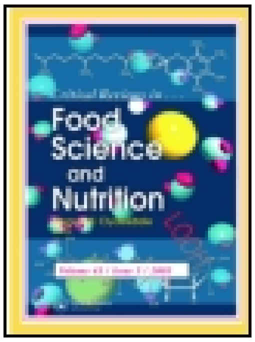

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Modification and improvement of biodegradable packaging films by cold plasma; a critical review

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ABSTRACT
Cold plasma is one of the techniques used in recent years to improve the functionality and interfacial attributes of biopolymers. Employing cold plasma for the treatment and modification of biopolymers possesses several advantages including its biocompatibility, elimination of toxic solvents usage, treatment consistency, and appropriateness for heat-sensitive ingredients. Most studies have presented the efficacious use of cold plasma treatment in improving structural, mechanical and thermal properties of film composites. In addition, cold plasma improves the film surface characteristics, particularly in protein-based films, through bringing up the polar functional groups onto the bio-composite surface, consequently increasing roughness, improving printability, increasing adhesion, and reducing contact angle; while it is not effective in the improvement of water vapor permeability of edible films. Cold plasma-treated edible packaging films experienced significant improvement where exposed to microbial contaminations, mainly due to the non-thermal nature of cold plasma technology leading to the protection of antimicrobial potency of bioactive compounds and antimicrobial constitutes. Therefore, it can be concluded that cold plasma treatment is an innovative strategy to strengthen the edible film characteristics as a promising alternative to the currently used chemical and physical modification approaches.

KEYWORDS
Cold plasma; biopolymers; biodegradable films; modification

Introduction

Packaging as a physical coating protects food products against physical, chemical and external microbiological agents (Zhang et al. 2020). Choosing the right packaging materials to increase the durability, and maintain the product quality and safety over the transportation and storage conditions is very important and critical in the food industry (Vahedikia et al. 2019; Bahrami et al. 2020). The four typical raw materials used in the packaging industry are paper, glass, metal, and plastic. Generally, plastics derived from petroleum derivatives have been widely used in food packaging due to their flexibility, low cost, low weight, heat sealing capability, and high mechanical strength (Pankaj and Thomas 2016; Pilevar et al. 2019).

The environmental challenges caused by the employing the synthetic polymers are basically owing to their non-degradable nature, damage to the ecosystem, global warming issues, and declining fossil resources, drawn the public attention to develop the bio-based materials like biodegradable films and coatings (Lee, Son, and Hong 2008; Mirzaei-Mohkam et al. 2020). Recent efforts have been increasingly made to use the biodegradable polymers derived from renewable sources, including polysaccharides, proteins, and lipids, as promising raw materials to fabricate edible films for food packaging applications (Jafarzadeh et al. 2020; Mohamed, El-Sakhawy, and El-Sakhawy 2020).

In general, edible films have a number of advantages such as inherent degradability, affordability, recyclability and availability through crops processing (Beikzadeh et al. 2020; Pankaj et al. 2015c). The technological application of natural polymer-based films has been restricted due to their inherent disadvantages such as poor mechanical and barrier properties, high water sensitivity (in case of protein and polysaccharide-based films), low surface functionality, poor printability, and adhesiveness (Heidemann et al. 2019; Pankaj and Thomas 2016; Romani et al. 2019b). Therefore, the use of different treatments is needed to improve their characteristics (Dehnad et al. 2014; Sharma, Jafari, and Sharma 2020).

There are several techniques to improve these features and modify polymer surfaces, including the use of cross-linkers, nanoparticles, ultraviolet irradiation, gamma rays, ion beams, laser treatment, plasticizers, flame treatment, mixing with other biopolymers, and plasma treatment

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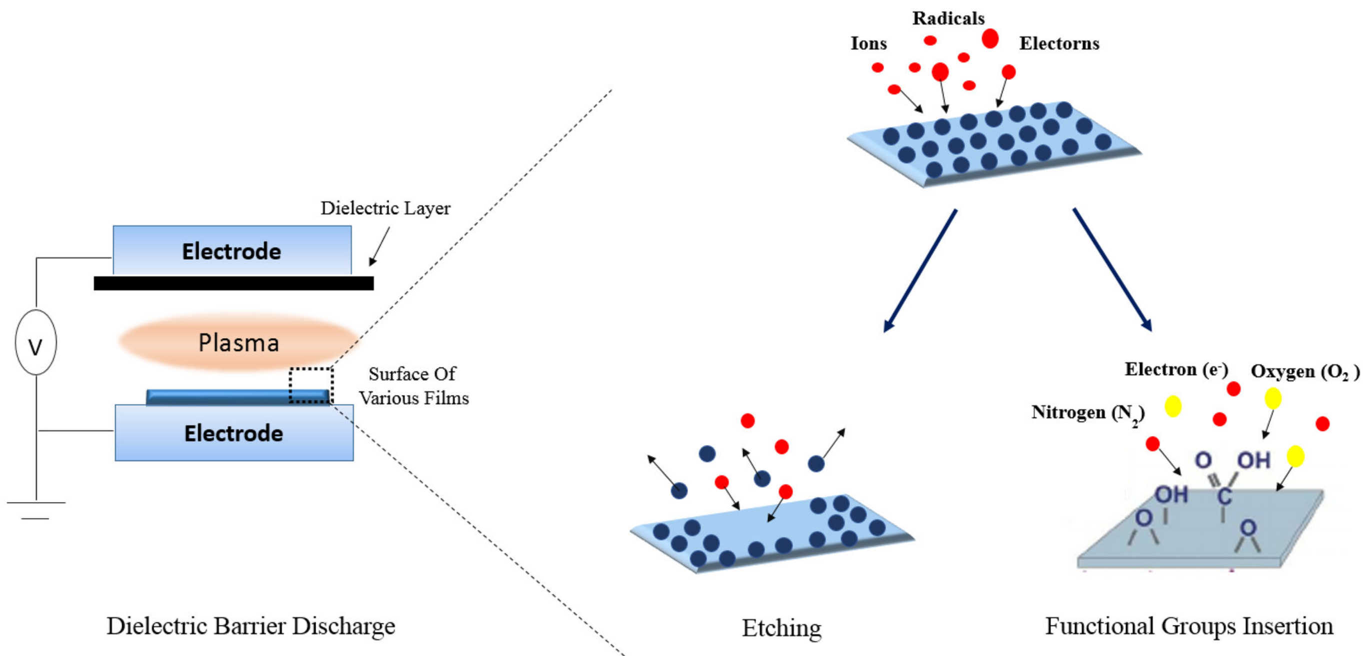

Figure 1. The main effects of cold plasma treatment on the surface of biopolymers.

(Kariminejad et al. 2018; Taghizadeh et al. 2018; Hashemi Tabatabaei et al. 2018; Hoseinnejad, Jafari, and Katouzian 2018; Joz Majidi et al. 2019; Sharma, Jafari, and Sharma 2020; Song et al. 2016). Studies have shown that cold plasma treatment (CPT) is effective on the physical, chemical, structural, thermal and antimicrobial properties of the obtained films (Misra et al. 2014; Pankaj et al. 2014c; Patil et al. 2014). Several investigations have been recently conducted on the changes in edible film properties as affected by CPT maintaining quality and increasing the shelf life of food products and also modifying the polymeric surface properties (Chen, Cheng, et al. 2020; Mir et al. 2020).

The term cold plasma (non-thermal plasma) refers to a type of partially or completely ionized gas which is basically generated by the action of negative and positive ions, electrons, molecules, atoms and free radicals in both excited or basic states, turning out to be an effective treatment with a wide array of applications in various industries. These generated hyper active constitutes are able to cleave the covalent bonds and generate various chemical reactions on any of the exposed surfaces (Kim, Lee, and Min 2014). The balance of reactions resulting from CPT can be modified by setting parameters such as the applied pressure, energy source/power, type and shape of electrodes, processing parameters, and the applied gas composition. In most cases, air, oxygen (O_2), helium (He), argon (Ar), and nitrogen (N_2) are applied to modify the surface attributes of various polymers (Song et al. 2016).

The cold plasma is a biocompatible, chemical-free, dry, and low-cost technology suitable for heat-sensitive materials, which is easy to generate and control (Honarvar et al. 2017). Accordingly, it can be considered a promising strategy to improve the critical characteristics of biopolymers. Therefore, the main core of the current study is to review the influences of CPT as a novel approach on the physicochemical, thermal, structural, and antimicrobial attributes of edible films. The review also identifies research gaps and lays direction for future research work in this area.

The production of plasma

The plasma terminology is recognized as the forth state of materials and refers to the ionized gases (Gavahian and Khaneghah 2020; Gavahian and Cullen 2020). Plasma is basically consisted of a series of highly reactive species such as free radicals, molecules, atoms, electrons, and ions, either in the excited or the basic states, possessing a pure neutral charge (Moradi et al. 2020; Pankaj 2015). The plasma can be formed by various processing temperatures and pressures, hence classified into thermal and non-thermal plasma, respectively, depending on the relative energy levels in electrons and heavy species of plasma. The thermal plasma requires a high pressure and power supply (pressures $>$ 105 Pa and power $>$ 50 MV), in which the main characteristic is the thermodynamic balanced among all generated species (i.e. electrons and heavy species) (Scholtz et al. 2015); while the non-thermal one so-called cold plasma is not able to provide an indigenous thermodynamic equilibrium (Chen, Cheng, et al. 2020; Pan et al. 2020).

Plasma can be generated by any energy source capable of ionizing the gases and producing the reactive species. Different energy sources including electric and electromagnetic fields, thermal, optical (UV), radioactive, electrical and X-ray can be employed to produce cold plasma (Ekezie, Sun, and Cheng 2017). From the practical point of view, the dielectric barrier discharge (DBD), which is created by the action of two parallel electrodes, is known as the frequently used plasma source for food industry applications (Pankaj, Wan, and Keener 2018), as shown in Figure 1. This technology is able to provide a significant adaptability for various applications due to its function and configuration. In addition, it is able to produce large volumes of cold plasma at ambient pressure (Heidemann et al. 2019; Pankaj et al. 2015b). The DBD device is mainly consisted of two counterpart metal electrodes, in which at least one of them is enclosed by a dielectric barrier (Pankaj, Wan, and Keener 2018). It has been stated that various factors such as plasma source, voltage, pressure, electrode design and distance, treatment time and type of reactive gas have a significant impact on the type and concentration of produced reactive species, although there are some challenges among researchers in terms of the interpretation and comparison of the experimental findings obtained by cold plasma implementation.

Changes in different attributes of edible films as treated by cold plasma

Surface attributes

Increasing the biopolymer surface roughness is one of the main post-CPT physical changes occurred as a result of etching effect phenomenon after bombarding the film surface by high energy plasma species including ions, atoms, molecules, free radicals and other excited particles. In fact, the energy transferred from the plasma onto the surface of biopolymers causes two main events (Figure 1): (i) elimination or re-aggregation of small particles with low molecular weight, presenting the physical etching arisen by the bombardment of high energy particles, and (ii) cleavage of chemical bonds, chains, and chemical degradation, demonstrating the chemical etching that occurs under the influence of plasma radicals (Akishev et al. 2008; Pankaj et al. 2017a; Pankaj and Thomas 2016). The etching effect is observed in different types of plasma sources (e.g. DBD, radio frequency, and microwave) and different employed gases (e.g. CO_2, N_2, O_2, Ar, and air), but the etching degree is strongly depending on the energy content of the obtained high-energy particles, plasma power, and uniformity of the exposed energy.

In general, the etching effect showed many applications in the packaging industry; for instance, it can control the diffusion coefficient of the reactive ingredients throughout the packaging film matrix. Pankaj et al. (2017a) noted that the thymol diffusion coefficient was increased after CPT of chitosan-based antimicrobial packaging films containing different levels of thymol (Pankaj et al. 2017a). Another effect of the increased surface roughness caused by CPT is the increased surface adhesion. For example, the adhesion of the two carboxymethyl cellulose (CMC) and polypropylene (PP) bilayer films was increased as a result of CPT, specifying the less use of synthetic polymers and possibility of higher biopolymer incorporation (Honarvar et al. 2017). Song et al. (2016) examined the key surface features of polylactic acid (PLA) films treated with cold oxygen plasma and reported that ink printability and adhesion were increased with elevated surface roughness by the CPT (Song et al. 2016).

Many other studies have shown that the film surface roughness increased after CPT, including the films made with gelatin (Pankaj et al. 2015b), corn starch (Santos et al. 2012), wheat starch (Sheikhi et al. 2020), rice, potato and tapioca starch (Pankaj et al. 2017c), chitosan (Pankaj 2015), corn zein (Dong et al. 2018), fish protein (Romani et al. 2019b), whey protein (Moosavi et al. 2020), sodium caseinate (Pankaj et al. 2014b), and soy (Oh, Roh, and Min 2016). The only case in which plasma has reduced the surface roughness is in the gluten film, that has been attributed to the shadowing effects of the employed film (Moosavi et al. 2020). According to the literature, the improvement in surface roughness is largely affected by the increase in plasma power (voltage) and exposure time. However it seems that the latter is more efficient, as the surface roughness of the plasma-treated chitosan and gelatin films didn't experienced any considerable changes once various voltages (powers) applied (Pankaj 2015).

Water vapor permeability (WVP)

Barrier properties are critical factors in the selection of packaging materials, as they determine the durability of the packaging material (Dong et al. 2018; Leroux et al. 2008). In general, packaging biopolymer films have a higher WVP than those reported for the typical petroleum-based films. Employment of modifications approaches in which the WVP is improved or at least doesn't change considerably, is very important to develop the usage of biopolymers for food packaging applications (Mirzaei-Mohkam et al. 2019; Pankaj and Thomas 2016).

The changes in WVP of CPT exposed edible films are summarized in Table 1. As shown, CPT was effective in improvement of WVP, while in most cases no significant changes or even drop in WVP was observed. As reported by Dong et al. (2018) the atmospheric cold plasma reduced the WVP values of all film samples, so that the WVP of plasma treated zein film (15 s exposure time) was 24.5% lower than that recorded for control sample (Dong et al. 2018). Comparable findings were also stated for plasma treated zein-chitosan blend composites (Chen et al. 2019). In another study, the efficacy of atmospheric CPT to improve the adhesion properties of multilayer starch-PLA and starch-polycaprolactone (PCL) films was investigated. The results showed that the cold plasma could fabricate multilayer films with suitable surface adhesion, and the water vapor barrier of the plasma treated multilayer films improved significantly; the WVP of the constructed composite films was 94% lower than the pure starch film (Heidemann et al. 2019). In general, CPT increases the curvature of the permeation pathway by creating cross-linking in flexible films, making it more difficult to migrate and permeate water, gases, and other small molecules, thereby reducing WVP (Chen et al. 2019).

Previous studies found no direct relationship between treatment power and time with WVP reduction; however, more interesting results have been obtained in studies where these two factors have been optimized simultaneously. For example, Oh, Roh, and Min (2016) examined the plasma treatment on defatted soybean meal films and figured out that the optimization of treatment power and time using response surface models not only caused a 24.4% decrease in WVP of the films, but also increased their tensile strength and flexibility (Oh, Roh, and Min 2016). The literature review showed that CPT is ineffective on the WVP values when fabricating the edible films of gelatin (Pankaj et al. 2015a), corn starch (Pankaj et al. 2015b), chitosan (Ulbin-Figlewicz, Zimoch-Korzycka, and Jarmoluk 2014), sodium caseinate (Pankaj et al. 2014b), and gluten-whey protein (Moosavi et al. 2020). This may be because of the fact that most of the changes caused by cold plasma are surface changes in hydrophilic groups and polymeric morphological features, while the WVP changes in edible films are mainly associated to the thermodynamic properties, vapor pressure, and concentration slope on both sides of the film surface (Moosavi et al. 2020; Pankaj et al. 2015b).

Contact angle

Contact angle is an indicator of the tendency of a liquid droplet (usually water) to disseminate on the flattened surface of different materials, signifying the wettability and hydrophilicity of edible films (Dong et al. 2018). The hydrophilicity of each film is an important feature for selecting it for packaging; because in fact, as the wettability of a film increases, its packaging capacity increases for printing and coating (Chen et al. 2019). It can be said that in all the studies who have used O_2, air and Ar gas for CPT of the surface of edible films, the cold plasma caused a decline in contact angle value and thus increased their wettability. Actually, cold plasma produces reactive species and radicals on the film surface that react with atmosphere oxygen, amplifying the various polar groups such as -COOH, -OH, and C = O groups on the film surface (Figure 1). Increasing these polar groups causes an increment in total surface energy and polarity, and ultimately an increase in film surface hydrophilicity (Honarvar et al. 2017; Pandiyaraj et al. 2008). Results of contact angle changes as affected by CPT are summarized in Table 1.

The contact angle has decreased significantly after CPT of the edible films produced by chitosan (Chamchoi et al. 2018), zein (Dong et al. 2018; Dong et al. 2020), chitosan-zein (Chen et al. 2019), sodium caseinate (Pankaj et al. 2014b), whey protein (Moosavi et al. 2020), gelatin (Pankaj et al. 2015a) and starch biopolymers (Pankaj et al. 2015b). It should be noted that the decrease in contact angle has been amplified at higher plasma exposure time in chitosan, zein and chitosan-zein composite films. Bastos et al. (2009) scrutinized the impact of cold sulfur hexafluoride (SF6) plasma on the corn starch films at different exposure times. It was shown that the contact angle was increased after CPT and in fact, more hydrophobic groups were obtained on the superficial layer of films. The results revealed that the contact angle of starch films increased up to 130° when the CPT time increased from 300 to 900 s. The main reason for the increase in contact angle in this study was incorporation of fluoride on the film surface, introducing more hydrophobicity on the film surface (Bastos et al. 2009). Therefore, from the outcomes of the mentioned study, it can be concluded that the type of the applied gas is very effective in contact angle results, despite the importance of treatment time and power factors.

Mechanical attributes

The mechanical characteristics of edible films are also critical factors to protect food quality and integrity over the handling, transportation and storage. The most important mechanical attributes of films are tensile strength (TS), elastic modulus (EM), and elongation at break (EAB) (Chen et al. 2019; Mohammadi et al. 2018). When doing CPT of edible films, the reactions such as degradation, cross-linking, and etching occur within the film structure, which can affect their mechanical attributes (Garavand et al. 2017). The impact of CPT on the mechanical attributes of composite films depends on different factors such as the plasma treatment time, edible film structure, type of the bonds on the film surface, presence of cross-linkers, and the cold plasma source. The mechanical results of cold plasma treated edible films are presented in Table 1.

CPT could be considered as an effective factor to develop the crosslinking between biopolymer functional groups. The plasma ions formed on the film surface cause the cleavage of the C-H and C-C bonds. The fabricated free radicals during CPT can contribute to the chain reactions with the produced surface radicals, leading to a considerable enhancement in TS value of the edible films (Suzuki et al. 1986). In this regard, Dong et al. (2018) reported that the TS and EAB values of zein films were improved by employing the extended atmospheric CPT time, in which the TS and EAB values. Approximately 10 MPa and 0.6% enhancement in comparison with the control sample when bombarded for 45 s, respectively; while more treatment time (60 s) was ineffective in boosting the mechanical attributes. The increase in TS can be due to the induced transformation and the production of ozone molecules, both resulting in conversion of sulfhydryl groups (S-H) to disulfide (S-S) bonds and then formation of intermolecular and intramolecular interactions within the zein film structure (Dong et al. 2018). Such findings are in line with other studies on plasma treated whey protein and gluten films (Anderson and Lamsal 2011; Qiu et al. 2004).

Besides time, the type of cold plasma process is also effective in altering mechanical attributes of packaging films. As an example, Moosavi et al. (2020) examined the effect of argon and air CPT on the mechanical characteristics of whey protein and gluten edible films. The TS values of whey protein films treated with argon plasma were increased from 6.9 MPa in control sample to 9.383 MPa and 12.314 MPa with increasing the treatment time 5 min and 10 min, respectively; while further plasma treatment for 15 min caused a drop in TS value of films. The argon CPT for the gluten films showed a dissimilar pattern in case of increasing TS value by extending process time; in brief, the TS values of control film (1.85 MPa) reached to 3.938 MPa and 3.044 MPa after 5 and 10 min of argon CPT, respectively, and the TS value was decreased after 15 min of argon CPT. In contrary, the TS values were significantly increased in air

Table 1. Physico-mechanical properties of biopolymer films exposed to cold plasma treatment.

Type of film	Film composition	Plasma treatment conditions	TS (%)	EB (%)	WCA (%)	WVP (%)	References
Chitosan	Chitosan (1 %) + glycerol 25% + lactic acid 0.5% + lysozyme (0, 0.5, and 1 %)	Low-pressure plasma, prototype-pulsed plasma reactor, helium, final pressure 20 kPa, frequency 70 kHz , power 1.2 kVA, time 0.5 and 10 min	Decreased TS (34.42%) in 5 min	Decreased EB (39.57%) in 5 min	Not significant	Not significant	(Ulbin-Figlewicz, Zimoch-Korzycka, and Jarmoluk 2014)
Polylactic acid (PLA)	PLA film (96% L-lactide with 37% crystallinity)	SWU-2 CPT system, microwave generator (2.45 GHz), O2, pressure 667 Pa, power 900 W, 40 min	Decreased	Decreased	Increased (16%)	NA	(Song et al. 2016)
Polylactic acid (PLA)	PLA film (4032D, thickness: 40 μm) + 10 mg/mL Nisin	Homemade plasma system, radio frequency generator 400 kHz, pressure 100 Pa, power 300 W, time 0, 15, 30, 45, and 60 s	NA	NA	Decreased (35%) in 15 s, then increased	NA	(Hu et al. 2018)
Chitosan	Chitosan (1%) + 1% acetic acid + Hexamethyldisilazane plasma-treated	Cold-plasma discharge of Hexamethyldisilazane, O_2, two-parallel-plate reactor, power 60W; frequency 13.56 MHz, time 2 min	NA	NA	Increased (28%)	Not significant	(Assis and Hotchkiss 2007)
Cornstarch	Cornstarch (5% w/v) + glycerol (15% w/w) + sulfur hexafluoride (SF6) plasma-treated	Glow discharge reactor, 13.56 MHz, cathode self-bias voltages −20 to -240V, time 20 to 900s, optimal conditions 900 s and the self-bias higher than −100 V	NA	NA	Increased (62.5%)	NA	(Santos et al. 2012)
Cornstarch	Cornstarch (5% w/v) + glycerol (15% w/w) + sulfur hexafluoride (SF6) plasma-treated	Glow discharge reactor, 13.56MHz, cathode self-bias voltages -100V, time 300 to 900s, optimal time 900 s	NA	NA	Increased	NA	(Bastos et al. 2009)
Chitosan	Chitosan solution 2% (w/v) which prepared from Perna Viridis shell powders + 2% acetic acid	Atmospheric pressure plasma jets (APPJs), argon, generator's voltage and current 8000 Vrms ,500 mA, time 15-60 s, distance to the syringe nozzle 10 − 20 mm	NA	NA	Decreased (90.3%) in 60 s	NA	(Chamchoi et al. 2018)
Carboxymethyl cellulose-coated polypropylene (PP/CMC), bilayer	CMC (1% w/v) + glycerol (50% v/w) + Zataria multiflora essential oil (ZEO) 1–4% (v/v(+ plasma-treated PP films	Atmospheric plasma system, air, voltage 14 kV , frequency 20 kHz, time 2 min	Decreased	Decreased	Decreased (40%)	Decreased (34%)	(Honarvar et al. 2017)
Polycaprolactone -and poly(lactic acid) - starch (PCL-, PLA- starch), multilayer	3% Cassava starch solutions + 0.8% glycerol + plasma treatment of PCL and PLA films	Atmospheric air cold plasma, barrier dielectric discharge (DBD) reactor, frequency 50 Hz, voltage 31 kV, and 1, 5, 10, 15, and 20 min	NA	NA	Maximum reduction: PCL film (70%) in 15 min, PLA film (35%) in 10 min	Decreased (94%) in warter vapor permeation rate for both PCL and PLA	(Heidemann et al. 2019)
Zein	Zein (15%, w/v) + 80% (v/v) ethanol solution	Atmospheric cold plasma (ACP), DBD-50 plasma			Decreased (34%) in 60 s		(Dong et al. 2018)

(*continued*)

Table 1. Continued.

Type of film	Film composition	Plasma treatment conditions	TS (%)	EB (%)	WCA (%)	WVP (%)	References
		reactor, voltage (65 V), time 5, 15, 30, 45, and 60 s	Increased TS (37.04%) in 45 s	Increased EB (0.62%) in 45 s		Decreased (24.50%) in 15 s	
Corn starch	High amylose corn starch (3%, w/v) + 10 ml (0.25 M) sodium hydroxide + 0.1 ml glycerol	Dielectric barrier discharge plasma, atmospheric air, step-up transformer (230V, 50 Hz), voltage 70 and 80 kV, time 5 min.	NA	NA	Decreased (60%) in 70 kV	Not significant	(Pankaj et al. 2015b)
Fish protein films	Fish proteins (3%, w/v) + glycerol (30%, w/w)	Alternating current (AC) glow discharge plasma, dry air, The high voltage input (4.4 kV, 60 Hz), time 2 and 5 min	Increased TS (13.34%) in 5 min	Increased EB (48.42%) in 5 min	NA	Not significant in 5 min, Increased (17%) in 2 min	(Romani et al. 2019a)
Whey protein and gluten	Whey protein solution: 6 % whey protein + 3 ml glycerol/ 100 ml gluten film solution (10% w/v): 10 % of wheat gluten + 0.3 % sodium sulfite + 45 ml ethanol + 3 % glycerol	Low pressure glow discharge plasma, air and argon gases, power 50 kW, time 5, 10, and 15 min	Whey protein: Increased TS (50%) with air, Increased TS (29.02%) with argon Gluten: Increased TS (28.02%) with air, Increased TS (39.15%) with argon	Whey protein: Increased EB (45.9%) with air, Increased EB (51.1%) with argon Gluten: Decreased EB (4.24%) with air, Decreased EB (35.48%) with argon	Whey protein: Decreased (32%) with air, Decreased (27%) with argon Gluten: Not significant	Not significant for both whey protein and gluten	(Moosavi et al. 2020)
Sodium caseinate	Sodium caseinate (5% w/w) + glycerol (protein: plasticizer ratio of 1:0.35)	Atmospheric dielectric barrier discharge (DBD) plasma, step-up transformer) voltage 230 V, frequency 50 Hz(, atmospheric air, voltage 60 and 70 kV , time 5 min	NA	NA	NA	Not significant	(Pankaj et al. 2014b)
Defatted soybean meal (DSM)	DSM/glycerol (at a ratio of 10:3) + polysorbate-20 (1% [w/w DSM])	Low pressure microwave-powered CPT system, argon, microwave generator (2.45 GHz), time 15 min, power 400 W	Not significant	Not significant	Increased (39%)	Decreased (24.4%)	(Oh, Roh, and Min 2016)
Corn Starch	4 % normal (30% amylose) and high amylose (50 and 70% amylose) corn starches + 30% w/w glycerol	Hexamethyldisiloxane (HMDSO) cold plasma treatment, radio frequency (RF) power generator 13.56 MHz, time 30 min, power 70W	NA	NA	Increased about 30%	NA	(Sifuentes-Nieves et al. 2019)
Zein and zein-chitosan	0.128 % chitosan + 8 mL acetic acid (1% v/v) + 32 mL anhydrous ethanol + 3.2 % zein	Dielectric barrier discharge (DBD) cold plasma, air, treatment power 100 W for 60-90 s	Increased TS (28.92%)	Increased EB (3%)	Zein: Decreased 43.87% Zein-chitosan: Decreased 55.73%	Decreased	(Chen et al. 2019)

Note: TS, Tensile strength; EB, Elongation at break; WCA, water contact angle; WVP, Water vapor permeability; NA, Data not available;

CPT by employing higher treatment times in both types of films compared to argon CPT. The main reason is that when films are exposed to argon CPT, the ionic bombarding (i.e. physical bombardment) and the production of various active particles such as oxygen/nitrogen radicals within the polymer network, as well as their interactions (i.e. chemical bombardment) cause the formation of cross-links on the film surface, while some electronic energies are used to stimulate the vibration and rotation of the gas molecule during the formation of air cold plasma (Moosavi et al. 2020; Morent et al. 2008).

Chen et al. (2019) also examined the influence of atmospheric CPT on the mechanical attributes of chitosan-zein blend films at different process times. The results showed that the zein film alone had weak mechanical properties (1.13% EAB and 29.5 MPa TS), and the TS value was decreased from 29.5 to 23.5 MPa and the EAB value was increased from 1.13 to 3.0% by adding chitosan to zein film without any CPT, representing a more flexible composite with less mechanical strength. The main reason may be related to the interaction of electrostatic bond or hydrogen bond, which results in the formation of a more flexible network structure. In the second step, applying CPT on the film surface led to the production of films with promoted EAB and TS values. The TS value in the zein-chitosan composite films reached to its maximum level (41.50 MPa) after 60 s of CPT, and the EAB enlarged to 4.13% in the same process time. However, because of the high energy from cold plasma, the long-term CPT (>90 s) reduced the EAB and TS values due to the loss of chitosan molecules and the formation of compressed zein network (Chen et al. 2019).

According to the previous studies, it can be said that the CPT of biodegradable films can cause a decrease or increase in the TS, EAB and EM values depending on the various factors such as treatment time, functional groups of edible films, type of treated film, type of cold plasma, and the interaction of these factors (Bastos et al. 2009; Ulbin-Figlewicz, Zimoch-Korzycka, and Jarmoluk 2014).

Structural changes

The monitoring of structure and/or microstructure of edible films plays an eminent role in recognizing the interactions inside the film network and is widely used to interpret various changes in their physical, thermal, and mechanical properties. One of the most important approaches to investigate the microstructure interactions of films is Fourier transform infrared (FTIR) spectroscopy. The CPT is as an effective strategy to promote the structural features of edible films. The FTIR results of CPT on edible films are presented in Table 2.

The CPT can cause various changes in the spatial structure of biopolymers and the performance of proteins. Moosavi et al. (2020) studied the effect of CPT on the characteristics of gluten and whey protein edible films. The FTIR findings showed that the peaks at 1234–1239 cm^{-1} were increased after CPT on protein-based films, indicating an increase in β-sheet structure in the polymer matrix. They reported an increase in the peak at 700 cm^{-1} after 10 min of CPT in whey protein films, in addition to the increase in SH group of the protein compartments, leading to the formation of cross-linkage and interactions within the film matrix. The peak intensity was far lower in the gluten films due to the limited amount of sulfhydryl-containing amino acids, but alternately the OH bonds were stronger in the gluten films due to the presence of glutamine and prolamin amino acids (Gontard, Guilbert, and Cuq 1992; Misra et al. 2015; Moosavi et al. 2020). Decreases in β-turn and random-coil structures and their transformation to ordered β-sheet structure due to CPT were also observed in zein and zein-chitosan blend films with a higher intensity of peaks at the range of 1600–1700 cm^{-1} (amid I). The β-sheet structure is based on hydrogen bonds, and increasing this structure can be effective in promoting the shear strength, flexibility, and barrier properties of edible films (Chen et al. 2019; Dong et al. 2018; Turasan et al. 2018). In post-CPT protein films, the bandwidth allocated to the OH group vibration was decreased, which could be due to the interactions between the protein chains and the hydrogen present in their structure (Bagheri et al. 2013; Moosavi et al. 2020).

Studies on gelatin, CMC and corn films have shown that the reactive species present in the plasma can excite the polymer surface of the films and disrupt C–C and C–H bonds, creating excited sites and oxygen-mediated groups on the film surface. Following the reaction of plasma reactive species with air oxygen, various functional groups such as carbonate, carboxyl, and ether are formed on the film surface (Honarvar et al. 2017; Pankaj et al. 2015a; Pankaj et al. 2015b). This phenomenon was also observed in the protein-based films with increasing and shifting peaks of 1048 and 1258 cm^{-1} for whey protein film and 1105 cm^{-1} for gluten film, matching to the C–O and C–O–C bonds. In addition, Pankaj et al. (2017b) found that CPT caused an increase in oxygen-containing groups without any significant changes in amide bonds of plasma treated chitosan films (Amaral, Granja, and Barbosa 2005; Pankaj et al. 2017b).

The CPT can increase the structural organization and improve the interconnection of the composite films by acting on the inter-chain links of the polymeric matrix or the interconnection of the composite films. Chen et al. (2019) investigated the impact of CPT on the structural characteristics of zein films. There were shifts in the 3300 and 1096 cm^{-1} bands, corresponding to the zein-chitosan hydrogen bonds, and the interaction between chitosan carboxyl group and zein amide group, respectively. In addition, the peak intensity in the region of 3700–3000 cm^{-1} was increased for the samples with the 60 s of CPT. This shift and increase in the peak intensity showed that the generated reactive species are able to improve the disclosure of C-O active groups in chitosan films and induce the formation of zein-chitosan hydrogen bonds. The CPT for 120 s, and the destruction of new functional groups could reduce the intensity of peaks at 3700–3000 cm^{-1} and 1750–1300 cm^{-1} regions and create a new peak associated to the carbonyl groups at about 1750 cm^{-1}. The formation of this peak is probably due to the protein oxidation and peptide bond

Table 2. Summary of reported studies on the structural changes (FTIR spectra) in cold plasma treated edible films.

Type of film	Plasma source	Treatment conditions	FTIR results	References
Chitosan	DBD plasma (230 V − 50 Hz)	Air plasma, voltage 60, 70 and, 80 kV, time 1, 2, 3, 4 and, 5 min	New absorption bands appeared at 1150 (asymmetric bridge oxygen stretching) 1060 and 1030 (C-O stretching in ether group) 990 and 950 (CH_3 rocking) 900 cm^{-1} (ring stretching)	(Pankaj et al. 2017a)
Starch/ Poly lactic acid	DBD plasma (50 Hz − 31 kV)	Air plasma, time 1, 5, 10, 15 and, 20 min	New band appeared at 1751 cm^{-1} (C = O)	(Heidemann et al. 2019)
Starch	(13.56 MHz- 0.45 mbar)	HMDSO plasma power 70 W, time 30 min	Decrease in the intensity of the peak at 1022 cm^{-1} (starch amorphous structure) New peaks appeared at 840 (Si-C), 2965 (CH_3), 1015 cm^{-1} (Si-O-C) and band of 3300 cm^{-1} (OH) disappeared	(Sifuentes-Nieves et al. 2019)
Corn starch	DBD plasma (230V- 50 Hz)	Air plasma voltage 60, 70 and, 80 kV, time 1 − 5 min	Increase in the peaks of 1154 and 1081 (C-O stretching vibration in C-O-H) and 1016 cm^{-1} (C-O stretching vibration in C-O-C) and shift in 1580 and 1648 cm^{-1} δ(OH)	(Pankaj et al. 2015b)
Zein	DBD plasma (65 V)	Air plasma, time 5, 15, 30, 45 and, 60 s	Increase in the bands of (3600-3100 cm^{-1}) and amid I (1700-1600 cm^{-1})	(Dong et al. 2018)
Zein/Chitosan	DBD plasma	Air plasma power 100 W, 30, 60, 90, 120 and, 150 s	Increase in the bands of 3700-3000 and 1700-1600 cm^{-1} and shift in peaks of 1096 and 3300 cm^{-1} New peak appeared for 120s cold plasma treatment at 1750 cm^{-1}	(Chen et al. 2019)
Poly lactic acid/ nisin	(400 kHz- 200-500 W)	Power 300 W, time 0, 15, 30, 45 and, 60 s	New peaks appeared at 2850 and 2918 cm^{-1} and for 45s and 60s cold plasma treatment at 1535 and 1656 cm^{-1}	(Hu et al. 2018)
CMC	(14 kV − 20 kHz)	Air plasma, time 2 min	Develop in band near 1750 cm^{-1} which is corresponding to C = O stretching vibration and decrease in the intensity of the bands at 3500-3600 (OH) and 2836-2950 cm^{-1} (C-H)	(Honarvar et al. 2017)
Protein	Glow discharge (0 − 100 W and 20 kHz)	Air plasma Power 50 W, time 5, 10 and, 15 min	Increase in the intensity of the bands at 1239-1234 cm^{-1} (B sheet structure) and 700 cm^{-1} Increase and shift in the bands of 1048 and 1258 cm^{-1} for whey protein films and 1105 cm^{-1} for gluten films (C-O and C-O-C) Decrease in the intensity of the peak at 2925 cm^{-1} (abstraction C from C-H)	(Moosavi et al. 2020)

cleavages in the films, indicating that long-term CPT should be avoided in the processing of films (Chen et al. 2019).

Hu et al. (2018) examined the effect of CPT on nisin-coated PLA films and reported that two peaks were appeared at 2918 and 2850 cm^{-1}, and one peak disappeared at 2998 cm^{-1} over the CPT in the time interval of 0 (for the control sample) to 60 s. These changes could be due to the coverage of the CH_3 group peak with the methoxy group once immobilized by nisin. As CPT applied for 60 and 45 s on the nisin-coated PLA films, the two new peaks could be observed at 1656 and 1535 cm^{-1} due to the presence of nisin, showing that the nisin had been coated well on the PLA films in both time intervals (Hu et al. 2018). Heidemann et al. (2019) observed no significant changes in the FTIR spectra of the PLA/starch and PCL/starch composite films, but the CPT for 10 min on PLA/starch films caused the appearance of a new peak at 1751 cm^{-1} (C = O), presenting a higher compatibility of PLA with starch and increased adhesion of these two components after 10 min of CPT (Heidemann et al. 2019).

In a study of the properties of edible starch films with different amylose contents by Sifuentes-Nieves et al. (2019) the changes was observed in the index of short-range crystalline structure of starch films after CPT. This index is measured by the ratio of two peaks at 1047 cm^{-1} (representing the structural ordered of starch) and 1022 cm^{-1} (representing starch amorphous part) (Agama-Acevedo et al. 2018; Flores-Silva et al. 2017; Sevenou et al. 2002). In this study, the intensity of the peak at 1022 cm^{-1} was reduced, following by an increase of 1022/1047 ratio in all films. These findings showed that plasma reactive species and treatment time improved a highly organized network, with the highest ratio of 1022/1047 to films by the amylose content of 30% and the lowest to those by the amylose content of 50%. In addition, the results showed that CPT caused the disappearance of the band at 3300 cm^{-1} (belonging to the O–H group) in all samples, most likely due to the effect of CPT on the water holding capability of starch films (Sarangapani et al. 2017; Zhang et al. 2015). The CPT also caused the coat formation on the film surface and reduced the water absorption in the starch films (Sifuentes-Nieves et al. 2019).

In general, the cold plasma can modify the structural characteristics of edible films by various mechanisms such as changing the spatial structures, forming excited sites, crosslinking between functional groups, and increasing the structural organization in biopolymeric network.

Thermal properties

The changes in heating/cooling behaviors and in some cases, thermodynamic and thermophysical aspects of biopolymers can be scrutinized by various approaches including differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) (Dong et al. 2018). The most important thermal indicators determined by DSC approach are melting temperature (T_m), glass transition temperature (T_g), and denaturation temperature (T_d). Evaluating these parameters can determine the structural and thermal changes induced by the CPT (Chen et al. 2019; Romani et al. 2019a). Table 3 summarizes the thermal characteristics of cold plasma-treated biopolymeric films.

The CPT has different effects on the thermal profile of films so that the thermal stability is increased in some cases. Dong et al. (2018) investigated the CPT on thermal behavior of zein films. The results showed that introducing CPT for 60 s promoted the T_m and T_d values, confirming the postponed thermal degradation compared to the untreated film. The probable reason for increase in thermal stability indices was associated to the cross-linking on the film surface due to the formation of novel functional groups of nitrogen and polar oxygen after the CPT (Dong et al. 2018). In addition, similar results were reported in zein-chitosan composite films. According to TGA results, an increase in endothermic peak from 93.60 °C to 99.83 °C during 60 s CPT confirmed the improved thermal stability and fabrication of a film with elevated functional and structural properties, due to the uniformity of the secondary structure of zein molecules, and higher hydrogen bonds between zein and chitosan molecules. In addition, the increase in the thermal degradation temperature of the zein-chitosan films during CPT at the degradation rate curves showed an improvement in the thermal stability and quality of the resulting films (Chen et al. 2019). The starch films also showed an increase in T_g and T_m values after expose to high-voltage atmospheric CPT at 5 min/80 kV, resulting in the formation of highly-organized uniform structures (Pankaj et al. 2017c).

In some studies, the effect of CPT on biopolymers showed a decrease in the T_g of films. In the sodium caseinate film, the T_g was reduced from 61.1 °C in the control sample to 46.8–50.9 °C during 5 min DBD plasma treatment. Such decrease is associated to the breakdown of the chemical bonds, chemical degradation, and chain scission of cold plasma-treated biopolymers through the influences of generated chemical etching (Pankaj et al. 2014b). Furthermore, comparable findings were also reported in cold plasma-treated fish protein films. The CPT reduced T_g and increased T_m compared to the control film, owing to the effect of physical and/or chemical etching phenomenon and increasing polar groups on the film surface (Romani et al. 2019a). The CPT has been ineffective on the thermal properties of PLA (Hu et al. 2018), chitosan (Pankaj et al. 2017a), thymol-loaded zein (Pankaj et al. 2014a), and corn starch (Pankaj et al. 2015b) films. It should be noted that the weight loss of cold plasma-treated corn starch films didn't show a significant difference compared to the untreated film, but a slight decrease occurred at a maximum degradation temperature at 242.5 °C in the untreated-control film to the range of 235-241 °C DBD plasma exposure for 5 min, due to the etching effects and scission of random chains from starch polymer (Pankaj et al. 2015b). In the PLA films, the T_g (approximately 60 °C) and T_m (approximately 153 °C) values did not change significantly because the CPT affected the structural changes in the film surface, improved the surface roughness and composition, and unlikely interfered the film bulk properties (Hu et al. 2018).

Table 3. Thermal properties of biopolymer films exposed to cold plasma treatment.

Type of film	Plasma treatment conditions	T_g (°C)	T_m (°C)	T_d (°C)	References
Polylactic acid (PLA)	SWU-2 CPT system, microwave generator 2.45 GHz, O_2 pressure 667 Pa, power 900 W for 40 min	Not significant	NA	NA	(Song et al. 2016)
Starch	High voltage atmospheric cold plasma treatment (HVACP), air, input voltage 110V, frequency 60 Hz, 80 kV for 5 min	Rice starch film: +1.5° (↑) Corn starch film: +14.6° (↑)	Rice starch film: +23.5° (↑) Corn starch film: +61.7° (↑)	NA	(Pankaj et al. 2017c)
Chitosan/thymol	Dielectric barrier discharge plasma, input voltage 230 V, frequency 50 Hz, 70 kV for 5 min	NA	NA	Not significant	(Pankaj et al. 2017a)
Zein	Atmospheric cold plasma (ACP), DBD-50 plasma reactor, voltage 65 V, time 5, 15, 30, 45 and, 60 s	NA	NA	+6.23° (↑) in 15 s	(Dong et al. 2018)
High amylose corn starch	Dielectric barrier discharge plasma, atmospheric air, step-up transformer) 230V, 50 Hz(, voltage 60, 70 and, 80 kV, time 5 min	NA	NA	−4.25° (↓)	(Pankaj et al. 2015c)
Fish protein films	Alternating current (AC) glow discharge plasma, dry air, high voltage input (4.4 kV, 60 Hz) , time 2 and 5 min	−20.7° (↓) in 2 min −36.98° (↓) in 5 min	+2.79° (↑) in 2 min +13.26° (↑) in 5 min	NA	(Romani et al. 2019b)
Sodium caseinate	Atmospheric dielectric barrier discharge (DBD) plasma, step-up transformer (voltage 230 V, frequency 50 Hz), atmospheric air, voltage levels of 60 and 70 kV, time 5 min	−12.25° (↓)	NA	NA	(Pankaj et al. 2014b)
Polylactic acid (PLA)/nisin	Homemade plasma system, radio frequency generator 400 kHz, pressure 100 Pa, power 300 W, time 0, 15, 30, 45, and, 60 s	Not significant	Not significant	NA	(Hu et al. 2018)
Defatted soybean meal (DSM)	Low pressure microwave-powered CPT system, argon, microwave generator 2.45 GHz, time 15 min, power 400 W	+2° (↑)	NA	NA	(Oh, Roh, and Min 2016)
Zein-chitosan	Dielectric barrier discharge (DBD) cold plasma, air, power 100 W, time 60s	NA	NA	+0.78° (↑)	(Chen et al. 2019)
Zein	Dielectric barrier discharge (DBD) plasma, step-up transformer (voltage 230 V, frequency 50 Hz), atmospheric air, voltage 70 kV, time 5 min	Zein: +2.1° (↑) Zein- thymol: Not significant	NA	NA	(Pankaj et al. 2014a)

Note: T_g, Glass transition temperature; T_m, Melting temperatures; T_d, Thermal degradation; NA, Data not available.

Various factors related to CPT (i.e. time, gas type, and plasma power) can affect the thermal properties of edible films. Chen et al. (2019) investigated the effect of CPT time (30,60,120 s) on the zein-chitosan composite films. The results showed that 60 s CPT increased the endothermic peak of the films by 6.23 °C when comparing with the control composite film and hence improved the thermal stability. However, long-term exposure to plasma (≥120 s) resulted in a 4.43 °C decrease in endothermic peak, caused protein oxidation and thus a decrease in thermal stability (Chen et al. 2019). In the lysozyme-loaded chitosan films exposed to helium plasma, the hydrolytic changes resulting from lysozyme activity led to the destruction of the chitosan molecular chains, reduced molecular weight, and decreased thermal degradation temperature (approximately 15 °C) (Ulbin-Figlewicz, Zimoch-Korzycka, and Jarmoluk 2014). Oh, Roh, and Min (2016) also examined a DSM film as treated by different cold plasma gas sources including air, O_2, N_2, Ar, and He. The results showed that the T_g increased in DSM films after helium and argon CPT due to the radical formation on the polymer surface and the cross-linking within the film matrix, and subsequently restricting the access to oxygen, which candidates the DSM film as a promising food coating. In contrast, drop of T_g to the lower temperatures after O_2 CPT can be attributed to the loading of oxygen containing functional groups into the biopolymeric matrix (Oh, Roh, and Min 2016).

Antimicrobial effects

The CPT is known as a novel approach to modify the surface characteristics, reduce contamination in edible packaging systems, and improve the safety level of a wide range of food products. However, the changes in active packaging systems containing some bioactive and/or antimicrobial compounds such as vanillin, nisin, glucose oxidize, lysozyme, triclosan, etc. should be carefully addressed before employing CPT (Denes and Manolache 2004; Lei et al. 2014; Pankaj and Thomas 2016).

CPT can facilitate the coating of bioactive materials on the film surface and improving their adsorption capacity. In this regard, Honarvar et al. (2017) used CPT to track the antimicrobial properties of *Zataria multiflora* essential oil (ZEO)-loaded CMC blends as a coating on the PP films. CPT caused a better attachment between polymer layers as an antimicrobial packaging, so that the CMC/PP bilayer film containing ZEO (1-4% v/v) showed significant inhibition zones for *Staphylococcus aureus*, *Bacillus cereus*, *Escherichia coli*, *Pseudomonas aeruginosa* and *Salmonella typhimurium*. Accordingly, the plasma-treated artificial PP layer coated with CMC biopolymer acts as a barrier against evaporation and loss of ZEO. In general, the antimicrobial properties increased as a function of ZEO dosage. The most sensitive and resistant bacterial strains were *S. aureus* and *P. aeruginosa*, respectively. The reason for the resistance is the presence of outer membrane in the Gram-negative bacteria (Honarvar et al. 2017). These results are in consistent with a study conducted by Hu et al. (2018) who showed that CPT caused successful nisin coating on the PLA surface, and the film produced an antimicrobial effect so that the viability of *Listeria monocytogen*es decreased by 2.25 log CFU/mL in the presence of the cold plasma treated films with 60 s plasma exposure; while the PLA film alone could not inhibit its growth. Thus, although the CPT does not increase the antimicrobial activity of PLA films, it does improve the absorption capacity of nisin on the film surface and then release it gradually to inhibit the microbial growth due to increased surface performance (Hu et al. 2018).

Low-pressure plasma treatment is very useful in inhibiting the bacterial growth due to the benefits such as uniform treatment and low temperature in the food industry, especially the meat industry. The antimicrobial effect of chitosan films incorporated with lysozyme (0, 0.5, and 1%) exposed to helium CPT was observed against psychotropic bacteria of *L. monocytogenes*, *Yersinia enterocolitica* and *Pseudomonas fluorescens.* The lysozyme concentration of 1% created a larger inhibition zone for *L. monocytogenes*, and *Pseudomonas fluorescens*. There were no significant differences between low-pressure CPT and antimicrobial activity. Accordingly, the interaction of plasma species with bacterial cells may inactivated the bacteria (Ulbin-Figlewicz, Zimoch-Korzycka, and Jarmoluk 2014). The CPT increases the release rate of the antimicrobial agents in the films by increasing the diffusion coefficient, so that the applied DBD plasma in the zein films containing thymol increased the diffusion rate and accelerated the release of thymol in the antimicrobial films in a food simulant. The main reason can be the increase in roughness as a result of the etching effects, and the reduction of the effective thickness of zein films after the CPT (Pankaj et al. 2014a). In addition, the results were in consistent with a study by De Vietro et al. (2017) who examined the organic-inorganic copper-based deposited thin coatings on polycarbonate (PC) by the low pressure argon plasma against two *Pseudomonas* spp. isolated from spoiled Fiordilatte cheese. The reduction in microbial load from 10^8 to 10^5 CFU/mL was observed in plasma-coated samples compared to the PC control film. The obtained antimicrobial effect is related to the release of copper ions, leading to its close interaction with the bacterial membranes (De Vietro et al. 2017).

According to these studies, the combination of various green approaches, like cold plasma together with the incorporation of bioactive substances, and protective coatings can cause an efficient food preservation strategy and inhibit the spoilage or pathogenic microorganisms.

Safety issues toward the use of cold plasma in edible films

The cold plasma technology has become one of the most important methods for the decontamination of food products and modification of edible films. The safety of this technology is very important due to its direct effect on food and consumers. Limited studies have been focused on the production of toxic compounds due to the interaction between plasma induced reactive species and food compounds so far (Ekezie, Sun, and Cheng 2017). In a study conducted by Thirumdas, Sarangapani, and Annapure (2015) the peroxide content of cold plasma-treated nuts enhanced significantly. They concluded that various undesirable chemical derivatives (e.g. aldehydes, keto acids, hydroxyl acids, and short chain fatty acids) can be generated by CPT (Thirumdas, Sarangapani, and Annapure 2015). Other effects of cold plasma on food products include reduced firmness of fruits and vegetables, accelerated discoloration, and increased acidity content. Therefore, the studies on the cold plasma optimization should be set specifically for each product. A few studies have also investigated the cold plasma effects on the production of toxic compounds in the biopolymers (Audic et al. 2001). For instance, Han et al. (2016) tested the CPT effects on the toxicity of edible DSM films in male and female Dawley Sprague rats (5000 mg/kg body weight (BW)/day and 1000 mg/kg BW/day) for 14 days and disclosed no signs of acute toxicity. The changes in blood hemoglobin, bilirubin, creatinine, hematocrit, and aspartate aminotransferase levels were still within the normal physiological range as well (Han et al. 2016).

According to the above studies, further safety and risk assessment investigations should be comprehensively performed on the cold plasma interactions with biopolymer components and also migration of the cold plasma induced residuals into the food products before implementation of this approach in commercial scales.

Conclusion

The technological application of many edible films in food packaging is restricted because of their poor structural, physical, mechanical and thermal attributes, as well as their poor printability and adhesion features. The core purpose of the current review was to scrutinize the effectiveness of cold plasma treatment as a novel and promising approach to modify the critical characteristics of edible films. The cold plasma technique has shown a great prospective to improve the polymer surface with superior performance properties. The effects of cold plasma treatment on the biodegradable films is influenced by various factors such as treatment time, gas type, plasma power, electrode design and distance, structure and components of the films. Taken as a whole, the cold plasma treatment could improve various thermomechanical, physical and structural attributes of edible packaging films in most cases. The cold plasma as an efficient technology improved the adhesion between the polymer layers in fabrication of multilayer films, without damaging the polymer bulk structure. In addition, the cold plasma could effectively prohibit the growth of microorganisms by enhancing the controlled release of bioactive substances on the film surface. Accordingly, it can be considered a promising strategy to improve the properties of edible films because it is a dry, suitable for in-line processing, easy production and control, and chemical-free process as well as no waste production. There are limited studies on the interaction of cold plasma species with the edible film components, its influence on the sensory aspects, and other health and safety issues which needs future research before the practical and commercial use of plasma technology.

Disclosure statement

No potential conflict of interest was reported by the authors.

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