



The Effects of Novel Thermal and Nonthermal Technologies on the Properties of Edible Food Packaging

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Abstract

Edible packaging is influenced by factors such as formulation, production technology, and solvent and additive properties. With the increase in the request for coating and film quality, appropriate form, and high product safety and storage period, various technologies such as high hydrostatic pressure, irradiation, ultrasound, high-pressure homogenization, cold plasma, and microwave have been reviewed. The present study states definitions and mechanisms of novel technologies. The experimental condition, packaging matrix, and the results pertaining to the effects of these technologies on various types of edible packaging is also discussed. The most of the matrix used for packaging was whey protein, soy protein isolate, chitosan, and gelatin. The technologies conditions such as power, frequency, time, temperature, dose, pressure, and voltage can have a significant influence on the application of them in film and coating. Therefore, finding the optimum point for the features of the technologies is important because improper use of them reduces the properties of the edible packaging.

Keywords Edible packaging · Film and coating · Nonthermal technologies · Mechanical properties

Introduction

Nowadays, researchers have studied the use of environmentally friendly packaging which includes natural polymers [63]. Natural polymers such as carbohydrates (chitosan, starch, alginate, celluloses, and hydrocolloids like gellan gum and seed-mucilages), lipids (waxes such as candelilla, bee, carnauba, glycerols, and fatty acids), proteins (gluten, collagen,

soybean, zein, and milk protein), and composites are utilized to generate novel packaging and reduce the consumption of synthetic polymers [10, 43]. Natural polymers are further applied to various coatings and films. Coatings are spread in liquid form on the food and eaten directly while films are used in solid forms [29]. Polysaccharides and protein films have appropriate mechanical characteristics and appearances. Protein films have more impressive gas barrier properties and better mechanical characteristics owing to their unique structure and higher intermolecular connection capability compared to other films [17]. Carbohydrate films are resistant toward gas, oil, and fat, and both protein and carbohydrate films have high water vapor permeability owing to their hydrophilic behavior [91]. Lipid films, on the other hand, are resistant to moisture loss. Despite the advantages of natural polymers, they have not yet been widely applied in food manufacturing due to their relatively high cost regarding this type of packaging and weak mechanical, sensory, and barrier properties (oxygen, carbon dioxide, aroma, and water vapor) of the produced films [74].

The difference in edible film formation is related to material and additive types and properties, formulation, and film production technology. In general, materials are dissolved in acetic acid, water, alcohol, and their mixture with other solvents, and the solution is then cast and dried under optimal

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conditions. Additives such as plasticizers (for brittleness reduction and increased flexibility and toughness), antimicrobial materials (for increasing the product's shelf-life), flavor, and color agents (for increased sensory properties and overall acceptability) can be used in the production of films [16, 71].

Novel technologies such as microwave, high hydrostatic pressure, irradiation, cold plasma, ultrasound, and high-pressure homogenization are applied with the purpose of quality improvement, thermal treatment, energy efficiency, preservation, texture and surface modification, analysis, and extraction to name a few [66, 97]. Therefore, this review attempts to discuss and address the definition and mechanism of novel technologies, the optimum conditions for the application of these technologies on the edible packaging, and the influences of the mentioned technologies on properties of edible packaging.

Novel Technologies

Microwave, high hydrostatic pressure, irradiation, cold plasma, ultrasound, and high-pressure homogenization are considered to be the most commonly applied packaging technologies. The influences of the mentioned technologies on some of the food edible packaging properties are summarized in Fig. 1.

Microwave

Electromagnetic radiation frequencies ranging from 300 MHz to 300 GHz create the effect of polarization and cause microwave heating. Microwave heating has advantages over traditional heating such as reducing the processing time and

maintaining the quality of food. Food materials have different dielectric properties which they store and spread when exposed to an electromagnetic field. Microwave is usually used in the food industry for pre-cooking, frozen material tempering, and drying [87].

From an industrial point of view, during film production and after spreading it over the plate, it is important to select the most appropriate method such as microwave for rapid drying. In the traditional approach, the film is dried under the air, taking about 24 h [40].

Microwave can heat the components based on the transfer of mass and heat through the interaction between polar material and microwave energy [72]. Because of the electromagnetic field generated by microwave, only the surface of the component is not influenced, and due to the high penetration depth, the inside parts of the materials are sufficiently heated. Furthermore, various food components have the divergence dielectric behavior and absorb heat differently and selectively [20].

Effect of Microwave on Edible Packaging

Kaya and Kaya [40] formed films containing whey protein isolate about (8 and 10% (w/w)) and dried by microwave. To do this, films were spread onto the plate and dried (20 °C, 18 h and 40 RH) and microwave condition (power 700 W, 2450 MHz, and 5 min). The result indicated that transfer rate of water vapor was directly related to the temperature and increased with it (from 4 to 30 °C). The films dried with both methods showed no main difference in terms of water vapor permeability (WVP) and modulus of elasticity (ME). Microwave method enhanced tensile strength (TS) and

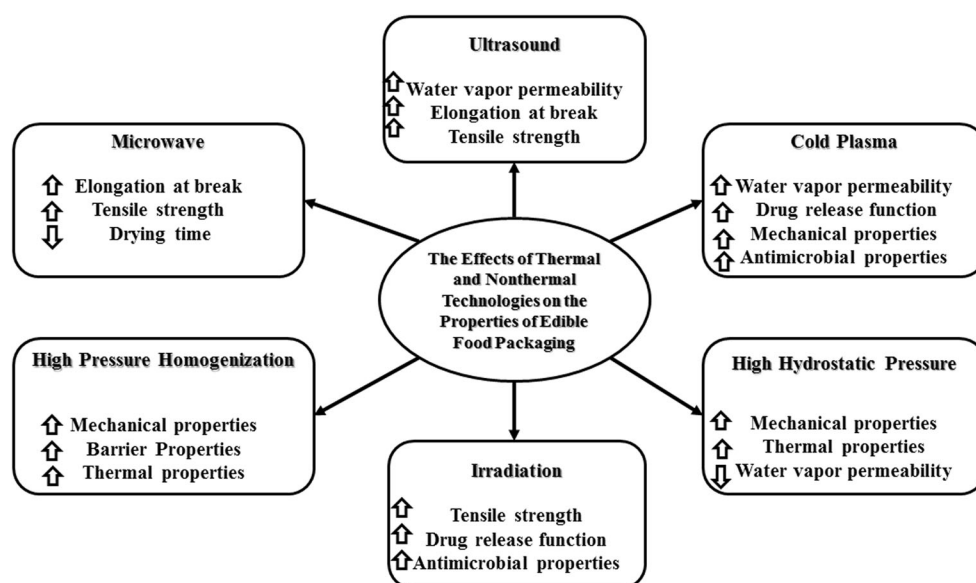


Fig. 1 The influence of technologies on the properties of edible food packaging

elongation at break (EAB) in film samples compared to room condition. In addition, dried samples by microwave had better haze and gloss values compared to others.

Cárdenas et al. [20] dried chitosan film at convection oven (12 h at 35 °C) and microwave (2450 MHz, 10 min). They dried chitosan films using two methods; microwave (full power, 10 min, 2450 MHz) and convection oven (35 °C for 12 h) and reported that microwave increased UV-vis light barrier property of films, although had no significant effect on their thermal and structural characteristic. In addition, Cárdenas et al. [21] reported that Cu nanoparticle in chitosan composite film due to connection to matrix filled binding points of film against water and accelerated the removal of non-bounded water during drying by microwave (full power, 10 min, 2450 MHz). The results of studies on microwave effects on edible packaging are summarized in Table 1.

Irradiation

Food irradiation is a physical treatment used to improve the shelf-life through reducing the spoilage of various vegetables, and animal and seafoods. This process consists of exposing foods to ionizing radiation chiefly electron beam (E-beam), UV, and γ where high-energy radiation expels electrons from atoms and ionizes the molecules. The international unit of measurement for the radiation E-beam and the gamma dose absorbed by the product is kilogray (kGy) and UV radiation is measured in nanometers (nm) [27, 46, 47, 53]. The use of radiation technique in food products was authorized in 1981 [99].

With radiation technique, packaging with desired functional characteristics can be obtained [4, 33]. In addition, packaging improves the physical and chemical quality of food products but does not significantly inhibit microbial growth. Irradiation is able to inhibit microbial growth and/or produce cross-linking films by covalently linking the protein molecules [19, 46, 47].

Food protein alteration is an important approach to improving the properties of the biopolymer applied to edible film production. The irradiation process on the protein cross-linking can result in the formation of free radicals, hydrogen abstraction, and novel connection inside chains, which improves the final structure properties. Furthermore, this process occurs rapidly without the need for catalyst and temperature rise [44].

Effect of Irradiation on Edible Packaging

E-beam irradiation (40–60 kGy) was investigated on the quercetin release level of film including gelatin and chitosan in hydroethanolic medium (30% ethanol) at room temperature. The induced irradiation created novel interactions and connections between chitosan and gelatin with the antioxidant

material, resulting in the increased quercetin level residual within the film following 60 kGy irradiation dose. However, the lag-time (the period needed previously the release begins) increased ten times. Therefore, the E-beam irradiation led to the entrapment of a significant amount of antioxidants [12]. Irradiation by new interactions between biopolymers has been used for packaging disinfection. Gamma irradiation (32 kGy) was used to generate cross-linked proteins and prepare proteins/glycerol and protein/glycerol/polysaccharide films. Structure analysis was performed by FTIR [93]. The second derivative FTIR spectrum showed an increase in the amount of β -sheet phase and a reduction in α -helix phase in γ -irradiated cross-linked proteins in comparison with no irradiation sample. Methylcellulose addition and γ -irradiation of proteins enhanced the puncture strength and had no significant effects on WVP. Irradiation induced 40% decay in the proteins/methylcellulose/peppermint formulation on day 8 while the control underwent 65% decay. Irradiation (γ) improves film characteristics through producing cross-connected protein.

The changes in structural parameters and the release levels of ferulic acid and tyrosol in film including gelatin and chitosan irradiated with E-beam at 60 kGy doses were studied. Ferulic acid can cause some connections with the polymer networks; non-irradiated films showed higher remaining ferulic acid compared with tyrosol. E-beam induced a loss of about 20% in tyrosol and 27% in ferulic acid residual trapped within the matrix of polymer while all tyrosol was released. Moreover, the TS value significantly increased and water vapor permeability decreased [11]. Through some covalent bindings with the polymer network, irradiation can reduce the additive diffusivity from packaging to outside.

The chitosan coating with ultraviolet ray were applied for the preservation of jujube during storage. UV irradiation restrained the rate of respiration, electrolyte leakage, and malonaldehyde level. In addition, combined treatment for 15 days displayed 49.5% weight loss lower compared to that in the untreated and uncoated type. In addition, the enzyme activities of treated jujubes were kept at a higher level, and the reduction in chlorophyll and vitamin C was controlled [100]. After absorbing the ultraviolet, the microorganism died due to the alteration of the molecular structure of the nucleoprotein and inhibition of metabolism.

Gamma irradiation (3 kGy) process was applied together with cinnamaldehyde and thyme oil in whey and soy protein coatings for shrimp. Changes in aerobic plate counts, bacterial growth, and sensory characteristics were investigated by Ouattara et al. [66]. The obtained results revealed that coating and γ -irradiation treatments had synergistic effects on the reduction in aerobic bacteria including *Pseudomonas putida* and aerobic plate counts (APCs). Without irradiation, an improvement of preventive influences was observed in the coating containing antimicrobial agents applied to the shrimp related

Table 1 The effects of microwave on edible packaging properties

Matrix	Experimental conditions	Findings	References
Whey protein isolate	Microwave: 700 W, 245 MHz, and 5 min	Microwave enhanced EAB and TS and showed no effect on WVP and ME.	[40]
Chitosan film	Microwave full power, 10 min, 2450 MHz	Microwave increased UV-vis light barrier and had no effect on thermal properties.	[20]

to the level of antimicrobial materials; with irradiation, on the other hand, the preventive influence was enhanced owing to the antimicrobial material interaction influence. Irradiation had no detrimental influences on the organoleptic parameters. Irradiation with coating showed synergistic influence in initial solution without additives. In another research, gamma irradiation (1–3 kGy) decreased the APCs in three groups of beef samples containing 0 and 0.5% of ascorbic acid and a sample including ascorbic acid (0.5 %) and packed with calcium caseinate coating. Also, in all samples, thiobarbituric acid reactive substances (TBARS) and –SH radical production were stabilized during storage in comparison with the control sample [67]. Gamma irradiation improved lipid oxidation and –SH radicals resulted in reduced bacterial growth.

Several food products coated with different solutions were treated with gamma ray up to 3 kGy. Irradiation combined with a coating completely inhibited the microbial growth in shrimp, decreased 2–3.5 log unit in the APCs of ready-to-eat pizzas, and significantly decreased the mold growth of strawberries. Contrary to uncoated/untreated sample, the shelf-life improved in shrimp and pizza. Gamma irradiation had no significant influence on the organoleptic parameters [68].

Edible coatings containing biodegradable materials combined with γ -irradiation prevent the microbial attack on the Hyani date fruits (considered to have high moisture content). This goal was achieved by preparing triple blend solutions (polyvinyl alcohol, chitosan, and tannic acids) using γ -irradiation with doses varying between 5 and 20 kGy. The results showed that with the increase in the irradiation dose, antimicrobial properties and the TS of edible coatings were improved. Moreover, γ -irradiation with tannic acid was able to increase the shelf-life of fruit in condition (12 °C and 98% RH) from 7 to 30 days [28].

Methylcellulose coating combined with citrus extract (CE), lactic acid bacteria metabolites (LAB), rosemary extract (RE), and organic acids (OA) was studied on the sensitivity of *Salmonella typhimurium*, *Escherichia coli*, and *Listeria monocytogenes* in broccoli florets. For this propose, florets were separately inoculated with each pathogen microorganism and packed with the coating and dipped in baths containing antimicrobial agents. Samples were irradiated with γ -irradiation at doses of 0 to 3.3 kGy. Following γ -irradiation, methylcellulose coating increased the radio sensitivity of food pathogens. The OA + CE, OA + LAB, and all irradiated

coatings significantly reduced *E. coli*, *S. typhimurium*, and *L. monocytogenes*, respectively [86].

In a study by Abad et al. [1], the tamarillo fruits were irradiated at doses of 250 to 1000 Gy and packed with the StaFresh 2505™ coating (the yellowish wax covering palm leaves with a thick layer and applied in coating fresh fruit). The irradiated and coated fruits were preserved under better conditions compared with the control samples. Weight loss and respiration of the fruits were 48 and 30% lower than the control during its shelf life. Firmness and appearance increased up to 70 and 40% compared to the control, respectively. Furthermore, radiation had no influence on fruit flavor. The results of the studies on irradiation effects on edible packaging are summarized in Table 2.

Cold Plasma

Recently, plasma technology has been employed as an alternative to other physical and chemical methods for food processing with high quality [31, 34]. Plasma is produced by applying energy to a gas blend, and it is as the fourth state of matter which is electrified gas along with ultraviolet photons, electrons, positive and negative ions, free radicals, atoms, and excited or non-excited gas molecules. These chemically reactive particles have a significant impact on food processing. Generally, there are two types of plasma, namely thermal and nonthermal (cold plasma). The thermal plasma is produced at extreme pressures (≥ 105 Pa) and requires up to 50 MW of power; also, the temperature of the electrons and ions of the plasma approach thermal equilibrium. Cold plasma, on the other hand, is generated by electrical discharge instead of heating the entire gas at atmospheric pressure and low levels of power [76, 80].

Cold plasma can be applied in the decontamination of food material with inactive microbial agents such as bacteria, bacterial spores, fungi, and viruses. Therefore, cold plasma treatment can be used as an alternative heat-based technique for sterilizing sensitive materials such as vitamins, proteins, volatile compounds, and polycarbonate and polythene [15, 62, 69]. The cold plasma has been reported to interact with ingredients of edible films such as proteins, lipids, carbohydrates (seed-mucilage), water, and phenolic compounds, through the addition or removal of the specific functional group. These interactions resulted in the uniformity of treatment, no use of

hazardous solvents, increased mechanical strength and flexibility, and improved hydrophobic properties; they also helped maintain the sealing properties of polymers, reduce gas permeation and undesirable contaminants without any traces, maintain atmospheric air, and increase elongation [6, 8, 9, 26, 60].

Effect of Cold Plasma on Edible Packaging

Chen et al. [23] produced film containing chitosan/ciprofloxacin/zein by plasma at $P = 100$ W for 30 s. The result of FTIR showed that films were well coated with zein, and XRD patterns confirmed that the cold plasma had no influence on crystal type. No significant changes were observed in thickness and encapsulation efficiency while surface free energy, thermal stability, and wet ability and bacterial growth were increased and reduced, respectively. Cold plasma improved the function of drug release in film.

Cold plasma was done on carboxymethyl cellulose (CMC)-coated polypropylene film including essential oils. First, polypropylene films were modified with cold plasma at $V = 14$ kV and $f = 20$ kHz for 2 min. CMC films including essential oils were then coated with plasma-treated polypropylene. The results showed that atmospheric cold plasma treatment was able to create C=O and O–H groups on the polypropylene films. Subsequently, contact angle, indicative of surface wettability, was reduced from 88.92° to 52.12° .

Cold plasma increased the mechanical and antimicrobial characteristics. In addition, plasma increased WVP while essential oil decreased it [36]. In general, plasma can be used as a pretreatment in the production of bilayer film because it makes better connection of natural film to synthetic polymers.

The effect of plasma on melon packed in polypropylene film was investigated [88]. Polypropylene film was subjected to cold plasma at 15 kV, 12.5 kHz, RH = 90% for 15 to 30 min for each side. The findings showed that dry matter and titratable acidity increased, although insoluble solid content was reduced. Furthermore, microbial shelf life significantly increased in 15-min treatment while the effect of cold plasma on microbial shelf life after 30 + 30 min was negligible. In general, cold plasma is an efficient method in the decontamination of fresh-cut-fruit.

Sifuentes-Nieves et al. [81] reported that hexamethyldisiloxane (HMDSO) cold plasma treatment ($P = 70$ W, ET = 30 min) enhanced hydrophobic characteristics in starch film and increased TS and Young's modulus. However, a reduction from 36 to 9% was observed in EAB value. These results suggested that the HMDSO plasma treatment is capable of producing starch-based films as a suitable packaging material.

Cold plasma ($P = 400$ W, ET = 15 min) was applied on defatted soybean meal film [65]. The films were treated with different types of plasma-forming gases including Ar, dry air, O₂, He, and N₂. No significant changes were observed in elastic modulus, TS and WVP. Lightness value and stretch

Table 2 The effects of irradiation on edible packaging properties

Type of irradiation	Matrix	Type of food	Experimental conditions	Findings	Reference
E-beam irradiation	Fish gelatin films	–	40 and 60 kGy	The irradiation decreased the release rate of quercetin	[12]
γ -Irradiation	Calcium caseinate-based coating	Ground beef	0, 1, 2, and 3 kGy	Irradiation significantly decreased APCs and stabilized TBARS and free SH	[67]
UV-irradiation	Chitosan coating	Jujube	253.7 nm	UV-irradiation controlled the rate of respiration and weight loss of fruit.	[100]
γ -Irradiation	Soy protein or whey protein isolate	Pre-cooked shrimp	3 kGy	Gamma irradiation inhibited the growth of aerobic bacteria	[66]
E-beam irradiation	Chitosan-gelatin films	Antioxidants (ferulic acid and tyrosol)	60 kGy	E-beam decreased the release rate of acid and tyrosol, and increased TS	[11]
γ -Irradiation	Soy and whey protein isolates coating	Pre-cooked shrimps, pizzas, and strawberries	0 and 3 kGy	Irradiation had effect on microbial growth and no effect on sensory characteristics	[68]
γ -Irradiation	Calcium caseinate, and whey protein isolate film	Strawberries	32 kGy	Gamma irradiation of proteins increased the puncture strength	[93]
γ -Irradiation	Polyvinyl alcohol/chitosan/tannic acid	Hayani date fruit	5 to 20 kGy	Irradiation enhanced the mechanical properties of fruit	[28]
γ -Irradiation	Methylcellulose coating	Broccoli florets	0–3.3 kGy	Gamma irradiation eliminated the growth of foodborne pathogens	[86]
γ -Irradiation	StaFresh 2505 ^{MT} coating	Tamarillo fruits	0.25–1 kGy	Irradiation reduced weight loss up to 48% and respiration rate and increased firmness, and appearance	[1]

ability increased in the case of all gases except for air, N₂ and Ar. The effect of cold plasma on smoked salmon packed with DSM film was further investigated. Cold plasma indicated no influence on the color of salmon while it delayed lipid oxidation and reduced the hardness [65].

Pankaj et al. [70] treated sodium caseinate film by plasma ($V = 60$ and 70 kV, $ET = 1$ – 5 min). Plasma was able to enhance hydrophilic property in films owing to the enhance in O–H and C=O groups. In addition, roughness and surface oxygen content and glass transition temperature increased and decreased, respectively. The effect of cold plasma on film and coating are summarized in Table 3.

Ultrasound

Edible films have weak mechanical properties in comparison with synthetic samples. Therefore, various physical and chemical technologies need to be done to overcome these problems. Ultrasound had beneficial effects on the processing and preservation of food. The ultrasound technology is divided into low and high intensities. In low-intensity technology, high frequency (2–20 MHz) and low power (100 mW/cm^2 to $< 1/\text{w}^2$) are used. This type as an analytical method examines information about quality properties of food [59]. But in high-intensity ultrasound, typically low frequencies range (20–100 kHz) and high power range (10 – 1000 W/cm^2) are used. This method had several application in food systems inducing filtration, fogging, crystallization, emulsification, cutting, degassing, oxidation and reduction reactions, drying, extraction, tenderization, cleaning, and sterilization [58, 59]. High-intensity type transmitted via a fluid environment create strings or cloudy bubbles. The bubble grows at critical sizes and will quickly disappear. The general process is called cavitation phenomenon, which involves the creation, growth, and breakdown of bubbles. The growth and breakdown of bubbles will result in the production of high temperatures and pressures in the matrix [5]. In addition, ultrasound can be used for increasing the mass transfer owing to the great temperature and pressure changes. The combination of microwave and ultrasound can accelerate the extraction technique for target materials from their matrix [48, 52].

Effect of Ultrasound on Edible Packaging

Ahmadi et al. [2] studied ultrasound treatment (35 kHz) for 5, 15, 30, and 45 min on methylcellulose-forming solutions. The time of ultrasound exposure had an inverse relationship with the amount of WVP, meaning an ultrasound process of 45 min produced the lowest WVP. The highest EAB and TS were obtained at 45 and 5 min, respectively. Following 5 min of ultrasound, mechanical properties were improved, although with the increase in time to 30 min, TS and EAB values of films were reduced. These results can be ascribed to the

cavitation phenomenon. The reduction in TS and EAB after 30 min can be the result of the increased cavitation size and number of bubbles. Growing bubbles create spaces between molecules and reduce film resistance. Increases in these parameters after 45 min of sonication can be due to the breakdown in chemical connections in the main chain of methylcellulose films and the formation of new chemical bonds, forming a denser network. Under the influence of high pressure and temperature due to solvent decomposition and dissolved molecules inside the system of bubbles, several reactive radicals are produced. According to the cavitation mechanism, the contact between the methylcellulose film solution and ultrasonic waves can cause the dissolved water and ethanol molecules to collapse, thereby creating hydrogen and hydroxyl radicals. Ultrasound can decrease WVP because of the creation of covalent connection between steam and water molecules and radicals. This reaction can possibly reduce WVP through trapping the water molecules inside the network. Furthermore, increasing the time of exposure with ultrasound waves can increase the number of radicals and covalent bonds and decrease WVP, respectively.

Fan et al. [30] used ultrasonic pretreatment (19 W, 5 min at room temperature) to modulate the interaction between the kidney bean protein isolate (KBPI) and chitosan and prepare composite films. The ultrasonic increased blending between KBPI and chitosan generated flexible films. Moreover, ultrasound pretreatment had no effect on the transmission of light, thereby increasing the opacity of the film.

Borah et al. [14] applied ultrasound treatment (40 ± 3 kHz, 50 W, $T = 45$, and 60 min) to composite film forming solutions of lime pomace and potato peel powder. Ultrasound treatment improved film properties with the increase in sonicated duration time, and decreased WVP and film moisture absorption in sample via 60-min sonication. In addition, ultrasound treatment increased the stretching properties of the composite films.

Sun et al. [84] confirmed that ultrasound treatment (up to 20 s, 24 kHz) is an appropriate method for solutions of soy protein films and positively affects the number and dispersion of soybean protein seeds. The size of the seeds decreased with the increase in the time of ultrasound exposure, resulting in a uniform appearance of the film. Also, the soy protein film structure of the ultrasound treatment was more uniform and its mechanical properties significantly improved, which ultimately caused a significant difference in TS and EAB.

Marcet Manrique et al. [56] applied ultrasound (20 kHz at several temperatures and times) in the egg yolk film-forming solution. Optimum ultrasound treatment was 45°C for 40 min for film preparation. Optimum conditions for ultrasound treatments improved the resolution of casting solutions, solubility, thickness, and mechanical characteristics of the prepared films. The results (lower particle size, lower poly dispersity index, and more film compression) showed that ultrasound

Table 3 The effects of cold plasma on edible packaging properties

Matrix	Type of food	Experimental conditions	Findings	References
Polypropylene film	Fresh-cut-melon	$V = 15$ kV, $f = 12.5$ kHz, RH = 90%, ET = 15, and 30 min	Increased dry matter, titratable acidity and shelf-life and decreased soluble solid content.	[88]
Chitosan-based film	–	$P = 100$ W (65 V, 1.5 A), $d = 5$ mm, ET = 30 s	Increased surface free energy, thermal stability, WVP, and drug release function and reduced bacterial growth.	[23]
Starch-based film	–	$P = 70$ w, ET = 30 min	Increased WVP, TS, Young's modulus, and hydrophobic property and decreased EAB.	[81]
Defatted soybean meal film	Smoked salmon	$P = 400$ W, ET = 15 min	Increased stretch ability and lightness and decreased lipid oxidation and hardness.	[65]
(CMC)-coated polypropylene film	–	$V = 14$ kV, $f = 20$ kHz, ET = 2 min	Increased WVP, antimicrobial and mechanical properties.	[36]
Sodium caseinate film	–	$V = 60$ and 70 kV, ET = 1–5 min	Increased the roughness, surface oxygen content, and hydrophilic property and decreased glass transition temperature.	[70]

was able to degrade protein aggregation by modifying the protein structure from the breaking point of covalent and non-covalent bonds.

Liu et al. [51] applied ultrasound treatment for 0, 10, 20, 30, and 40 min at 40 kHz frequency and 50 W to produce composite film solutions using tea polyphenol/polyvinyl alcohol by stripping method. Ultrasound treatment decreased the TS. The best overall film properties were achieved at 2:8 volume ratio of tea polyphenol/polyvinyl alcohol and 30-min ultrasound duration.

Zhong et al. [101] determined the effects of different ultrasound treatments (20 °C, 0–30 min, 25 kHz, and 0, 90, 180, and 270 W) on the blending film of methylcellulose/stearic acid. Exacerbation of the treatment condition, including ultrasound exposure time, resulted in reduced viscosity of the methylcellulose/stearic acid composite emulsions and increased the homogenization of fat distribution and internal microstructure of films. Ultrasound treatment improved mechanical and superficial hydrophobic properties. The treated sample showed the lowest WVP for 10 min and 270 W. However, excessive exposure to ultrasound reduced mechanical properties and moisture inhibition and created enormous spaces in the polymer matrix, leading to a negative effect on film performance. Furthermore, ultrasound improved the hydrophobic surface characteristics of composite films in the appropriate range. In general, ultrasound, as a modification form of film-forming emulsions, significantly enhances the compositional properties of films.

Cheng et al. [24] made use of sonication (20 kHz for 0, 2.5, 5, 10, 15, and 30 min at 60 ± 3 °C) to measure the dispersions of gelatinized maize starch film-forming solutions. Ultrasound treatment improved transparency, moisture resistance, and film structure. Furthermore, this treatment enhanced the starch amylose solubility and the free mobility of polymers in starch dispersion, resulting in a sharp reduction in viscosity and increased solubility even for 10% dispersion.

Marcuzzo et al. [57] applied ultrasound treatment at 24 Hz for (3–12) min on gluten-based film-forming solutions because protein films obtained from gluten in acidic conditions exhibited some of the problems in protein dispersion. Sonication process is considered as a physical method for improving protein dispersion and the appearance of this film without adding a chemical additive. Gluten had a high tolerance to ultrasound treatment, a useful approach to improving the hydrophilic surface properties and appearance of films.

Rodriguez-Turienzo et al. [73] applied sonication (820 W, 35 kHz for 1, 15, and 60 min) on the whey protein coating-forming solutions for frozen salmon fish. The results showed a reduction in drip loss in thawing and after cold storage in coated fish treated for 60 min than those sonicated for 15 min. The ultrasound treatment had no effect on the color of frozen fish, but enhanced the whiteness of the salmons during cooking compared to samples coated with un-sonicated whey protein. These coatings had no influence on sensory characteristics of fish. Ultrasound treatment significantly inhibited the lipid oxidation of salmon fillet compared to uncoated and un-sonicated samples. Therefore, ultrasound treatment of whey protein solutions can reduce the oxidation of frozen fish fats without adding chemicals and enhanced the shelf-life of products.

Banerjee et al. [7] used sonication (acoustic power, 168 kHz and 520 kHz for 0.5 and 1 h) to produce sodium caseinate and whey protein concentrate (WPC) films. Sonication process enhanced the TS of films. The average of TS in treated film was 224% compared to the untreated film. The ultrasound process in sodium caseinate films was more effective compared with WPC film. The intermediate power with low-frequency levels led to a much better TS in sodium caseinate film. Increasing the time of ultrasound exposure resulted in more powerful films.

Wang et al. [96] produced modified microcrystalline wheat bran cellulose (MWBC) by acid hydrolysis of wheat-bran

cellulose (WBC) using microwave/ultrasonic system (300 W, 30 °C, and 15 min). Then they formed a film of it. The result indicated that ultrasonic/microwave system enhanced tensile strength (TS) and water holding capacity (WHC) and reduced oxygen permeability (OP) and water vapor permeability (WVP) contents in films containing MMWBC due to decreasing of particle size and increasing of free hydroxyl numbers and interactions of carboxyls with amino components. In general, this system varied mechanical characteristics due to effect on size, packing style, distribution, and shape of filler particles. Also, ultrasonic/microwave system improved thermal properties such as T_g and T_c due to breaking of hydrogen links and happening of acid hydrolysis in wheat-bran cellulose amorphous part that maintain stable of crystalline part.

Wang et al. [97] determined the effect of microwave/ultrasonic system (20 °C, 500 W, 0, 10, 20, 30, and 40 min) on film containing soy protein and titanium dioxide. With the increase of microwave/ultrasonic system time up to 20 min increased TS, homogenous of structure and WHC and reduced WVP and OP. This system produced films with compact and homogeneous surfaces due to reducing of particle size, increasing of particle surface, free hydroxyls, and interaction of particles together, although longer time of treatment, could destroy matrix and produce a weak film.

Wang et al. [98] determined the effects of ultrasound/microwave treatment (20 °C to avoid of oleic acid oxidation, 15 min and 500 W) on soybean protein isolate (SPI) edible films with different proportions from oleic acid to stearic acid. In summary, variations in stearic acid and oleic acid ratios and microwave/ultrasound treatment had important impact on WVP and angular contact angle. Film containing 3:2 ratio of stearic acid to oleic acid prepared under microwave/ultrasound condition (20 °C, 15 min, and 500 W) indicated the lowest WVP and the highest angle (135°). The lower temperature and period of microwave may rely on activating and facilitating the influence of radiation on the solid phase emission [79]. However, the effect of ultrasound causes cavitation (creation, growth and breakdown of bubbles) in the solution [25]. Consequently, ultrasound/microwave process (15 min and 500 W) resulted in the creation of compressed-films, followed by improved contact angles. Also, the surface of treated films is fairly uniform because ultrasound/ microwave treatment improves the mixing of films, resulting in a relatively smooth and continuous surface [96]. The results pertaining to studies on ultrasound and ultrasound/microwave effects on edible packaging are summarized in Table 4.

High-Pressure Homogenization

High-pressure homogenization (HPH) develops the structural and physicochemical characteristics of packaging thus it can

be applied in film production [32, 37, 74, 82]. HPH treatment has been employed in the food industry to process various food products, including meat, fruits, juices, and vegetables with a pressure range of 100 to 800 MPa depending on the application purpose [3]. The influence of HPH process depends on the applied pressure, temperature, storage time, and molecular size [64]. Several studies have reported that the HPH process reduces the internal viscosity, increases the power of inflation [54], forms a weak gel [95], decreases temperature and enthalpy gelatinization [38], and affects the crystalline structure [22, 94].

Effect of HPH on Edible Packaging

Saricaoglu et al. [75] used HPH treatment at a pressure between 0 and 150 MPa on meat protein solution for film forming. By enhancing pressure to 100 MPa in suspensions treated, the particle size decreased and then increased due to protein accumulation. The reduction in particle size decreased water solubility and increased WVP and TS. The reduction in the size of the particle protein resulting from the increase in the pressure up to 100 Mpa led to the homogeneous distribution of their particles. All samples were homogeneous except the sample homogenized with 150 MPa. The non-porous and smooth film resulted in a higher film clarity. Additionally, the EAB values increased by the increase in pressure to 100 MPa, but reduced with a pressure to 150 MPa. In general, HPH treatments to 100 MPa improved the solution characteristics and the preventive and mechanical properties of film.

Shahbazi et al. [77] evaluated starch under the influence of HPH at 14 and 20 MPa for production of film including starch and κ -carrageenan. It can be concluded that this method is safe for starch, inexpensive, and fast. In addition, the HPH process produced smooth hydrogels with stronger gel nets, and reduced the degree of crystallization in starch grains and the amount of crystallization relative. The HPH process resulted in a better dispersion of starch in the κ -carrageenan matrix, which ultimately increased water resistance and film obstruction properties. The produced film under HPH had the highest hydrophobic level and TS value. These changes were more pronounced when applied with a high level of homogenization pressure. HPH had no influence on starch granules integrity. However, the many points and cavities appearing outside the granule were increased with the increase in process intensity. In addition, the pressure produced during HPH can cause physical damage to the starch granule. The probable changes in the shape and appearance of granules were due to the partial gelatinization caused by the increase in the temperature during homogenization [94]. Changes and cavities created at the cross section of wheat starch were due to the high pressure and shear of sonication, but the integrity of granules did not change [55].

Table 4 The effects of ultrasound and ultrasound/microwave on edible packaging properties

Matrix	Experimental Conditions	Main findings	Reference
Methylcellulose film	Frequency (35 kHz) for times (5, 15, 30, and 45 min)	WVP, TS and EAB increased.	[2]
Chitosan/bean protein isolate film	Power (19 W) for 5 min at room temperature	The opacity of the film increased and produced flexible film.	[30]
Potato peel/lime pomace film	Frequency (40 ± 3 kHz), power (50 W), for 45 and 60 min	Film properties improved with increasing ultrasound time.	[14]
Soy proteins film	Frequency (24 kHz) for 0–20 s	Uniformity and mechanical properties (TS and EAB) improved.	[84]
Egg yolk film	Frequency (20 kHz) at several temperatures and times	The resolution of solutions, mechanical properties, thickness and solubility of film improved.	[56]
Tea polyphenol/polyvinyl alcohol based film	Power (50 W), Frequency (40 kHz) for 0, 10, 20, 30, and 40 min	TS reduced.	[51]
Methylcellulose/stearic acid blending film	Power (0, 90, 180, and 270 W), frequency (25 kHz) at 20 °C for 0–30 min	The viscosity reduced and increased fat distribution, internal microstructure, and mechanical properties.	[101]
Gelatinized maize starch film	Frequency (20 kHz) for (0, 2.5, 5, 10, 15, and 30 min) at 60 ± 3 °C	The viscosity reduced and enhanced solubility of starch amylose.	[24]
Gluten-based film	Frequency (24 Hz) for 3–12 min	Enhanced protein dispersion and the appearance of film.	[57]
Whey protein film	Power (820 W), frequency (35 kHz) for (1, 15, and 60 min)	Drip loss in thawing and lipid oxidation decreased and had no change on the color of frozen fillets and sensory properties.	[73]
Whey protein/sodium caseinate concentrate film	Power (low-high), frequency (168 kHz and 520 kHz), for (0.5 and 1 h)	TS increased. Sonication in sodium caseinate films showed more effective than whey protein concentrate film.	[7]
Soy protein isolate + WBC + MWBC film	Microwave/ ultrasonic system: 30 °C and 300 W for 15 min	Ultrasound/ microwave improved TS and WHC and reduced WVP and OP.	[96]
Soy protein isolate/ TiO ₂ film	Microwave/ ultrasonic system: 20 °C, 500 W for 0, 10, 20, 30, and 40 min	System time up to 20 min increased TS, homogenous of structure and WHC and reduced WVP and OP.	[97]
SPI + oleic and stearic acids	Microwave/ ultrasonic system: 20 °C, 15 min, and 500 W	Ultrasound/ microwave improved the mixing of film resulted in uniformity of surface.	[98]

Molinaro et al. [61] studied the influence of pressure combined with storage time and temperature on gelatin solution. Optimum HPH process was set at pressure (600 MPa) and time (30 min) at 20.45 °C. Shelf life increased in products pecked by films produced using this method.

The films produced in optimal conditions showed no significant influence on thermal and mechanical characteristics and water vapor transmission rate. The transmission rate value was reduced at pressures above 600 MPa. Oxygen transmission rate decreased when a high pressure was applied to a gelatin-based film solution for a long time at room temperature may be due to the presence of a dense polymer matrix affecting oxygen transmission rate that blocks the release of oxygen molecules [45].

Longer high pressure produced films with compact polymer matrix and decreased oxygen transmission rate. High-pressure treatment influenced the structure of gelatin films and prevented the creation of semi-crystalline region, hence the reduction in the crystalline phase. Heremans and Smeller [35] reported that the pressure from 500 to 600 MPa was sufficient to make compatible variations in protein. In addition, the reduction in the enthalpy showed the amount of crystalline inside the system due to the high-pressure mechanical forces. High pressure increased mechanical properties in films. The mechanical forces during

high-pressure treatment increased rigidity in the gelatin gel due to the improvement of hydrogen bonding. Optimum conditions had a significant increase in water-proofing properties of film [61]. The higher density in the gelatin-based film structure reduced the rate of water vapor transmission value due to the increase in the resistance of films to the water releases [89]. Films produced under high-pressure treatments were lighter, redder, and more rigorous than control films. The enhance in lightness is be due to the increase in light diffusion from denatured proteins [85]. A summary of studies on HPH effects in packaging are reported in Table 5.

High Hydrostatic Pressure

As a nonthermal process, high hydrostatic pressure (HHP) has been applied to the structural and physical modification of biopolymers including protein and polysaccharide. The reaction balance of the system moves toward to the reduction of exterior forces under high-pressure situation; consequently, with decreasing volume, the HHP leads to chemical reaction and modifications in physical structure [50]. Additionally, HHP can prevent the loss of moisture during processing and cause physical modification in the film properties [49, 90].

Effect of HHP on Edible Packaging

High hydrostatic pressure (HHP) can be used for physical modification of starch. The application of this method induces a unique starch gelatinization at room condition compared to samples treated under thermal condition [18, 39, 41, 90]. Starch granules were partially decomposed by high pressure, and the gel texture became harder and had less amount of amylose release compared with samples treated by the thermal method [13, 18, 90, 92].

Kim et al. [42] gelatinized starch by HHP to produce buckwheat and tapioca starch films. Films prepared via HHP had better physical properties, water resistance, and thermal properties compared to those prepared by heat treatment process regardless of the starch type. Consequently, HHP can be applied as a cold gelatinization method in the preparation of starch films. A high degree of hydrostatic pressure processing at 600 MPa (20 °C, 20 min) and thermal processing (90 °C, 20 min) was used for starch gelatinization. As a result, films prepared under HHP had higher TS and EAB compared with those under thermal conditions, regardless of the starch type. Buckwheat starch films produced by HHP had lower WVP and higher water solubility in comparison with heat treatment films. Starch films prepared using HHP are able to maintain a higher moisture content in the film matrix compared to thermal processing films, and water can act as a plasticizer in starch-based films [78]. In addition, film solutions prepared using HHP have less viscosity compared to those treated by thermal conditions mainly because of the crystalline structure residue that prevents the melting of amylopectin molecules by amylose until some are stabilized [83]. HHP in starchy films results in higher formation enthalpy and improves the thermal stability of films [42]. In general, the optical properties of films prepared using HHP can be the result of various reasons such as sample type and process condition (pressure, time, and temperature).

Conclusion

Edible films and coatings are placed on/or within foods and have special functions such as mechanical protection of food, inhibition of material transfer (water, gas, fat), preservation, and transfer of food components and additives such as colors and flavors and prevention of microorganism growth. Widespread researches have been studied for novel thermal and nonthermal technologies to improve edible film and coating properties and their application in food industry. As a result, to improve the novel thermal and nonthermal effects on packaging, different parameters such as technology properties, types of edible film and coating, type of food matrix, and packaging storage condition must be considered. As a

suggestion, the combination of different technology effects on edible film and coating features can be considered.

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Table 5 The effects of HPH on edible packaging properties

Matrix	Experimental conditions	Findings	Reference
Deboned chicken meat proteins film	Treatment at a pressure between 0 and 150 MPa	Improvement of film-forming solutions and mechanical and barrier properties of film (HPH about 100 Mpa)	[75]
Buckwheat and tapioca starch films	600 MPa (20 °C, 20 min) and thermal processing (90 °C, 20 min)	Improvement of physical properties, water resistance and thermal properties of film	[42]
κ-carrageenan/starch blend film	14 MPa (two and five passes) and 20 MPa (two passes)	Improvement mechanical properties and WVP	[77]
Gelatin-based packaging films	(600 MPa) and time (30 min) at 20.45 °C	Improvement of water-proofing properties of film	[61]

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