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REVIEW

Cold plasma treatment advancements in food processing and impact on the physiochemical characteristics of food products

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Abstract

Cold plasma processing is a nonthermal approach that maintains food quality while minimizing the effects of heat on its nutritious qualities. Utilizing activated, highly reactive gaseous molecules, cold plasma processing technique inactivates contaminating microorganisms in food and packaging materials. Pesticides and enzymes that are linked to quality degradation are currently the most critical issues in the fresh produce industry. Using cold plasma causes pesticides and enzymes to degrade, which is associated with quality deterioration. The product surface characteristics and processing variables, such as environmental factors, processing parameters, and intrinsic factors, need to be optimized to obtain higher cold plasma efficiency. The purpose of this review is to analyse the impact of cold plasma processing on qualitative characteristics of food products and to demonstrate the effect of cold plasma on preventing microbiological concerns while also improving the quality of minimally processed products.

Keywords Decontamination · Cold plasma · Pesticide degradation · Enzyme activity

Introduction

Fruits and vegetables have become a necessary component of an individual's nutritional framework since they are high in minerals, vitamins, and fibers (Pandey et al., 2022). It has been established that eating plenty of raw fruits and vegetables on a daily basis can lower the threat of cardiovascular disease and cancer cell lines (Boffetta et al., 2010). Concerns relating to food preservation and food safety are growing in

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importance among food producers and consumers all over the world.

Thermal treatment is a prevalent preservation method for extending food product shelf life by reducing microbiological contamination. Despite its high efficacy, it has the disadvantage of diminishing nutritional and organoleptic properties (Pandiselvam et al.,2017). Nonthermal methods are a type of food preservation that do not require high temperatures to eliminate microorganisms and increase the shelf life of food. These methods include using high pressure, pulsed electric fields, UV light, and cold plasma (Singh et al., 2022; Mukhtar et al., 2022; Stranska et al., 2023). These methods are often combined with other preservation methods, such as refrigeration and packaging, to achieve the best preservation results. Additionally, nonthermal methods are known to maintain the nutritional value and flavor of food better than traditional preservation methods that use high heat. Cold plasma (CP) is a new technique that has recently piqued the interest of the food sector as it is a low energyconsuming non-thermal method that can effectively target specific microorganisms or enzymes. Additionally, CP does not leave any toxic residues, making it a safe and environmentally friendly preservation method (Ucar et al., 2021; Sruthi et al., 2022; Rao et al., 2023). Nonthermal techniques, unlike heat treatment, preserve the natural aroma and flavor of foods while boosting microbiological food safety without significantly degrading quality (Charoux et al., 2020; Charoux et al., 2021). Cold plasma which is a commonly used method for surface treatment whereas, Plasma chemistry is a complex field with many distinct species and chemical reactions occurring on various time scales (Pankaj et al., 2017). Preference is given to Cold plasma over other techniques because of its various benefits and applications like Cold plasma has high reactivity and is thermodynamically non-equilibrium, making it useful in a variety of sectors, including agriculture, food, packaging, and medicine (Nivetidhaet al., 2021). Because of their chilly nature, plasmas are appropriate for heat-sensitive items (Sruthi et al., 2022; Prithviraj et al., 2021).

A typical CP generation includes a particular carrier gas, a low energy input suitable power source, and electrodes composed of specific materials (Mandal et al., 2018). Because cold plasma cannot permeate the product, microbial inactivation occurs on the surface with minimal influence on the interior nutritional or composition functions of the raw food (Pasquali et al., 2016; Sruthi et al., 2022). Various studies were conducted to enhance the effectiveness of cold plasma treatment to provide safer, fresher, and minimally processed food products. This review presented a comprehensive evaluation of the cold plasma technique in various food products with potential future challenges. Based on this, the prime objective of the review is to analyze the effect of cold plasma processing on qualitative parameters of food products. The study demonstrated how cold plasma could protect against microbial concerns and improve the quality of food products.

Principles and mechanism of plasma technology

Plasma is the fourth state of matter, an ionized plasma containing many activities like free radicals, ions, electrons, etc. Plasma has a net neutral charge and may exist in either its ground or excited states. It is produced at various pressures and temperatures by energizing a neutral gas, and is therefore classed as thermal or nonthermal plasma (Burm, 2012). High pressure levels (10^5 Pa), power up to 50 MW are needed for thermal plasma propagation, as well as thermal equilibrium amongst heavier species and electrons owing to the components' homogenous gas temperature (Scholtz et al., 2015).

On the other side, nonthermal plasma, which is also known as non-equilibrium plasma, generates at lower pressures and powers with no localized thermodynamic equilibrium. Generally, the given energy dissociates the gas into a plethora of reactive species, which undergo further reactions like excitation, de-excitation, and ionization. The food industry is particularly interested in the nonthermal plasma because it may be useful for processing food at low temperatures. Furthermore, the trajectory for application as well as the quantity and make-up of reactive species, are affected by the technique used during cold plasma production. Determining the technological pathways for plasma formation, which include those that produce plasma under atmospheric pressure as well as those that function under lower pressure, is crucial as a result (Ekezie et al., 2017). Some of the methods used to create cold plasma include gliding arc discharge, radio frequencies, dielectric barrier discharge, corona glow discharges, inductively coupled plasmas, microwave-induced plasma and atmospheric glow discharge. The cold plasma's electron constituent absorbs the majority of the linked electrical energy. Figure 1 outlines various cold plasma applications in food matrices.

Plasma generated at atmospheric pressure

Recent developments in plasma engineering have led to plasma sources operating at atmospheric pressure. Plasma generators like corona discharge, radio frequency plasma, gliding arc discharges (GAD), and dielectric barrier discharges (DBD). DBD is a method of cold plasma technology that creates a plasma field by applying high-voltage electrical discharge between two electrodes separated by a dielectric barrier. The dielectric barrier is an insulating material that prevents the electrical discharge from reaching the ground and confines the plasma to a specific area. The advantages of DBD include its relative simplicity, lower

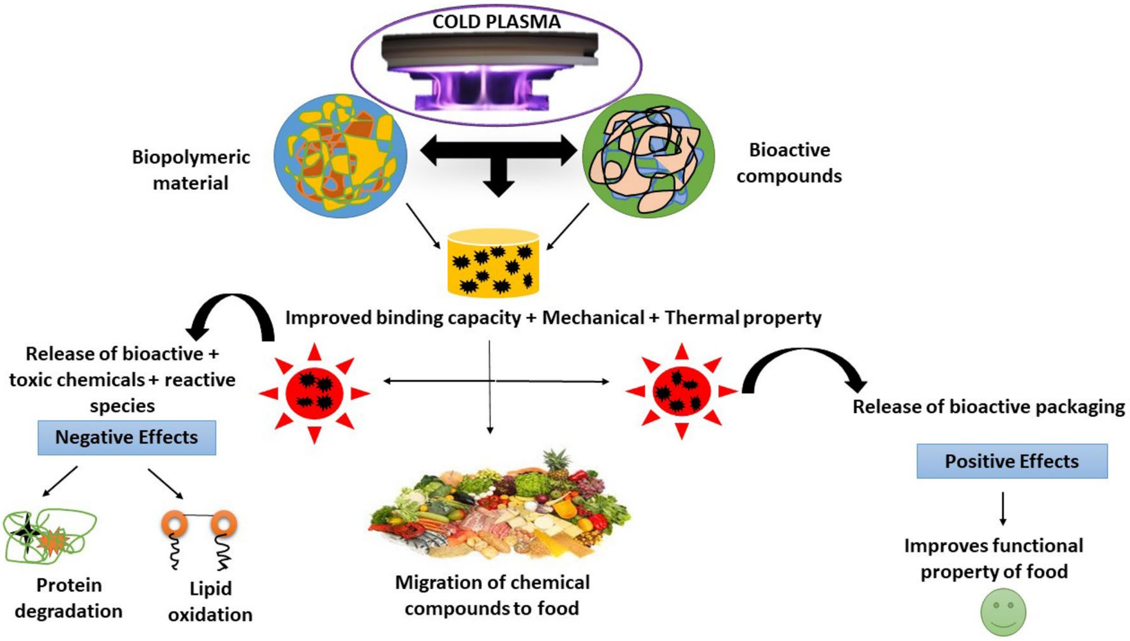

Fig. 1 Diagrammatic representation of cold plasma application in food matrices

gas flow rate, use of multiple gases, flexibility due to variable electrode geometries, as well as uniform discharge igniting across several meters. Furthermore, since the technique needs high ignition voltages of 10 kV, sufficient adequate precautions must be taken. The creation of ozone and ultraviolet (UV) light and its use in CO_2 lasers and excimer lamps are typical uses (Surowsky et al., 2014; Ekezie et al., 2017).

Gliding arc discharge (GAD) is produced in an atmospheric reactor with more than two diverging metallic electrodes running at a high voltage difference of 9 kV and 100 mA. An arc typically forms between the narrowest inter-electrode zone when humidified air is forced into the discharge gap amongst the electrodes. The incoming gas into the diverging area then blows this arc away. Depending on the settings, GAD may generate both nonthermal and thermal plasmas. This approach is very adaptable for both surface as well as liquid treatments and has been used in practical studies addressing the breakdown of chemical pollutants such as organic components, industrial wastes, and solvents found in water, as well as bacterial decontamination. A large electric field surrounds sharp, pointed electrodes to create the CDP, a dispersed path for plasma combustion that accelerates the ionization energy of randomly generated electrons to that of nearby gas molecules or atoms (Scholtz et al., 2015). It is often produced at high voltage and also happens mostly on one electrode.

Furthermore, the technology is low-cost as well as straightforward to execute. It has been used for surface treatment, microbial cleaning, electro-precipitation, and other applications, although they are limited to non-homogeneous diminutive regions. On the other side, radio frequency plasma is often generated whenever gas is put inside a pulsating electromagnetic field created by an induction coil or separate electrodes maintained outside the reactor. This kind of plasma, similar to microwaves, uses well-known complexity and works at frequencies ranging from Hz to MHz (Ekezie et al., 2017). The nonthermal plasma produced at reduced pressures is essentially defined by microwave-powered (MP) plasma, which is propelled by electromagnetic waves having frequencies in the 100 MHz range. In contrast to electrode-based approaches, microwave discharges are produced via a magnetron that directs microwaves into a working chamber through a coaxial connection. The process gas then absorbs the irradiation, generating heat and ionization processes through inelastic collisions. MP plasma is useful since it lacks electrodes as well as could be simply ignited in air. Additionally, there are little gas requirements and frequent large-scale emissions of reactive species. Despite the fact that MP plasma is spatially constrained, its usage in wide regions needs an array of discharges similar to the organization of plasma jets (Niemira, 2008; Surowsky et al., 2014).

Cold plasma applications in food processing

Microorganism inactivation efficacy on fruit and vegetable surfaces

Cold plasma, as the name indicates, is an active ionized medium kept at ambient temperature and pressure by a constant energy source. Because they are heat-sensitive organic substances, fresh fruit, liquids, as well as live biological tissue are all suitable candidates for cold plasma therapy (Anbarasan et al., 2022). The primary active compounds in plasma include (i) Charged particles (ii) Stable conversion products (iii) Free radicals, (iv) Energetic, (v) Excited atoms and molecules photons. In previous years, molecular dynamics (MD) simulations have shed light on the impacts of numerous reactive species on the components of the bacterial cell wall and also endotoxins (Neyts et al., 2015; Yusupov et al., 2012). The decontamination mechanism of cold plasma in food processing is illustrated in Fig. 2. Effect of ROS and RNS on cold plasma has been depicted in Fig. 3.

According to literature assessments, cold plasma is one of the most effective strategies for inactivating several spoilage and harmful bacteria in food items. Cold plasma inactivated gram-positive or gram-negative bacteria in various ways (Han et al., 2016). Gram-positive bacteria i.e. *Staphylococcus aureus* have shown to be inactivated mainly by intracellular disruption and moderate envelope damage, while Gram-negative bacteria i.e. *Escherichia coli* were found to be mainly inhabited by low-level DNA mutation and cell leakage. Plasma therapy has been proven effective for a variety of food elements and microbiological species (Athukorala et al., 2009; Min et al., 2017). Many elements that are used, like the type of substrate as well as the features of the microorganism to be disintegrated, determine the plasma's efficacy. The utilization of cold plasma in food items including cherry tomatoes (Misra et al., 2014a; 2014b), apples (Buler et al., 2017), kiwi (Ramazzina et al., 2015), Melons (Tappi et al., 2016), lettuce leaves (Min et al., 2017), blueberry (Sarangapani et al., 2016), chicory leaves (Pasquali et al., 2016), was reported to be efficacious to extend their shelf stability. This technology is also useful for heat sensitive foods as its temperature is close to ambient temperature. The various applications of cold plasma technology to preserve or improve the quality and safety of fruits and vegetables are stated in Table 1.

Plasma treatment's effect on the enzymatic inactivity of fruits and vegetables

Endogenous enzymes may assist in the browning of fruits and vegetables (Tappi et al., 2016; Han et al., 2019). Cold plasma could be used for enzymatic inactivation to minimize browning. Han et al. (2019) treated horseradish peroxidase (HRP) with an atmospheric pressure plasma jet and observed that structure breakdown and microstructure deformation lowered HRP's residual activity to around 17%. Bußler et al. (2017) utilized microwave plasma torch to efficiently inactivate POD and PPO activity in fresh-cut potatoes and apples. PPO activity in fresh-cut apple and potato tissue decreased by about 62% and 77% after 10 min of treatment, respectively. They also revealed that after 10 min of treatment, PPO activity was lowered by around 62% and 77% in fresh-cut apple and potato tissue, respectively. POD activity in fresh-cut apples and potatoes decreased by about 65% and 89% after 10 min of plasma treatment, respectively. Tappi et al. (2014) utilized DBD plasma to treat fresh-cut apples for 10, 20, and 30 min and observed that PPO residual ability lowered linearly as treatment duration enhanced (up to

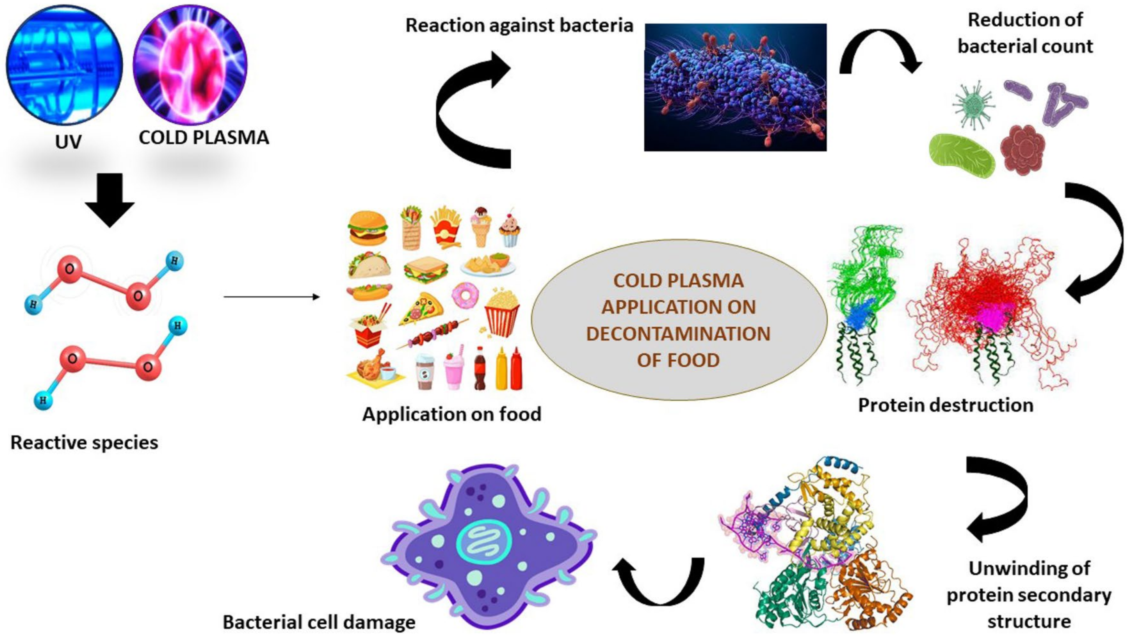

Fig. 2 Decontamination mechanism of cold plasma in food processing

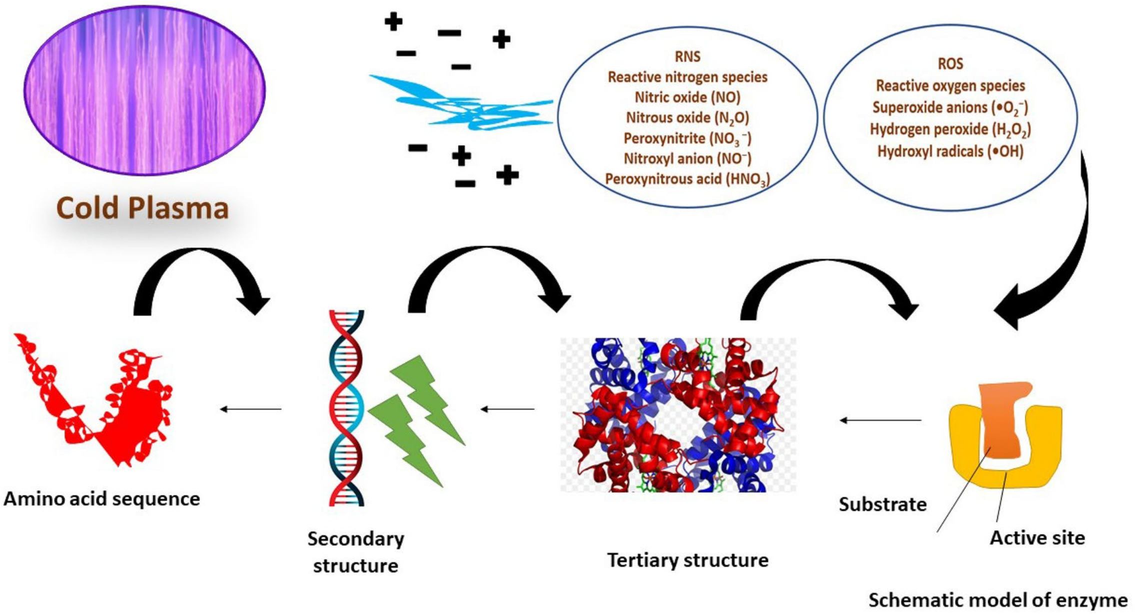

Fig. 3 Effect of RNS and ROS on cold plasma

about 42%). Likewise, Tappi et al. (2016) discovered that fresh-cut melon treated with plasma exhibited decreased PME and POD activity. The cold plasma aided modulation of enzyme activity in various fruits and vegetable products is presented in Table 2.

Inactivation kinetics of plasma technology

Plasma technology reduces undesirable browning reactions and loss of nutritional and sensory quality. Processing fresh cut and dried goods requires inactivating polyphenol oxidase enzymes and peroxidase. The innate enzymatic activity of freshly cut fruits can now be inhibited using plasma technology (Mir et al., 2016; Tappi et al., 2016). Both intrinsic and extrinsic factors govern cold plasma's ability to inactivate enzymes. Predictive kinetic modeling is a very helpful technique for determining the best treatment settings to attain the desired levels of microbiological or enzymatic deactivation required for food safety as well as stability. The first-order kinetics model is frequently used to explain how food enzymes become inactive when heated (Eq. (1)) (Anthon and Barrett, 2002).

$$\frac{At}{Ao} = -kt \tag{1}$$

where A_0 is the initial enzymatic activity, At is the activity at time t (s), and k (s^{-1}) is the inactivation rate constant.

This approach has shown to work successfully for a variety of enzymes while employing nonthermal techniques, including PEF (Giner et al., 2000), HPP (Terefe et al., 2010), ultraviolet light (Neves et al., 2012) as well as ultrasound (Cruz et al. 2006). Furthermore, it has been observed that the first-order approach is ineffective for peroxidase deactivation by cold plasma (Pankaj et al., 2013). Also, the deactivation has been observed to follow a sigmoidal logistic equation shown in Eq. (2).

$$A = \frac{100 - Amin}{1 + \left(\frac{t}{t50}\right)^p} + Amin \tag{2}$$

where t50 is the time at which half of the peak activity occurs, A_{min} (≥ 0) is the minimal value that the logistic function can achieve, and p is the power term.

Additionally, it has been proven that whole strawberries treated with plasma inactivate peroxidase in a sigmoidal manner (Misra, 2014a). According to the inactivation data observed by Pankaj et al. (2013) and Surowsky et al. (2014), the occurrence of different forms of the enzyme after extensive treatments could be ascribed to the presence of numerous types of the enzyme, most likely the result of the aggregation of monomers into more complex forms with increased resistance to cold plasma (Pankaj et al., 2013). Inactivation data is best demonstrated by the Weibull model for alkaline phosphatase, although if sigmoidal models have typically provided a good explanation for PPO and POD inactivation (Segat et al., 2016).

According to Liu et al. (2016), the molecular structure of the enzyme, mass transfer amongst the gas and fluid phase, as well as the enzyme's surroundings (buffer/cellular matrix) are the main factors that affect enzyme inactivation (Misra, 2014b). Food scientists frequently utilize kinetic and empirical models, however, they do not provide a clear picture of

Table 1 Application of cold plasma on Microorganisms of different fruits and vegetables

Food and food product	Plasma generation source	Microorganisms	Major findings	References
Fresh cut apple	Cold plasma, 29.6 W 3, 5, 10, 15, and 20 min Nitrogen (N_2), Ar, O_2, and Ar-O_2—40 ml/ min 1300 to 1370	*Escherichia coli* and *Listeria innocua*	Treatments with Ar, O_2, or an Ar–O_2 combination for 20 min were most efficient in inactivating *E. coli*, whereas treatment with N_2 for 20 min decreased *L. innocua* the most	Seguraponce et al. (2018)
Blueberry juice quality	Cold plasma Jet, 1000 Hz, 2, 4 and 6 min, Argon (Ar) and Oxygen (O_2) 11 kV 1.0 L	*Bacillus* spp.	The increase in treatment duration and O_2 concentration resulted in a considerable increase in *Bacillus* death. CP treatment considerably boosted the concentration of phenolics as compared to heat treatment, and it also helped blueberry juice retain its natural hue	Hou et al. (2019)
Fresh strawberries and spinach	Atmospheric cold plasma, 900 W 5, 7, 10, 13, 20, 22, 24 and 27 min Ozone 0 100 kV	*E. coli* and *L. innocua*	3.8 log10 CFU/ml reductions were obtained with continuous treatment against *L. innocua* inoculated on strawberries	Ziuzina et al. (2020)
Apple slice of different types (Pink Lady, Fuji, Red Delicious, Modi)	Cold Plasma, 150 W 30 and 60 min 150 W	*E. coli*	A noticeable reduction of superficial browning was observed in all cultivars but not always proportionally to treatment time. Textural parameters were affected by plasma treatments only in Red Delicious apples	Tappi et al. (2019)
Fresh cut melon	Cold Plasma, 2.5 kHz 19 V 30 min (15 each side) And 60 min (30 each side) Air gas 15 kV	*E. coli*	Qualitative parameters of freshcut melon (soluble solid content, dry matter, color, texture) were only weakly affected. Peroxidase and pectin methylesterase activities were slightly inhibited by the treatment up to respectively about 17 and 7%	Tappi et al. (2016)
Blue berries	Atmospheric Cold Plasma, 50 Hz 2, 5 min Atmospheric air 60 and 80 kV	*E. coli*	Inhibition of pesticides 75.62–80.18%	Sarangapani et al. (2016)
Bulk romain lettuce	Atmospheric Cold Plasma, 0 and 2400 Hz,10 min Atmospheric air 42.6 kV	*E. coli*	More reduction (1.1 log CFU/g lettuce) was observed at the top layer, but shaking the container increased the uniformity of the inhibition. The treatment did not significantly change the surface morphology, color, respiration rate, or weight loss of the samples, nor did these properties differ significantly according to their location in the bulk stack	Min et al. (2016)
Tomato	Atmospheric Cold Plasma, 50 Hz, 5, 10, 15, and 30 min, 15 and 60 kV	*E. coli*	The highest log reduction of 6 log CFU mL^{-1} was achieved in a population of *E. coli* after 15 min of ACP treatment at 60 kV, which was sustained up to a storage duration of 48 h	Prasad et al. (2017)

Table 1 (continued)

Food and food product	Plasma generation source	Microorganisms	Major findings	References
Groundnuts	Cold Plasma, 13.56 MHz 40 and 60 W at 0–30 min Atmospheric air 1500 and 1950 V	*A. flavus* and *A. parasitcus*	Results showed complete disintegration of the fungal spore membrane due to electroporation and etching caused by the reactive species of plasma. In 40 W 15 min and 60 W 12 min plasma-treated samples more than 70% and 90% reduction in aflatoxin B1 content was observed	Devi et al. (2017)
Orange juice	DBD, Air/MA65 (65% O_2, 30% CO_2, 5% N_2), 90 kV, 30–120 s	*Salmonella enterica*	No significant change in Brix or pH, Vit. C is reduced by 22% in air, PME activity reduced by 74% in air and 82% in MA65, maximum total color difference is less than 1.2	Xu et al. (2017)
Cashew apple juice	PE-100, 80 kHz, N2, 10–50 mL/min, 5–15 min, 30 kPa	NA	No significant change in Brix or pH, Vit. C is reduced by 22% in air, PME activity reduced by 74% in air and 82%in MA65. Maximum total color difference is less than 1.2	Rodriguez (2017)
Prebiotic orange juice	DBD, 70 kV (50 Hz), 15–60 s	NA	Degradation of oligosaccharides in the juice, Decrease in pH, Increase in L* value and slight reduction in chroma and hue angle, Decrease in total phenolic content and antioxidant capacity in some cases	Almeida et al. (2015)
White grape juice	DBD, 60 Hz, 80 kV, 1–4 min, air	*Saccharomyces cerevisiae*	No significant change in pH, acidity and electrical conductivity of the juice. An increase in non-enzymatic browning with minimal total color difference. Decrease in total phenolic, total flavonoids, DPPH free radicals scavenging and antioxidant capacity. An increase in total flavonols content	Pankaj et al. (2017)
Pomegranate juice	Plasma jet, 25 kHz, Ar, 0.75–1.25 dm3/min, 3–7 min	NA	Increase in total anthocyanin content and no visual differences in color	Kovaˇcevi´et al. (2016)
Apple juice	DBD 30–50 W, 1 min	*E. coli*	Change in colour, toxicity, and pH	Liao et al. (2017)

Table 2 Cold plasma aided modulation of enzyme activity in various food products

Enzyme	Target	Source	Processing parameters	Outcome	References
POD	Tomato extract	Dielectric barrier discharge	Voltage: 30–50 kV; Frequency: 50 Hz; Operation time: 0–5 min; Gas: Air	Voltage and time dependent inactivation; Inactivation follows a sigmoidal logistic function	Pankaj et al. (2013)
Polyphenol oxygenase	Fresh cut apples	Dielectric barrier discharge	Voltage: 15 kV (peak to peak) from DC source; Frequency: 12.7 kHz; Operation Time: 10, 20 and 30 min; Gas: Air; Flow rate: 1.5 m/s	Linear decrease in activity with treatment time; Residual activity of 88, 68 and 42% after 10, 20 and 30 min of treatment	Tappi et al. (2014)
POD	Strawberry	Dielectric barrier discharge	Voltage: 30–50 kV; Frequency: 50 Hz; Operation time: 0–5 min; Gas: Air	Voltage and time dependent inactivation; Inactivation follows a sigmoidal logistic function	Misra, (2014a)
POD	Fresh cut melon	Dielectric barrier discharge	Voltage: 15 kVp-p from DC source; Frequency: 12.5 kHz; Operation Time: 15 + 15, 30 + 30 min; Gas: air	Residual activity were 91% and 82% after 15 + 15 and 30 + 30 min treatment respectively	Tappi et al. (2016)
Polymethyl esterase	Fresh cut melon	Dielectric barrier discharge	Voltage: 15 kVp-p from DC source; Frequency: 12.5 kHz; Operation Time: 30, 60 min; Gas: air	15 + 15 min treatment was ineffective; residual activity was 94% after 30 + 30 min treatment	Tappi et al. (2016)
	Fresh cut apple	Cold plasma	Cold plasma, 29.6 W 3, 5, 10, 15, and 20 min Nitrogen (N_2), Ar, O_2, and Ar–O2—40 ml/min 1300 to 1370	Treatments with Ar, O_2, or an Ar–O_2 combination for 20 min were most efficient in inactivating *E. coli*, whereas treatment with N_2 for 20 min decreased *L. innocua* the most (p 0.05)	Seguraponce et al. (2018)
	Fresh Strawberries and Spinach	Atmospheric cold plasma	Atmospheric cold plasma, 900 W 5, 7, 10, 13, 20, 22, 24 and 27 min Ozone 0 100 kV	3.8 log10 CFU/ml reductions were obtained with continuous treatment against *L. innocua* inoculated on strawberries	Ziuzina et al. (2020)
	Blueberry Juice Quality	Cold plasma jet	Cold Plasma Jet, 1000 Hz, 2, 4 and 6 min, Argon (Ar) and Oxygen (O2) 11 kV 1.0 l	The increase in treatment duration and O_2 concentration resulted in a considerable increase in Bacillus death. CP treatment considerably boosted the concentration of phenolics as compared to heat treatment, and it also helped blueberry juice retain its natural hue	Hou et al. (2019)

the underlying process. It was shown that it would be beneficial to use molecular docking simulations to examine the activity of significant reactive species on food enzymes, their molecular level interaction, also the consequences of the food matrix environment (Attri et al., 2015; Ali et al., 2016).

Cold plasma for toxin and pesticide degradation

Food toxic chemicals may be naturally present in certain foods, including goitrogens, inhibitors, saponins, trypsin, and lectins. Also, toxins like mycotoxins, endocrine disruptors, and pesticides are also found in various food and water systems, presenting a major danger to consumer health and safety. Now, only a few nonthermal techniques are available to break down dangerous components contained in food, among which cold plasma has shown promise. Pesticide residues on vegetables are efficiently removed or reduced using the cold plasma procedure (Pandiselvam et al., 2022; Sarangapani et al., 2016). Since the chemical bonds of particular food contaminants are being attacked, research on pesticides on abiotic surfaces has shown that both ROS and RNS play a significant role in the breakdown of pesticides. The effectiveness of disintegration depends on reactive species concentrations, which are regulated by plasma production type. Cold plasma breakdown of mycotoxin and pesticides is a crucial research concern for food scientists, and the bulk of current research is focused on this area. Mycotoxin's susceptibility to heat processing has stimulated much research into other processing techniques. Cold plasma significantly destroys mycotoxin in numerous foods (Ten Bosch et al., 2016; Siciliano et al., 2016). Pesticides are mainly employed in agriculture to reduce crop losses brought on by insects, but many of them are also hazardous to humans. Various foods have been successfully cleaned of pesticide residues using the cold plasma method (Bai et al., 2009; Misra et al., 2014a; 2014b; Sarangapani et al., 2017a; 2017b; 2017c; Misra, 2015). Exposure duration (30, 60, 90, 120 s), distance (0, 20, 40, 60, 80 cm), discharge power (30, 60, 90, 120 w) from the center of the induction coil, and levels of organophosphorus pesticides all have an impact on efficiency degradation. It has been demonstrated that insecticides containing organophosphorus degrade into less harmful chemicals than the original pesticide molecule. Employing an in-package high voltage DBD plasma reactor, Sarangapani et al. (2017a; 2017b; 2017c) investigated the efficiency of cold plasma for pesticide breakdown on blueberries (e.g., boscalid and imidacloprid).

Effect of cold plasma on physiochemical properties of food

A variety of parameters influence fresh-cut food quality, including appearance, texture, flavour, and nutritional value (Pankaj et al., 2018). Consumers judge fresh fruit and vegetables on their look and freshness. Food products were exposed to a powerful electric field as well as a variety of reactive gas species during the cold plasma process. Owing to the presence of reactive species, cold plasma could interact with almost all food components, changing the physicochemical properties (such as glucose, pH, vitamins, respiration rate, and anthocyanin) as well as organoleptic (such as taste, color, and texture) characteristics of different fresh horticulture produce (Pankaj et al., 2018; Muhammad et al., 2018). Therefore, it is crucial to research how cold plasma affects quality aspects. The impact of cold plasma on several food product qualities is summarised in Table 3.

Effect of cold plasma treatment on color

Food color significantly affects how consumers perceive products and, as a result, how effective they are. Pigments (natural or artificial) or chemical reactions are the primary causes of food color (non-enzymatic or enzymatic). Any unfavorable color alteration in food items as a consequence of processing would be a prime hindrance to adoption. Depending on the degree of the treatment, cold plasma treatments have been shown to have varying impacts on the color of fresh fruits and vegetables. Applying cold plasma to strawberries, kiwifruit, apples, cherry tomatoes, lettuce, and carrots resulted in no appreciable color loss (Bermdez-Aguirre et al., 2016; Misra et al., 2014a; 2014b; Niemira, 2008; Ramazzina et al., 2015; Ziuzina et al., 2016). Several studies observed mild color changes after Cold plasma treatments (Wang et al., 2012; Misra et al., 2014a; 2014b). In other experiments, such as blueberry, longer treatment durations resulted in a color loss (Lacombe et al., 2015; Sarangapani et al., 2017a; 2017b; 2017c).

Similarly, following Cold Plasma processing, the overall color changes in fruit juices were found to be minimal and undetectable to the naked eye (Xu et al., 2017; Kovacevic et al., 2016). Saffron quality was similarly reduced after enhanced input voltage and also by adding oxygen into the working environment, according to Amini et al. (2017). According to some research, color changes might be because of the partial disintegration of pigments, including anthocyanin or chlorophyll. Overall, our findings suggest that cold plasma processing has little influence on food color at shorter treatment durations. The product type (solid or liquid or whole or cut), plasma processing parameters (power, time, working gas, input voltage), and storage conditions all impact the color. Cold Plasma technique has also been shown to provide appealing color effects in many food goods. Thirumdas et al. (2016) observed that plasma treatment increased brown rice's brightness and also whiteness index. Yong et al. (2017) utilized cold plasma to create pig jerky without

Table 3 Effect of cold plasma processing on quality parameters of food products

Sample	Plasma generation source	Quality observation	References
Orange juice	Dielectric barrier discharge	• No significant change in Brix or pH • Vit.C is reduced by 22% in air • PME activity reduced by 74% in air and 82% in MA65 • Maximum total color difference is less than 1.2	Xu et al. (2017)
White grape juice	Dielectric barrier discharge	• No significant change in pH, acidity and electrical conductivity of the juice • An increase in non-enzymatic browning with minimal total color difference • Decrease in total phenolics, total flavonoids, DPPH free radicals scavenging and antioxidant capacity • An increase in total flavonols content	Pankaj et al. (2017)
Prebiotic orange juice	Dielectric barrier discharge	• Degradation of oligosaccharides in the juice • Decrease in pH • Increase in L* value and slight reduction in chroma and hue angle • Decrease in total phenolic content and antioxidant capacity in some cases	Almeida et al. (2015)
Pomegranate juice	Plasma jet	• Increase in total anthocyanin content • No visual differences in color	Kovaˇcevi´c et al. (2016)
Cashew apple juice	PE	• Decrease in vitamin C at higher flow rate • Increase in sucrose content while glucose and fructose contents decreased • Longer treatment promoted higher polyhphenol and total flavonoid content	Rodríguez et al. (2017)
Strawberry	Dielectric Barrier Discharge	• Strawberries in high oxygen mixture showed higher firmness with similar respiration rates • Some changes L* and a* values were observed	Misra et al. (2014a, b)
Blueberry	Dielectric Barrier Discharge	• Decrease in firmness, total phenol, flavonoid and anthocyanin on extended cold plasma treatment at the higher voltage level • Significant increase in total soluble solid • No significant change in acidity and color (except fruit darkening at 80 kv for 5 min)	Sarangapani et al. (2017a, b, c)
Radish sprouts	Microwave plasma	• No change in color, water activity, ascorbic acid concentration and antioxidant activity • Lower moisture content during storage	Oh et al. (2017)
Golden delicious apples	Gliding arc plasma	• No changes in color and texture	Niemira (2008)
Kiwifruit	Dielectric barrier discharge	• Improved color retention and reduced darkened area formation during storage • No significant changes in color, hardness, vitamin C and antioxidant activity • Longer treatment increase soluble solid content • 15% decrease in chlorophyll a on day 0 with no difference on day 4	Ramazzina et al. (2015)
Melon	Dielectric Barrier Discharge	• No change in acidity, soluble solid content, dry matter, color and texture • 17% and 7% reduction in peroxidase and PME activities respectively	Ramazzina et al. (2016)
Fresh fruit and vegetable slices (pears, cucumbers and carrots)	Plasma micro-jet	• Less than 5% moisture loss in all three samples after 8 min treatment • Minimal change in total color difference • 3.6%, 3.2% and 2.8% reduction of vitamin C in cucumber, carrot and pear slice, respectively	Wang et al. (2012)
Cherry tomatoes	Dielectric Barrier Discharge	• No significant difference in color, firmness, pH or total soluble solids	Ramazzina et al. (2016)

the addition of sodium nitrite in another trial. They were able to create a comparable redness/color in the pork jerky without utilizing any artificial nitrite additives by employing certain plasma processing conditions.

Effect of cold plasma treatment on texture

Food products retain their texture after being processed with CP. There was no significant difference in fresh fruits and vegetables after CP processing of strawberries, melons, apples, and also cherry tomatoes (Misra et al., 2014a; 2014b; Niemira et al., 2008; Tappi et al., 2016; Ziuzina et al., 2016; Ziuzina et al., 2016). However, Sarangapani et al. (2017a; 2017b; 2017c) and Lacombe et al. (2017) found a reduction in firmness following CP processing of blueberries (2015). The blueberry softening was connected to mechanical damage induced by the plasma jet's high air-flow rates and the temperature increase throughout the processing. A study on CP processing of strawberries in modified atmospheric packaging found that an environment with high oxygen content (65% $O_2 + 16\% N_2 + 19\% CO_2$) retained firmness better than an environment rich with nitrogen (90% $N_2 + 10\% O_2$) (Misra et al., 2014a; 2014b). According to this study, plasma gas substantially influences the hardness of treated goods. Texture retention is enhanced in elevated oxygen conditions & also ozone processing has also been demonstrated in studies (Wszelaki et al., 2000; Runguang, 2011). It is hypothesized that better firmness retention is due to a slowed rate of ripening as a stress response to the high oxygen environment. Grain, legume hardness, and chewiness were decreased following CP treatment (Sarangapani et al., 2016). These firms also indicated that the plasma-treated goods required less time to soak/cook. According to Misra et al. (2015), the elastic modulus, peak integral, viscous modulus, as well as dough strength all rose. They also investigated the influence of CP on the secondary structure of flour protein. These investigations illustrate the capability of CP technique for tailor-made visco-elastic characteristics in processing food components.

Effect of cold plasma treatment on pH and acidity

The pH as well as acidity are qualities that are carefully controlled in the majority of processed foods. Any considerable change may adversely influence the flavour, texture, and shelf stability of the item. On the other hand, fresh fruits and vegetables have significant variances owing to changes in production processes, varietal differences, ambient circumstances, and other variables. Several research has shown that CP treatment affects the pH of food commodities (Lee et al., 2015; Almeida et al., 2015). The relationship of moisture with the plasma reactive gases in the meal was the primary source of the changes in pH and acidity following plasma treatment. Plasma species' interactions with surface water produced acidic components only on the surface of solid food commodities, but liquid food commodities impacts were more prominent. According to Oehmigen et al. (2010), the cause of acidification in air plasma treatments is the production of nitric acid by reactive nitrogen species like NO. Nevertheless, numerous studies discovered that CP treatments had no effect on the pH of food items with buffering capacity (Pankaj et al., 2017; Xu et al., 2017). These results imply that a variety of factors, like biological activity of living cells, buffering capacity, or the chances of liquid coming from wounded cells on the surface washing away acids, the impact plasma on the pH of complex food matrices (Misra, 2016).

Effect of cold plasma treatment on protein and enzymes

Numerous researchers have analyzed the impact of CP treatment on proteins as well as enzymes in the food matrix (Misra et al., 2016). The impact of CP on important dietary enzymes is shown in Table 4. According to Li et al. (2014), protein denaturation by CP may be produced by plasma reactive species interacting with amino acids, as well as secondary structure loss due to helix and sheet loss (Segat et al., 2016). The type of protein, kind of enzyme, plasma type, reactive gas, sample volume, processing parameters, or enzyme media all impact protein denaturation and enzyme inhibition by CP. According to Attri et al. (2015), although enzyme inactivation may be a beneficial tool for food processing, numerous challenges must be addressed, including improved processing conditions, a better knowledge of deactivation mechanisms, or the protective influence of various food compounds. Albertos et al. (2017) analyzed the impact of CP on muscle protein in fresh mackerel and discovered that it decreased immobilized water in the myofibrillar network. A study on wheat flour revealed that sulfhydryl groups, as well as the creation of disulfide bonds, undergo oxidation and change protein structure, influencing structural and functional characteristics.

Effect of cold plasma treatment on carbohydrates

Carbohydrates significantly influence the definition and preservation of the quality of various food products. All reducing sugars, including fructose, glucose, and non-reducing sucrose, were degraded by cold plasma processing of cashew apple juice (Rodriguez et al., 2017). They also demonstrated that the sucrose content increased after extended exposure to cold plasma, which they attributed to the breakdown of polymerized oligosaccharides. After CP

Table 4 Effect of plasma treatments on the enzymatic inactivity of fruits and vegetables

Product	Enzyme	Plasma generation source	Results	References
Mushrooms (*Agaricus bisporus*)	Superoxide dismutase	Plasma jet, 18 kV, 10 kHz, 98% Ar + 2% O_2, 5 L/min	SOD activity was higher in plasma treated mushroom during storage	Xu et al. (2017)
Fresh-cut apples	Polyphenol oxidase	Dielectric Barrier Discharge, 150 W, 15 + 15, 30 + 30 min, Air, 1.5 m/s	Noticeable reduction in superficial browning but not proportional to treatment time Variable effects on PPO activity Effect were strictly cultivar dependent	Tappi et al. (2016)
Fresh-cut melon	Pectin methylesterase	Dielectric Barrier Discharge, 15 kV, 12.5 kHz, 15 + 15, 30 + 30 min, Air	15 + 15 min treatment was ineffective Residual activity was 94% after 30 + 30 min treatment	Tappi et al. (2016)
Fresh-cut melon	Peroxidase	Dielectric Barrier Discharge, 15 kV, 12.5 kHz, 15 + 15, 30 + 30 min, Air	Residual activity were 91% and 82% after 15 + 15 and 30 + 30 min treatment, respectively	Tappi et al. (2016)
Fresh-cut apples	Polyphenol oxidase	Dielectric Barrier Discharge, 15 kV, 12.7 kHz, 10–30 min, Air, 1.5 m/s	Linear decrease in activity with treatment time. Residual activity of 88%, 68% and 42% after 10, 20 and 30 min of treatment	Tappi et al. (2014)

treatment of prebiotic orange juice, Almeida et al. (2015) observed a comparable enhancement in sucrose, reduction in fructose, and disintegration of oligosaccharides with an elevated level of polymerization. The primary mode of degradation, according to the research, is ozonolysis, which results in the breaking of glycoside linkages, depolymerization of the macromolecule, and also oxidation of functional groups to produce carbonyl as well as carboxyl components, hydroperoxides, lactones or CO_2 (Ben'ko et al., 2015; Almeida et al., 2015). The impact of CP treatment on polysaccharides in legumes and grains has received the greatest attention. The CP treatment improved the water absorption rate in black gram, which they ascribed to membrane etching and an elevation in water binding sites caused by plasma reactive species fragmentation of starch and protein. Thirumdas et al. (2016) discovered a decrease in brown rice boiling time, demonstrating the existence of polar functional groups amongst starch granules. They also observed that the level of gelatinization increased after plasma processing. In a study on rice starch, Thirumdas et al. (2016) discovered a reduction in pasting temperature, gelatinization temperature, amylose content, retrogradation propensity, and also the extent of hydrolysis. Altogether, CP treatment caused starch depolymerization and cross-linking, influencing its functional, structural, as well as rheological properties.

Effect of cold plasma treatment on vitamins

Vitamin sensitivity to various processing techniques is essential for food products to keep their nutritional properties. While certain vitamins, including pyridoxine (B6), riboflavin (B2), or biotin, were relatively stable, others, like vitamins A, C, and E, & such also thiamin (B1), were not (Dionisio et al., 2009). Most research on CP processing of food commodities has primarily focussed on vitamin C stability (ascorbic acid). Numerous research on the CP processing of raw fruits and vegetables discovered no substantial change in the amount of ascorbic acid following plasma treatment. There was no substantial impact on ascorbic acid in lettuce, kiwifruit, and also radish sprouts (Ramazzina et al., 2015; Oh et al., 2017; Song et al., 2015).

When applied to plasma, ascorbic acid does not considerably deteriorate; only negligible losses have been documented. The vitamin C content of fresh fruits and fruit juices, on the other hand, has been found to significantly increase according to some research. The voltage and length of plasma exposure are the two key factors that determine how well plasma affects vitamin C. Larger voltages (80 kV) might boost the amount of vitamin C, but only when used for a brief duration (5 min). Even after extended exposure times, lowering the applied voltage (20–25 kV) seems to improve the amount of vitamin C (15–30 min). Few studies have examined the effects of cold plasma on vitamins A, B, D, and K, and the underlying mechanisms remain a mystery. Pro-vitamin A content was raised by glow discharge plasma application at low fluences (time × plasma flow). At larger fluences, however, degradation of this pro-vitamin was seen. B3 and B6 levels have reportedly increased, however at higher fluences no degradation was seen (Fernandes and Rodrigues, 2021).

Additionally, after the plasma processing of chopped fruits and vegetables, the amount of ascorbic acid dropped by 4% (Wang et al., 2012). Ascorbic acid levels in orange juice & Cashew apple juice decreased after CP treatment (Xu et al., 2017; Rodriguez et al., 2017). Ascorbic acid degradation during processing might be ascribed to interactions with ozone as well as other oxidizing plasma species. The degradation of ascorbic acid was regulated by the type of sample (whole/cut), manufacturing period, and plasma gas. However, a study on the impact of CP on various vitamins in dietary goods and the disintegration process is necessary.

Effect of cold plasma treatment on lipids

For muscle foods, lipid oxidation is a serious problem since it can cause unwanted changes in colour, taste, odour, and shelf life. Ladikos et al. (1990) describe the oxidation of lipids as a complicated procedure, including free radical chain processes that produce fatty acyl peroxides or other oxidation products. The thiobarbituric acid reactive compounds (TBARS) and peroxide value (PV) are widely used to evaluate lipid oxidation. Because CP is frequently seen as a sophisticated oxidation method, it is critical to investigate its impact on the lipids found in muscle meals. Choi et al. (2016) found no substantial impact on lipid oxidation following CP processing in fresh and frozen pork, beef jerky (Kim et al., 2014), and raw pork (Ulbin-Figlewicz et al., 2016). However, after treating fresh pork and beef for 10 min an improvement in the oxidation of lipids was observed (Jayasena et al., 2015). When pork loin was exposed to plasma gas containing oxygen-, it enhanced lipid oxidation. CP treatment significantly increased lipid oxidation in fresh mackerel strips, according to research by Albertos et al. (2017). They observed a rise in Peroxide Value from 6.89 to 37.57 meq, active oxygen/kg lipids, and dienes from 1.42 to 5.56 mmol of hydroperoxides/kg lipids after plasma processing at 80 kV for 5 min. They discovered that oleic acid (C18:1, n-9) or eicosapentaenoic acid (C20:5, n-3) levels decreased following plasma processing. Sarangapani et al. (2017a; 2017b; 2017c) show cold plasma lipid oxidation to adhere to the Criegee process. In beef fat and dairy matrices, they also identified aldehydes (hexanal, pentenal, ozonides, nonanal, or nonenal), carboxylic acids (nonanoic acid, 9-oxononanoic acid, octanoic acid), and hydroperoxides (9- and 13-hydrperoxy-octadecadienoylglycerol species). The number of research on the impact of CP on lipids in various foods is quite low. According to the findings, treatment duration and plasma gas might be key elements impacting lipids' oxidation. Yepez and Keener (2016) found a unique CP therapeutic function. They demonstrated that hydrogen plasma might be utilized to make partly hydrogenated soybean oil with no generation of trans-fatty acids. CP techniques have demonstrated distinct benefits over conventional hydrogenation procedures in that it may be carried out at ambient temperature and at atmospheric pressure without the need of a catalyst. Although this method shows promise as a substitute for standard catalytic hydrogenation, more study is required to improve the treatment process as well as assess the performance of partly hydrogenated oil generated from CP.

Effect of cold plasma treatment on antioxidant

Antioxidant activity is a near indication of different flavonoids, polyphenols, and flavanols contained in food items, even though it is related to quality features employed in the food industry. The redox properties of phenolic compounds, such as their ability to absorb singlet oxygen and chelate transition metals, may be responsible for their antioxidant advantages (Shan et al., 2005). The oxygen radical absorbance capacity (ORAC), 3-ethyl-benzothiazoline-6-sulfonic acid (ABTS) radical scavenging activity, ferric reducing ability of plasma (FRAP) assay or 2,2-diphenyl-1-picrylhydrazyl (DPPH) scavenging activity are frequently used to assess the antioxidant activity of food. A wide range of outcomes has been recorded for the influence of CP treatment on the total phenolic content of food items. Lamb's lettuce, white grape juice, and orange juice all demonstrated a decrease in total phenols (Almeida et al., 2015; Pankaj et al., 2017; Grzegorzewski et al., 2017). According to Rodriguez et al. (2017) and Sarangapani et al. (2016), there was a considerable increase in cashew apple juice with blueberries, whereas Ramazzina et al. (2016) found no discernible impact on apples. These differences across the published studies suggest that more study is required to comprehend the molecular effects of CP on polyphenols. After CP treatment, no discernible changes in the antioxidant capability of radish sprouts, kiwifruits, or red chicory were observed (Oh et al., 2017; Ramazzina et al., 2015; Pasquali et al., 2016; Kim et al., 2017). Following CP treatments, various studies have discovered a decline in the antioxidant ability of white grape juice, apples, or cashew apple juice after prolonged exposure (Pankaj et al., 2017; Rodrguez et al., 2017). According to Almeida et al. (2015), whereas indirect mode treatment showed no appreciable effects, direct mode plasma treatment decreased the antioxidant capability of prebiotic orange juice. These studies show that CP's effects on food antioxidant activity depend on a variety of factors, including the type of food items, exposure method, plasma production source, or process parameters.

Cold plasma is a nonthermal, innovative method that showed promise in food decontamination. The discrepancies between the studies that have been described demonstrate the necessity of mechanistic research to comprehend the interactions between plasma reactive species and dietary components. Studies on optimization are also required to reduce quality-harming consequences, including quick lipid oxidation, vitamin loss, and sensory properties. Complete knowledge of the mechanics or strict control of quality attributes would be necessary for cold plasma technology to realize its full capability on a commercial basis.

Challenges of cold plasma treatment in food processing

Every food processing procedure must assure food safety. Cold plasma's toxicological impacts on food as well as packaging materials, have been investigated. However, a lot of ROS were produced by the cold plasma, with ozone being the main antibacterial ROS. The US Food and Drug Administration (US-FDA) has enacted specific rules and regulations to limit the quantity of ozone in plasma; however, no comparable laws exist for the other ROS detected in cold plasma (Sarangapani et al., 2018). Additionally, the toxicological impact of cold plasma on the edible layer in male and female Sprague–Dawley rats was examined, and it was determined to have a negligible impact (Han et al., 2016). When employed under typical working circumstances, cold plasma is frequently safe. Before being used in industrial settings, each functioning system and the food it produces may also be thoroughly inspected for any potentially dangerous components.

Globally, emerging technology has a wide range of regulatory ramifications. The use of cold plasma in food commodities and food packaging in the US has been approved by the Food and Drug Administration (FDA), the Environmental Protection Agency (EPA), and the United States Department of Agriculture (USDA). The use of atmospheric cold plasma to cure the harshest process conditions constantly without harming individuals, the economy, the environment, or society is sufficient, according to the Federal Food, Drug, and Cosmetic Act 408. Additionally, the USDA–FSIS may approve any future uses of atmospheric cold plasma for poultry, beef, or eggs (USDA-Food Safety Inspection Service). As long as novel foods do not pose health hazards, have negative nutritional consequences, or deceive customers, they should be allowed. The European Food Safety Authority's specialist scientific team collects the necessary information (EFSA). Only new foods that have been given marketing approval by the EFSA are allowed.

Learning about reactive plasma species and their purification procedures is the only way to meet the many challenges that may be transformed into opportunities in the use of cold plasma. Color is such an important aspect of food and drink consumption that researchers struggle to keep it after cold plasma treatment. The cold plasma source for industrial applications must be developed, put together, and installed without disrupting the ongoing production process. A lower sample size or volume is required for laboratory work. Processing demands, however, are actually rather substantial. Therefore, substantial volumetric scale-up is required for continuous and trouble-free operation. Maintaining plasma homogeneity is essential throughout scale-up, which includes creating a plasma source that can provide the plant with the necessary capacity.

Future research ideas on the use of cold plasma in food processing

This nonthermal processing technique, which makes use of a variety of gas mixtures, has a lot of potential and is unique in that it significantly reduces microbial growth and enzyme activity while also changing the barrier properties or giving packing materials specialised functionality. Furthermore, there were no or modest impacts on the physicochemical (pH or acidity, anthocyanidin, respiration, and rate vitamins) as well as organoleptic (color, taste, or texture) quality features of the treated produce. Despite these recent advancements, there are still research gaps in the areas of removing allergens or antinutritional elements from raw produce, enhancing mass transfer and structure–property modification, estimating the risk of potentially toxic byproducts, and preventing packaging-related deposition components from migrating to fresh produce. Due to the complexity of plasma and interaction systems, it is difficult and inconsistent to determine the specific mechanisms driving reactive species interactions with their intended targets, and the majority of findings are based on assumptions. Perhaps in the future, cold plasma will be combined with other interventional therapies (such as chitosan). The main challenges or potential for atmospheric CP as a useful food processing technique are effective process control, regulatory approval, and validation to promote consumer acceptance. In the near future, a lot more study with an emphasis on widespread applications will be needed.

Due to its potential role in nonthermal food processing, CP treatment of food products has attracted attention during the past 10 years. There have been many tests on established uses, while others have looked at novel methods to use nonthermal plasma in the food industry. Given the foregoing, it is conceivable to conclude that CP technology has a place in the food industry. Protein isolates and films can be physically altered using CP, a practical nonthermal approach. Improved solubility, emulsification, and decreased allergenicity are just a few benefits of CP. Plasma has the power to alter the quaternary, primary, secondary, and tertiary architectures of enzymes. One major drawback of using CP is the potential loss of protein thermal stability. Although this problem might be solved by chemically altering proteins, industrial-scale plasma treatment still raises safety concerns.

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Declarations

Conflict of interest The authors have no conflicts of interest to declare.

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