at 13.56 GHz for 60, 90, and 120 s at 75, 100, 125, and 150 W.	Higher power plasma application (120s at 150 W) was shown to completely destroy any live cells after one week of storage, reducing L. monocytogenes by 8 log cycles.	[16]
Atmospheric gas and a 15 kHz dielectric barrier discharge plasma were used to create cold plasma for 0, 2.5, 5, and 10 min.	*Escherichia coli, Listeria monocytogenes, & Salmonella typhimurium* all underwent complete inactivation after being exposed for 4, 10, and 75 s, respectively. With longer exposure times, a considerable reduction on cheddar cheese was seen. Additionally, after being exposed to DBD for 10 min, *Listeria monocytogenes, Escherichia coli and Salmonella typhimurium* colonies all underwent complete inactivation and experienced decreases of 2.1, and 3.2 log CFU/g, correspondingly.	Yong et al., 2015
DBD with 15 kHz, followed by 1, 3, and 5 min treated with plasma	Following treatments of 10, 60, and 90 min, *Listeria monocytogenes, Salmonella typhimurium, and Escherichia coli*, were fully inactivated in nutrient agar. Colonies of 2.26, 3.11, and 2.88 log CFU/g decreased after 15 min of waiting. Dielectric barrier discharge therapy. The number of colonies was also declining throughout the post-storage phase.	Yong et al., 2015
3.5 kV DBD plasma with a 50% duty cycle and a square wave low frequency of 50 kHz	Helium and a He/O2 combination resulted in significant reductions in *Escherichia coli* with log values ranging from 0.09 to 1.47 log and 0.05 to 1.98. He and the He–O2 combination reduced the count of *Staphylococcus aureus* by 0.05–0.45 log and 0.08 to 0.91 log, respectively.	[17]
Milk		
A DBD Cold Plasma with a frequency of 15 kHz was used to generate plasma. Voltage variation categories (0, 40, 50, 60, 70, and 80 V for 120 s) and difference in time groups both received cold plasma treatment of 70 V for 0, 15, 30, 60, 90, and 120 s.	Plasma treatments at 70 and 80 V for 120 s and 70 V for 90 and 120 s were equal to Pasteurization and Ultra High Temperature based on number of colonies.	Wu et al., 2020
Aron gas plasma at 2, 3, and 4 kHz frequencies lasting 2 min, and 4 kHz for 30–120 s	Compared to pasteurization, plasma treatment considerably reduced bacterial population and enhanced microbiological quality during storage.	[18]
CP using 9 kV-generated argon gas. Samples were exposed for 2 min at frequencies of 2.5 and 4 kHz.	*E. coli* were completely destroyed by Cold Plasma in raw milk and pasteurized milk after 2 min of 4 kHz exposure.	[19]
A corona discharge device with a 9 kV power supply was used to produce Cold Plasma. Old	The decrease in *E. coli* cell viability (log CFU/mL) in skimmed milk, semi-skimmed,	[20]

(continued on next page)

Table 2 (*continued*)

Treatment	Findings	Reference
Cold Plasma at 9 kV was applied for 0, 3, 6, 9, 12, 15, and 20 min at a low temperature of 35 °C.	and whole milk was 57%, 56, 54, and respectively.	
Encapsulated DBD plasma operated at 15 kHz in ambient air for 5 and 10 min.	DBD treatment decreased the amounts of *E. coli, Listeria monocytogenes,* and *Salmonella typhimurium,* in the samples by 2.46, 2.40, 2.43 and log CFU/mL after exposure for 10 min.	[21]
linear micro discharge jet, at 13.56 MHz frequency, and helium gas, treatments lasted anywhere between one and 12 min.	*Prototheca zopfii* was reported as more responsive to Cold Plasma than antifungal drugs because of the production of numerous free radicals.	[22]

CP= Cold plasma, V = Voltage, DBD = Dielectric barrier discharge.

perfect environment for pathogenic and spoilage microbes to proliferate [85]; Biesalski., 2005). As a result, it is critical for consumer safety to remove harmful bacteria from meat and meat-based goods. Furthermore, extending shelf life by getting rid of dangerous microbes in meat as well as meat-based products is essential for food security and the long-term viability of the meat business [86]. Decontamination of meat and meat-based products is a unique issue in the meat business because meat's nature not only allows it to be very perishable but also offers an extremely high degree of sensitivity in its degradation of physical characteristics whenever exposed to standard sterilizing methods. Meat can be a breeding ground for pathogens like *L. monocytogenes, E. coli* O157:H7, *C. jejuni,* and *Salmonella species* that can infect humans with severe food-borne illnesses [87].

The microbicidal actions of cold plasma on numerous microorganisms in meat and meat-based goods have also been investigated and mentioned in Table 3. Prior studies found that plasma treatment lowered L. monocytogenes levels in inoculated meat as well as meat-related goods by 0.59–6.52 Log CFU/g. [88–90]; Janasena et al.,2015; [91, 92]. The impact of cold plasma therapy on eggs, meat, and meat products is shown in Table 3. In fresh fish, the application of air plasma treatment for about 7 min can reduce bacterial load and increase sensory attributes, for the industrial use of cold plasma technology in fresh seafood, a wide range of studies are still required to investigate different species, different gas composition, processing time, and voltage [93].

4.4. Fruits and vegetables

Fruits and vegetables are widely consumed across the world. The majority of fruits are consumed raw, which increases the quality and safety concerns. Conventionally the fruits &vegetables are cleaned or decontaminated with clean water and surface disinfectants. Cold plasma treatment can effectively replace chlorine as well as water for fruit and vegetable disinfection. Various fruits and veggies, including berries, melons, pears, kiwis, and cherries, were subjected to cold plasma treatment. The findings demonstrate that cold plasma treatment of fruit and veggie surfaces alters the pH as well as the acidity in the final product. Also, they discovered that during storage, the treated produce has some variations in structure and hue [57]. Additionally, several investigations reported no appreciable changes in the antioxidant activity or composition of the fruits treated with plasma [94].

Cold plasma treatment (100 kV-5 minutes) decreased the number of mesophiles, yeast, as well as molds in sliced carrots by almost 2 logs; however, the method preserved the carotenoid content and texture [95]. *Salmonella typhimurium* was reduced by plasma treatment by 1.76, 2.72 & 0.94 log CFU/g on lettuce, strawberries as well as potatoes, correspondingly [44]. Some of the research data on cold plasma effect on various fruits and veggies are enlisted in Table 4.

4.5. Effect on food components

CP can dose-specifically increase or decrease the total amount of bioactive chemicals [96]. Compared to other conventional procedures, Cold plasma preserves the color's intensity in fruits and veggies, including strawberries, carrots, and pomegranates [95,97]. Application of cold plasma retained more ascorbic acid (366 mg/L for 10 min and 362.49 mg/L for 15 min) than other nonthermal methods, such as ultrasound (363.16 mg/L in 10 min and 358 mg/L for 15 min). Nevertheless, ascorbic acid levels decreased following both treatments as compared to unprocessed tomato beverages (385.13 mg/L) (Mehta et al.,2019). Using the cold plasma technique in cherry marasca juice increased the retention of phenolic acid and anthocyanin compared to conventional pasteurization (Garofuli et al.,2014). Cold plasma increased the phenolic concentration in the pomegranate juice by 33.03% [98]. Whereas the Cold plasma treatment decreased antioxidant components (Vitamin C) in pear [99], orange juice [100], Fuji apple peel and pulp (Gozzi et al.,2013), and cucumber [32]. These results emphasize the importance of Cold plasma process improvement for many culinary applications as the technology moves closer to commercialization.

4.6. Effect on packing material

Food packaging materials defend food components from the outside environment during handling, transit, and dissemination. Materials for

Table 3
The impact of cold plasma therapy on eggs, meat, and meat products.

Food material	Source of plasma	Treatment	Microorganism	Findings	Reference
Lamb meat	Dielectric barrier discharge	f = 50 Hz, V = 80 kV, ET = 10min	*Brochothrix thermosphacta*	2 log cycles reduction	Patange et al., 2017
Shreds of dried squid	Corona Discharge	f = 58 kHz, d = 25 mm, V = 20 kV, ET = 3 min	Aquatic bacteria, Aerobic bacteria, *S. aureus*	Log units of 1.6, 2.0, 0.9 inhibited	Choi et al., 2017
Eggshell	Dielectric barrier discharge	f = 10–12 kHz, V = 25–30 kV, RH = 80%, ET = 10min, 25min.	*S. enterica*	Microbial population fall to 102 cells per egg, below the threshold for detection	Georgescu et al., 2017
Packaged beef loin vacuum sealed	Dielectric barrier discharge	P = 29.9 W, f = 9 kHz, d = 2 cm.	*S. aureus, L. monocytogenes, E. coli*	2 log decrease	Bauer et al., 2017
Chicken eggs	Atmospheric cold plasma with high voltage	f = 60 Hz, V = 85 kV, ET = 15min	*S. enteritidis*	decrease of ≤5.53 log CFU/egg	Wan et al., 2017
Egg shells	Plasma jet at atmospheric pressure	f = 1 MHz, V = 2–3 kV, ET = 5 min	*S. Enteritidis*	The decrease factor varies between 0.22 and 2.27 log CFU/egg.	Moritz et al., 2017
Pork butt	Dielectric barrier discharge	f = 15 kHz, P = 2 W, ET = 10 min	*L. monocytogenes, E. coli, S. Typhimurium*	≥2.04 log CFU/g decrease	[23]
Beef	Dielectric barrier discharge	f = 20 MHz, V = 6 kV, ET = 5 min	*E. coli*	Decrease of 1.82 log CFU/cm^2	[24]

V = Voltage, P = Power, ET = exposure time, RH= Relative humidity, f = frequency, d = distance.

Table 4
Cold plasma treatment's impact on Fruits and vegetables.

Food material	Treatment	Result	Reference
Apple	For 480 s, the plasma was subjected to argon and 0.1% oxygen.	*Citrobacter freundii* population decreases to 5 log cycle	[25]
Blueberry	At a working range of 7.5 cm, a cold plasma jet interacts with air.	Total aerobic plate count decreased by 0.8–1.6 log.	[26]
Cabbage	Nitrogen is added to cold plasma. Cold plasma using a He–O gaseous combination	*S. typhimurium* log decrease of 1.5. The number of *Listeria monocytogenes* was lowered by 0.3–2.1 log.	[27] [27]
Dried figs	Cold plasma using a He–O gaseous combination	*Escherichia coli* dropped from 0.5 to 1.3 log CFU/g.	[27]
Cherry tomato	30 kV Root mean square cold plasma voltage for 30, 60, 180, and 300 s	a total fungi growth prevention with fruit quality maintained	[28]
Tomato	Dielectric barrier discharge	*L. innocua* population decreased to 3.50 $\log_{10}$ CFU/sample	[29]
Carrot, tomato, Lettuce.	Atmospheric pressure cold plasma	*E. coli* decrease of 1.6 log in tomato, lettuce, and carrot	[30]
Cherry tomato, Strawberry	70 kV Root Mean Square voltage for atmospheric cold plasma	*Escherichia coli, Salmonella, Listeria* populations were decreased.	[31]
Spinach leaves	Dielectric barrier discharge	Reduced L. *innocua* population by 1.30 $\log_{10}$ CFU/sample	Zuzana et al., 2020
Pear, Cucumber, Carrot.	Air with plasma micro jet	decrease of *Salmonella* by 4–5 logs	[32]
Legume seeds	Cold plasma under low pressure	*Penicillium* spp. and *Aspergillus* spp. were decreased by 3 log.	[33]
Button mushroom	Water treated with plasma	Bacterial microbial number decreased by 1.5 log and fungal counts decreased by 0.5 log.	[34]
Romaine lettuce	Dielectric barrier discharge	*E. coli* population decreased to 1.10 log CFU/g	[35]

packaging are decontaminated with cold plasma outside, where the shade effect is minimal because the plasma circulates all around the exterior [101]. Cold plasma also shows certain food packaging material modifications along with microbial decontamination. Cold plasma treatments are utilized to alter the exterior of the polymer and increase its surface energy, enhancing its resilience, wetting, printability, adherence, and sealing. Surface-activated compounds either respond to it or create cross-links with chains of polymers on the surface [102]. Polymer foils and laminates' binding abilities can be conserved by cold plasma [103]. The Immobilization of biologically active functional substances, including nicin, glucose oxidase, lysozyme, sodium benzoate, vanillin, as well as antimicrobial peptides incorporation in the packaging material by plasma technique, has been intensively investigated on the expanding field of antimicrobial together with active packaging [104–109].

Endospores of *Bacillus atrophaeus* with DNA damage and vegetative cells as a result of a synergistic interaction between Ultraviolet light and cascaded direct plasma Additionally, dielectric barrier discharge has been observed [110]. When container materials are limited, but functionality is not compromised, such a treatment approach demonstrates effective decontamination in a brief amount of time. The impact of cold plasma's implications for various packing materials Table 5.

5. Plasma processing limitations and toxicology

Plasma processing has some downsides, including a rise in acid levels, a decrease in pigmentation, a reduction of fruit firmness, and a spike in lipid oxidation [54]. The use of hydrogen gas plasma for hydrogenation is preferable due to formation of more atomic, ionic and excited hydrogen atoms which are energetically active. However, the use of hydrogen as a feed gas could be the source of atomic hydrogen required to convert unsaturated to saturated bonds. *Trans*-fatty acids were not produced as a result of the hydrogenation utilizing cold plasma. Nevertheless, other investigations have demonstrated that plasma treatments can cause secondary lipid oxidation and negligible *trans*-fatty acid levels. To prevent practical implications, it is therefore vital to optimise the plasma characteristics, processing condition, feed gas type and composition [111]. However, it has been reported that plasma treatment can result in the production of hydrogen peroxide, hydroxyl radicals, and superoxide anions contributes to the removal of microorganisms. These ROS may induce lipid oxidation by eliminating hydrogen from the food materials [112]. Certain detrimental impacts were observed in pig, buffalo meat, poultry, sushi, and marine foods [113], where the 2-thiobarbituric acid reactive compounds as well as peroxide value increased. Cereals, including brown rice, white rice, wheat flour, and nuts, and peanuts have all experienced the same oxidation (Lee et al., 2018; [12]. After being exposed for 5 min to atmospheric non-equilibrium plasma, the spinach leaves' discoloration and wilting effects were noticed. According to Ref. [21], after 10 min of treatment, milk's pH decreased when plasma was applied. Another drawback is that using direct plasma results in a loss of fruit firmness [28]. It has observed that dielectric barrier discharge plasma in air can be used to degrade carbendazim (MBC) in aqueous solution. In a study, the maximum achieved degradation rate of MBC (0.5 μg/mL) was 89.04% under the optimal frequency, voltage, storage time and treatment time and storage period. The efficient degradation of MBC was

Table 5
Cold plasma's impact on various packing materials.

Material	Plasma type	Treatment	Result	Reference
High Density Polyethylene	RF discharge Ar: O_2	50–150 W	Reduce the effects of aging by enhancing crystallinity	[36]
Low Density Polyethylene	RF discharge (Ar plasma)	100 W	Contact angle decreases nonlinearly	[37]
Low Density Polyethylene	Corona discharge	600 W	Temporary hydrophobic recovery	[38]
Polyethylene Terephthalate	Glow discharge	10 W	Contact angle decline, roughness, crystallinity upsurge.	[39]
Polyethylene Terephthalate	Microwave plasma	2860 MHz	lowering of the contact angle	[40]
Polyethylene Terephthalate	Jet plasma	285 V	decline in contact angle as well as wettability	[41]
Polypropylene	Dielectric barrier discharge plasma	3–20 kV, 25–50 kHz	Modest doses cause a small amount of contact angle recovery; both moderate and elevated dosages cause contact angle reduction.	[42]

attributed to the active species, such as ·OH, O_3, O^{-2}, and H_2O_2 radicals [114].

Cold plasma technique possesses various advantages over the thermal techniques such as design versatility, non-thermal, economical and environmentally friendly nature, enhanced antimicrobial efficacy and prevention of cross-contamination and over current hydrogenation method, CP can be performed at room temperature, under atmospheric pressure without any catalyst [7]. Food processing at lower temperatures allows gentle treatment of crucial vitamins and the preservation of nutrients and flavors [115]. However, cold plasma in some cases possess certain drawbacks regarding food safety, energy, and operational cost. CP treatments are advanced oxidation processes which may cause detrimental effects to bioactive lipids instead of preserving its activity. Besides, the ability of nanoemulsions or cold plasma to insert cells membrane have unknown effects on biological matrix [116].

6. Conclusion

The extensive research, however, is concentrated on microbial inactivation investigations, with little consideration paid to food quality. It has been shown that both during treatment and storage, cold plasma application affects the qualitative features of food items. It gives researchers a chance to learn more about how cold plasma affects food items' physical, chemical, and sensory qualities. This review study looks at the impact of cold plasma application on grains, meat, milk, fruits & vegetables, in addition to how cold plasma affects the components of food and packaging material. Cold plasma is a potential nonthermal approach that, under ideal circumstances, can increase food safety with no influence on food quality. The procedure for regulatory clearance is still unknown, though. There is a dearth of research on the biosecurity, allergies, toxicity, and lethality of Cold plasma therapy on foods. In order to understand plasma's chemical reaction and process, as well as the effects of its byproducts on food, additional study on the genotoxic/cytotoxic impact of cold plasma treatment is needed.

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.

Data availability

No data was used for the research described in the article.

References

[1] C.M. Galanakis, Functionality of food components and emerging technologies, Foods 10 (1) (2021) 128.
[2] S.K. Sonawane, S. Patil, Nonthermal Plasma: an advanced technology for food industry, Food Sci. Technol. Int. 26 (8) (2020) 727–740.
[3] Y.M. Zhao, M. de Alba, D.W. Sun, B. Tiwari, Principles and recent applications of novel nonthermal processing technologies for the fish industry—a review, Crit. Rev. Food Sci. Nutr. 59 (5) (2019) 728–742.
[4] G.B. Awuah, H.S. Ramaswamy, A. Economides, Thermal processing and quality: principles and overview, Chem. Eng. Process: Process Intensif. 46 (6) (2007) 584–602.
[5] M.S. Rahman, Food preservation: overview, Handbook Food Preservat. (2007) 21–36.
[6] S.K. Pankaj, Thermal processing of food, in: Advances in Food Biotechnology, John Wiley & Sons Ltd., Hoboken, NJ, USA, 2015, pp. 681–692.
[7] S.K. Pankaj, Z. Wan, K.M. Keener, Effects of cold plasma on food quality: a review, Foods 7 (1) (2018) 4.
[8] F.J. Barba, C.M. Galanakis, M.J. Esteve, A. Frigola, E. Vorobiev, Potential use of pulsed electric technologies and ultrasounds to improve the recovery of high-added value compounds from blackberries, J. Food Eng. 167 (2015) 38–44.
[9] E. Roselló-Soto, C.M. Galanakis, M. Brnčić, V. Orlien, F.J. Trujillo, R. Mawson, F. J. Barba, Clean recovery of antioxidant compounds from plant foods, by-products and algae assisted by ultrasounds processing. Modeling approaches to optimize processing conditions, Trends Food Sci. Technol. 42 (2) (2015) 134–149.
[10] C. Sarangapani, Y. Devi, R. Thirundas, U.S. Annapure, R.R. Deshmukh, Effect of low-pressure Plasma on physico-chemical properties of parboiled rice, LWT–Food Sci. Technol. 63 (1) (2015) 452–460.
[11] R. Thirumdas, R.R. Deshmukh, U.S. Annapure, Effect of low temperature plasma on the functional properties of basmati rice flour, J. Food Sci. Technol. 53 (6) (2016) 2742–2751.
[12] R. Thirumdas, R.R. Deshmukh, U.S. Annapure, Effect of low temperature plasma processing on physicochemical properties and cooking quality of basmati rice, Innovat. Food Sci. Emerg. Technol. 31 (2015) 83–90.
[13] K.H. Lee, H.J. Kim, K.S. Woo, C. Jo, J.K. Kim, S.H. Kim, W.H. Kim, Evaluation of cold plasma treatments for improved microbial and physicochemical qualities of brown rice, Lwt 73 (2016) 442–447.
[14] C. Sarangapani, R. Thirumdas, Y. Devi, A. Trimukhe, R.R. Deshmukh, U. S. Annapure, Effect of low-pressure Plasma on physico–chemical and functional properties of parboiled rice flour, LWT–Food Sci. Technol. 69 (2016) 482–489.
[15] D. Chen, P. Peng, N. Zhou, Y. Cheng, M. Min, Y. Ma, R. Ruan, Evaluation of Cronobacter sakazakii inactivation and physicochemical property changes of non-fat dry milk powder by cold atmospheric plasma, Food Chem. 290 (2019) 270–276.
[16] H.P. Song, B. Kim, J.H. Choe, S. Jung, S.Y. Moon, W. Choe, C. Jo, Evaluation of atmospheric pressure plasma to improve the safety of sliced cheese and ham inoculated by 3-strain cocktail Listeria monocytogenes, Food Microbiol. 26 (4) (2009) 432–436.
[17] H.J. Lee, S. Jung, H.S. Jung, S.H. Park, W.H. Choe, J.S. Ham, C. Jo, Evaluation of a dielectric barrier discharge plasma system for inactivating pathogens on cheese slices, J. Anim. Sci. Technol. 54 (3) (2012) 191–198.
[18] S.B. Ponraj, J.A. Sharp, J.R. Kanwar, A.J. Sinclair, L. Kviz, K.R. Nicholas, X.J. Dai, Argon gas plasma to decontaminate and extend shelf life of milk, Plasma Process. Polym. 14 (11) (2017), 1600242.
[19] S.B. Ponraj, J. Sharp, J.R. Kanwar, A.J. Sinclair, L. Kviz, K.R. Nicholas, X.J. Dai, Sterilization of cow's milk using liquid plasma, in: Proceedings of the 22nd International Symposium on Plasma Chemistry, Antwerp, Belgium, 2015, pp. 5–10.
[20] C. Gurol, F.Y. Ekinci, N. Aslan, M. Korachi, Low temperature plasma for decontamination of E. coli in milk, Int. J. Food Microbiol. 157 (1) (2012) 1–5.
[21] H.J. Kim, H.I. Yong, S. Park, K. Kim, W. Choe, C. Jo, Microbial safety and quality attributes of milk following treatment with atmospheric pressure encapsulated dielectric barrier discharge plasma, Food Control 47 (2015) 451–456.
[22] E. Tyczkowska-Sieron, J. Markiewicz, B. Grzesiak, H. Krukowski, A. Glowacka, J. Tyczkowski, Cold atmospheric plasma inactivation of Prototheca zopfii isolated from bovine milk, J. Dairy Sci. 101 (1) (2018) 118–122.
[23] D.D. Jayasena, H.J. Kim, H.I. Yong, S. Park, K. Kim, W. Choe, C. Jo, Flexible thin-layer dielectric barrier discharge plasma treatment of pork butt and beef loin: effects on pathogen inactivation and meat-quality attributes, Food Microbiol. 46 (2015) 51–57.
[24] A.C. Stratakos, I.R. Grant, Evaluation of the efficacy of multiple physical, biological and natural antimicrobial interventions for control of pathogenic Escherichia coli on beef, Food Microbiol. 76 (2018) 209–218.
[25] B. Surowsky, A. Froehling, N. Gottschalk, O. Schlüter, D. Knorr, Impact of cold Plasma on Citrobacter freundii in apple juice: inactivation kinetics and mechanisms, Int. J. Food Microbiol. 174 (2014) 63–71.
[26] A. Lacombe, B.A. Niemira, J.B. Gurtler, X. Fan, J. Sites, G. Boyd, H. Chen, Atmospheric cold plasma inactivation of aerobic microorganisms on blueberries and effects on quality attributes, Food Microbiol. 46 (2015) 479–484.
[27] H. Lee, J.E. Kim, M.S. Chung, S.C. Min, Cold plasma treatment for the microbiological safety of cabbage, lettuce, and dried figs, Food Microbiol. 51 (2015) 74–80.
[28] N.N. Misra, K.M. Keener, P. Bourke, J.P. Mosnier, P.J. Cullen, In-package atmospheric pressure cold plasma treatment of cherry tomatoes, J. Biosci. Bioeng. 118 (2) (2014) 177–182.
[29] D. Ziuzina, N.N. Misra, P.J. Cullen, K.M. Keener, J.P. Mosnier, I. Vilaró, P. Bourke, Demonstrating the potential of industrial scale in-package atmospheric cold plasma for decontamination of cherry tomatoes, Plasma Med. 6 (3–4) (2016).
[30] D. Bermúdez-Aguirre, E. Wemlinger, P. Pedrow, G. Barbosa-Cánovas, M. Garcia-Perez, Effect of atmospheric pressure cold plasma (APCP) on the inactivation of Escherichia coli in fresh produce, Food Control 34 (1) (2013) 149–157.
[31] D. Ziuzina, S. Patil, P.J. Cullen, K.M. Keener, P. Bourke, Atmospheric cold plasma inactivation of Escherichia coli, Salmonella enterica serovar Typhimurium and Listeria monocytogenes inoculated on fresh produce, Food Microbiol. 42 (2014) 109–116.
[32] R.X. Wang, W.F. Nian, H.Y. Wu, H.Q. Feng, K. Zhang, J. Zhang, J. Fang, Atmospheric-pressure cold plasma treatment of contaminated fresh fruit and vegetable slices: inactivation and physiochemical properties evaluation, The European Physical J. D 66 (10) (2012) 1–7.
[33] M. Selcuk, L. Oksuz, P. Basaran, Decontamination of grains and legumes infected with Aspergillus spp. and Penicillum spp. by cold plasma treatment, Bioresour. Technol. 99 (11) (2008) 5104–5109.
[34] Y. Xu, Y. Tian, R. Ma, Q. Liu, J. Zhang, Effect of Plasma activated water on the postharvest quality of button mushrooms, Agaricus bisporus, Food Chem. 197 (2016) 436–444.
[35] S.C. Min, S.H. Roh, B.A. Niemira, J.E. Sites, G. Boyd, A. Lacombe, Dielectric barrier discharge atmospheric cold plasma inhibits Escherichia coli O157: H7, Salmonella, Listeria monocytogenes, and Tulane virus in Romaine lettuce, Int. J. Food Microbiol. 237 (2016) 114–120.

[36] I. Banik, K.S. Kim, Y.I. Yun, D.H. Kim, C.M. Ryu, C.E. Park, Inhibition of aging in plasma-treated high-density polyethylene, J. Adhes. Sci. Technol. 16 (9) (2002) 1155–1169.
[37] M. Ataeefard, S. Moradian, M. Mirabedini, M. Ebrahimi, S. Asiaban, Investigating the effect of power/time in the wettability of Ar and O2 gas plasma-treated low-density polyethylene, Prog. Org. Coating 64 (4) (2009) 482–488.
[38] M. Pascual, R. Balart, L. Sanchez, O. Fenollar, O. Calvo, Study of the aging process of corona discharge plasma effects on low density polyethylene film surface, J. Mater. Sci. 43 (2008) 4901–4909.
[39] K.N. Pandiyaraj, V. Selvarajan, R.R. Deshmukh, M. Bousmina, The effect of glow discharge plasma on the surface properties of Poly (ethylene terephthalate)(PET) film, Surf. Coating. Technol. 202 (17) (2008) 4218–4226.
[40] A. Kamińska, H. Kaczmarek, J. Kowalonek, The influence of side groups and polarity of polymers on the kind and effectiveness of their surface modification by air plasma action, Eur. Polym. J. 38 (9) (2002) 1915–1919.
[41] K. Gotoh, A. Yasukawa, K. Taniguchi, Water contact angles on poly (ethylene terephthalate) film exposed to atmospheric pressure plasma, J. Adhes. Sci. Technol. 25 (1–3) (2011) 307–322.
[42] D.J. Upadhyay, N.Y. Cui, C.A. Anderson, N.M.D. Brown, Surface oxygenation of polypropylene using an air dielectric barrier discharge: the effect of different electrode–platen combinations, Appl. Surf. Sci. 229 (1–4) (2004) 352–364.
[43] Y. Ucar, Z. Ceylan, M. Durmus, O. Tomar, T. Cetinkaya, Application of cold plasma technology in the food industry and its combination with other emerging technologies, Trends Food Sci. Technol. 114 (2021) 355–371.
[44] A. Fernandez, E. Noriega, A. Thompson, Inactivation of Salmonella enterica serovar Typhimurium on fresh produce by cold atmospheric gas plasma technology, Food Microbiol. 33 (1) (2013) 24–29.
[45] E. Sainz-García, F. Alba-Elías, Advances in the application of cold plasma technology in foods, Foods 12 (7) (2023) 1388.
[46] N.N. Misra, S.K. Pankaj, A. Segat, K. Ishikawa, Trends in food science & technology cold plasma interactions with enzymes in foods and model systems, Trends Food Sci. Technol. 55 (2016) 39–47.
[47] D. Knorr, A. Froehling, H. Jaeger, K. Reineke, O. Schlueter, K. Schoessler, Emerging technologies in food processing, Annu. Rev. Food Sci. Technol. 2 (2011) 203–235.
[48] A. Dey, P. Rasane, A. Choudhury, J. Singh, D. Maisnam, P. Rasane, Cold plasma processing: a review, J. Chem. Pharmaceut. Sci. 9 (2016) 2980–2984.
[49] N.M. Coutinho, M.R. Silveira, R.S. Rocha, J. Moraes, M.V.S. Ferreira, T. C. Pimentel, A.G. Cruz, Cold plasma processing of milk and dairy products, Trends Food Sci. Technol. 74 (2018) 56–68.
[50] P. Bartos, P. Kriz, Z. Havelka, A. Bohata, P. Olsan, P. Spatenka, et al., Plasma technology in food industry: mini-review, Kvasny Prumysl 63 (3) (2017) 134–138.
[51] C. Hertwig, N. Meneses, A. Mathys, Cold atmospheric pressure plasma and low energy electron beam as alternative nonthermal decontamination technologies for dry food surfaces: a review, Trends Food Sci. Technol. 77 (2018) 131–142.
[52] R. Mandal, A. Singh, A.P. Singh, Recent developments in cold plasma decontamination technology in the food industry, Trends Food Sci. Technol. 80 (2018) 93–103.
[53] M. Stoica, P. Alexe, L. Mihalcea, Atmospheric cold plasma as new strategy for foods processing-an overview, Innovat. Rom. Food Biotechnol. 15 (2014).
[54] R. Thirumdas, C. Sarangapani, U.S. Annapure, Cold plasma: a novel nonthermal technology for food processing, Food Biophys. 10 (1) (2015) 1–11.
[55] R. Thirumdas, A. Trimukhe, R.R. Deshmukh, U.S. Annapure, Functional and rheological properties of cold plasma treated rice starch, Carbohydr. Polym. 157 (2017) 1723–1731.
[56] C. Sudheesh, K.V. Sunooj, S.K. Sinha, J. George, S. Kumar, P. Murugesan, V.A. S. Kumar, Impact of energetic neutral nitrogen atoms created by glow discharge air plasma on the physico-chemical and rheological properties of kithul starch, Food Chem. 294 (2019) 194–202.
[57] R.B. Nisha, R. Narayanan, Review on cold plasma technology: the future of food preservation, Int. J. Chem. Stud. 7 (2019) 4427–4433.
[58] R. Mishra, S. Bhatia, R. Pal, A. Visen, H. Trivedi, Cold plasma: emerging as the new standard in food safety, Res. Inv. Int. J. Eng. Sci. 6 (2) (2016) 15–20.
[59] B.A. Niemira, A. Gutsol, Nonthermal plasma as a novel food processing technology, Nonthermal Processing Technol. Food (2011) 272–288.
[60] P.K. Chu, J.Y. Chen, L.P. Wang, N. Huang, Plasma-surface modification of biomaterials, Mater. Sci. Eng. R Rep. 36 (5–6) (2002) 143–206.
[61] K. Fricke, I. Koban, H. Tresp, L. Jablonowski, K. Schröder, A. Kramer, T. Kocher, Atmospheric Pressure Plasma: a High-Performance Tool for the Efficient Removal of Biofilms, 2012.
[62] S. Bußler, V. Steins, J. Ehlbeck, O. Schlüter, Impact of thermal treatment versus cold atmospheric plasma processing on the techno-functional protein properties from Pisum sativum 'Salamanca', J. Food Eng. 167 (2015) 166–174.
[63] H. Zhang, D. Ma, R. Qiu, Y. Tang, C. Du, Nonthermal plasma technology for organic contaminated soil remediation: a review, Chem. Eng. J. 313 (2017) 157–170.
[64] K. Shimizu, J. Kristof, M.G. Blajan, Applications of dielectric barrier discharge microplasma, Atmospheric Pressure Plasma-from Diagnostics Applicat. (2018) 71–93.
[65] J. Ehlbeck, U. Schnabel, M. Polak, J. Winter, T. Von Woedtke, R. Brandenburg, K. D. Weltmann, Low temperature atmospheric pressure plasma sources for microbial decontamination, J. Phys. Appl. Phys. 44 (1) (2010), 013002.
[66] V. Scholtz, J. Julák, V. Kříha, The microbicidal effect of low-temperature plasma generated by corona discharge: comparison of various microorganisms on an agar surface or in aqueous suspension, Plasma Process. Polym. 7 (3-4) (2010) 237–243.
[67] K.D. Weltmann, R. Brandenburg, T. von Woedtke, J. Ehlbeck, R. Foest, M. Stieber, E. Kindel, Antimicrobial treatment of heat sensitive products by miniaturized atmospheric pressure plasma jets (APPJs), J. Phys. Appl. Phys. 41 (19) (2008), 194008.
[68] M. Roy, Protective hard coatings for tribological applications, in: A.K. Tyagi, S. Banerjee (Eds.), Materials under Extreme Conditions, Elsevier, UK, 2017, pp. 259–292.
[69] C. Sarangapani, G. O'Toole, P.J. Cullen, P. Bourke, Atmospheric cold plasma dissipation efficiency of agrochemicals on blueberries, Innovat. Food Sci. Emerg. Technol. 44 (2017) 235–241.
[70] A.L. Wszelaki, E.J. Mitcham, Effects of superatmospheric oxygen on strawberry fruit quality and decay, Postharvest Biol. Technol. 20 (2) (2000) 125–133.
[71] Z. Runguang, Effect of ozone treatment on the quality of strawberry fruit during storage, Acad. Period. Farm Prod. Process 7 (2011) 19–22.
[72] C. Sarangapani, R.Y. Devi, R. Thirumdas, A.M. Trimukhe, R.R. Deshmukh, U. S. Annapure, Physico-chemical properties of low-pressure plasma treated black gram, LWT–Food Sci. Technol. 79 (2017) 102–110.
[73] R. Thirumdas, C. Saragapani, M.T. Ajinkya, R.R. Deshmukh, U.S. Annapure, Influence of low pressure cold plasma on cooking and textural properties of brown rice, Innovat. Food Sci. Emerg. Technol. 37 (2016) 53–60.
[74] Y. Li, A. Kojtari, G. Friedman, A.D. Brooks, A. Fridman, H.F. Ji, Decomposition of L-valine under nonthermal dielectric barrier discharge plasma, J. Phys. Chem. B 118 (6) (2014) 1612–1620.
[75] A. Segat, N.N. Misra, P.J. Cullen, N. Innocente, Effect of atmospheric pressure cold plasma (ACP) on activity and structure of alkaline phosphatase, Food Bioprod. Process. 98 (2016) 181–188.
[76] I. Albertos, A. Martín-Diana, P.J. Cullen, B.K. Tiwari, S.K. Ojha, P. Bourke, D. Rico, Effects of dielectric barrier discharge (DBD) generated plasma on microbial reduction and quality parameters of fresh mackerel (Scomber scombrus) fillets, Innovat. Food Sci. Emerg. Technol. 44 (2017) 117–122.
[77] Z. Qu, G. Chen, J. Wang, X. Xie, Y. Chen, Preparation, structure evaluation, and improvement in foaming characteristics of fibrotic pea protein isolate by cold plasma synergistic organic acid treatment, Food Hydrocolloids 134 (2023), 108057.
[78] Ó. Rodríguez, W.F. Gomes, S. Rodrigues, F.A. Fernandes, Effect of indirect cold plasma treatment on cashew apple juice (Anacardium occidentale L.), LWT. Food Sci. Technol. 84 (2017) 457–463.
[79] F.D.L. Almeida, R.S. Cavalcante, P.J. Cullen, J.M. Frias, P. Bourke, F. A. Fernandes, S. Rodrigues, Effects of atmospheric cold plasma and ozone on prebiotic orange juice, Innovat. Food Sci. Emerg. Technol. 32 (2015) 127–135.
[80] J. Guo, Z. He, C. Ma, W. Li, J. Wang, F. Lin, L. Li, Evaluation of cold plasma for decontamination of molds and mycotoxins in rice grain, Food Chem. 402 (2023), 134159.
[81] A. Sarkar, T. Niranjan, G. Patel, A. Kheto, B.K. Tiwari, M. Dwivedi, Impact of cold plasma treatment on nutritional, antinutritional, functional, thermal, rheological, and structural properties of pearl millet flour, J. Food Process. Eng. 46 (5) (2023), e14317.
[82] N. Nikmaram, K.M. Keener, The effects of cold plasma technology on physical, nutritional, and sensory properties of milk and milk products, LWT 154 (2022), 112729.
[83] M. Dharini, S. Jaspin, R. Mahendran, Cold plasma bubbling: impact on safety, physicochemical properties, and nutritional quality of sesame milk, Food Bioprod. Process. 139 (2023) 109–120.
[84] G. Akarca, A. Atik, İ. Atik, A.J. Denizkara, The use of cold plasma technology in solving the mold problem in Kashar cheese, J. Food Sci. Technol. (2023) 1–9.
[85] A.U. Alahakoon, D.D. Jayasena, h S. Ramachandra, C. Jo, Alternatives to nitrite in processed meat: up to date, Trends Food Sci. Technol. 45 (1) (2015) 37–49.
[86] J. Lee, C.W. Lee, H.I. Yong, H.J. Lee, C. Jo, S. Jung, Use of atmospheric pressure cold plasma for meat industry, Korean J. Food Sci. Animal Resources 37 (4) (2017) 477.
[87] N.N. Misra, C. Jo, Applications of cold plasma technology for microbiological safety in meat industry, Trends Food Sci. Technol. 64 (2017) 74–86.
[88] E. Noriega, G. Shama, A. Laca, M. Díaz, M.G. Kong, Cold atmospheric gas plasma disinfection of chicken meat and chicken skin contaminated with Listeria innocua, Food Microbiol. 28 (7) (2011) 1293–1300.
[89] B. Kim, H. Yun, S. Jung, Y. Jung, H. Jung, W. Choe, C. Jo, Effect of atmospheric pressure plasma on inactivation of pathogens inoculated onto bacon using two different gas compositions, Food Microbiol. 28 (1) (2011) 9–13.
[90] H.J. Lee, H. Jung, W. Choe, J.S. Ham, J.H. Lee, C. Jo, Inactivation of Listeria monocytogenes on agar and processed meat surfaces by atmospheric pressure plasma jets, Food Microbiol. 28 (8) (2011) 1468–1471.
[91] H.J. Kim, H.I. Yong, S. Park, W. Choe, C. Jo, Effects of dielectric barrier discharge plasma on pathogen inactivation and the physicochemical and sensory characteristics of pork loin, Curr. Appl. Phys. 13 (7) (2013) 1420–1425.
[92] H.I. Yong, H. Lee, S. Park, J. Park, W. Choe, S. Jung, C. Jo, Flexible thin-layer plasma inactivation of bacteria and mold survival in beef jerky packaging and its effects on the meat's physicochemical properties, Meat Sci. 123 (2017) 151–156.
[93] S. Mol, T. Akan, S. Kartal, S. Coşansu, Ş.Y. Tosun, D.Ü. Alakavuk, K. Bostan, Effects of air and helium cold plasma on sensory acceptability and quality of fresh sea bass (Dicentrarchus labrax), Food Bioprocess Technol. 16 (3) (2023) 537–548.
[94] H. Chutia, C.L. Mahanta, N. Ojah, A.J. Choudhury, Fuzzy logic approach for optimization of blended beverage of cold plasma treated TCW and orange juice, J. Food Meas. Char. (2020) 1–13.

[95] N.K. Mahnot, L.P. Siyu, Z. Wan, K.M. Keener, N.N. Misra, In-package cold plasma decontamination of fresh-cut carrots: microbial and quality aspects, J. Phys. Appl. Phys. 53 (15) (2020), 154002.
[96] M.R. Silveira, N.M. Coutinho, E.A. Esmerino, J. Moraes, L.M. Fernandes, T. C. Pimentel, A.G. Cruz, Guava-flavored whey beverage processed by cold plasma technology: bioactive compounds, fatty acid profile and volatile compounds, Food Chem. 279 (2019) 120–127.
[97] S. Rana, D. Mehta, V. Bansal, U.S. Shivhare, S.K. Yadav, Atmospheric cold plasma (ACP) treatment improved in-package shelf-life of strawberry fruit, J. Food Sci. Technol. 57 (1) (2020) 102–112.
[98] Z. Herceg, D.B. Kovačević, J.G. Kljusurić, A.R. Jambrak, Z. Zorić, V. Dragović-Uzelac, Gas phase plasma impact on phenolic compounds in pomegranate juice, Food Chem. 190 (2016) 665–672.
[99] A. Berardinelli, L. Vannini, L. Ragni, M.E. Guerzoni, Impact of atmospheric Plasma generated by a DBD device on quality-related attributes of "abate fetel" pear fruit, in: Plasma for Bio-Decontamination, Medicine and Food Security, Springer, Dordrecht, 2012, pp. 457–467.
[100] X.M. Shi, G.J. Zhang, X.L. Wu, Y.X. Li, Y. Ma, X.J. Shao, Effect of low-temperature Plasma on microorganism inactivation and quality of freshly squeezed orange juice, IEEE Trans. Plasma Sci. 39 (7) (2011) 1591–1597.
[101] M.S. Banu, P. Sasikala, A. Dhanapal, V. Kavitha, G. Yazhini, L. Rajamani, Cold plasma as a novel food processing technology, Int. J. Emerg. Trends Eng. Dev. 4 (2) (2012) 803–818.
[102] D.A. Laroque, S.T. Seó, G.A. Valencia, J.B. Laurindo, B.A.M. Carciofi, Cold plasma in food processing: design, mechanisms, and application, J. Food Eng. 312 (2022), 110748.
[103] M. Heise, W. Neff, O. Franken, P. Muranyi, J. Wunderlich, Sterilization of polymer foils with dielectric barrier discharges at atmospheric pressure, Plasma Polym. 9 (1) (2004) 23–33.
[104] A. Ghanem, A. Ghaly, Immobilization of glucose oxidase in chitosan gel beads, J. Appl. Polym. Sci. 91 (2) (2004) 861–866.
[105] G.G. Buonocore, M. Sinigaglia, M.R. Corbo, A. Bevilacqua, E. La Notte, M.A. Del Nobile, Controlled release of antimicrobial compounds from highly swellable polymers, J. Food Protect. 67 (6) (2004) 1190–1194.
[106] P. Appendini, J.H. Hotchkiss, Review of antimicrobial food packaging, Innovat. Food Sci. Emerg. Technol. 3 (2) (2002) 113–126.
[107] M. Mastromatteo, L. Lecce, N. De Vietro, P. Favia, M.A. Del Nobile, Plasma deposition processes from acrylic/methane on natural fibres to control the kinetic release of lysozyme from PVOH monolayer film, J. Food Eng. 104 (3) (2011) 373–379.
[108] N.N. Misra, B.K. Tiwari, K.S.M.S. Raghavarao, P.J. Cullen, Nonthermal plasma inactivation of food-borne pathogens, Food Eng. Rev. 3 (3) (2011) 159–170.
[109] S.A. Fernandez-Gutierrez, P.D. Pedrow, M.J. Pitts, J. Powers, Cold atmospheric-pressure plasmas applied to active packaging of apples, IEEE Trans. Plasma Sci. 38 (4) (2010) 957–965.
[110] P. Muranyi, J. Wunderlich, H.C. Langowski, Modification of bacterial structures by a low-temperature gas plasma and influence on packaging material, J. Appl. Microbiol. 109 (6) (2010) 1875–1885.
[111] R. Thirumdas, Partial hydrogenation of oils using cold plasma technology and its effect on lipid oxidation, J. Food Sci. Technol. 60 (6) (2023) 1674–1680.
[112] M. Gavahian, A.M. Khaneghah, Cold plasma as a tool for the elimination of food contaminants: recent advances and future trends, Crit. Rev. Food Sci. Nutr. 60 (9) (2020) 1581–1592.
[113] P. Kulawik, C. Alvarez, P.J. Cullen, R. Aznar-Roca, A.M. Mullen, B. Tiwari, The effect of nonthermal plasma on the lipid oxidation and microbiological quality of sushi, Innovat. Food Sci. Emerg. Technol. 45 (2018) 412–417.
[114] J. Wang, C. Xing, J. Xia, H. Chen, J. Zhang, W. Yan, Degradation of carbendazim in aqueous solution by dielectric barrier discharge cold plasma: identification and toxicity of degradation products, Food Chem. 403 (2023), 134329.
[115] C. Dupas, A.M. Baglieri, C. Ordonaud, D. Tom, M.N. Maillard, Chlorogenic acid is poorly absorbed, independently of the food matrix: a Caco-2 cells and rat chronic absorption study, Mol. Nutr. Food Res. 50 (2006) 1053–1060.
[116] C.M. Galanakis, Emerging technologies for the production of nutraceuticals from agricultural by-products: a viewpoint of opportunities and challenges, Food Bioprod. Process. 91 (4) (2013) 575–579.