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Review

Combining Non-Thermal Processing Techniques with Edible Coating Materials: An Innovative Approach to Food Preservation

Arezou Khezerlou [1], Hajar Zolfaghari [1], Samira Forghani [2], Reza Abedi-Firoozjah [3], Mahmood Alizadeh Sani [4], Babak Negahdari [5], Masumeh Jalalvand [5], Ali Ehsani [6,*] and David Julian McClements [7,*]

1 Students Research Committee, Department of Food Sciences and Technology, Faculty of Nutrition and Food Sciences, Tabriz University of Medical Sciences, Tabriz 5166614711, Iran
2 Department of Food Science and Technology, Faculty of Agriculture, Urmia University, Urmia 5166614711, Iran
3 Student Research Committee, Department of Food Science and Technology, School of Nutrition Sciences and Food Technology, Kermanshah University of Medical Sciences, Kermanshah 5166614711, Iran
4 Food Safety and Hygiene Division, Environmental Health Engineering Department, School of Public Health, Tehran University of Medical Sciences, Tehran 5166614711, Iran; saniam7670@gmail.com
5 Department of Medical Biotechnology, School of Advanced Technologies in Medicine, Tehran University of Medical Sciences, Tehran 5166614711, Iran
6 Nutrition Research Center, Department of Food Sciences and Technology, Faculty of Nutrition and Food Sciences, Tabriz University of Medical Sciences, Tabriz 5166614711, Iran
7 Department of Food Science, University of Massachusetts Amherst, Amherst, MA 01003, USA
* Correspondence: ehsani@tbzmed.ac.ir (A.E.); mcclements@foodsci.umass.edu (D.J.M.)

Abstract: Innovative processing and packaging technologies are required to create the next generation of high-quality, healthy, safe, and sustainable food products. In this review, we overview the potential of combining edible coating materials with non-thermal processing technologies to improve the quality, increase the safety, extend the shelf life, and reduce the waste of foods and plastics. Edible coatings are typically assembled from food-grade structuring ingredients that can provide the required mechanical and barrier properties, such as proteins, polysaccharides, and/or lipids. These materials can be fortified with functional additives to further improve the quality, safety, and shelf life of coated foods by reducing ripening, gas exchange, and decay caused by bacteria and fungi. Non-thermal processing techniques include high hydrostatic pressure, pulsed light, ultrasound, and radiation technologies. These technologies can be used to inhibit the growth of pathogenic or spoilage microorganisms on packaged foods. Examples of the application of this combined approach to a range of highly perishable foods are given. In addition, the impact of these combined methods on the quality attributes of these food products is discussed.

Keywords: edible coatings; non-thermal processing; innovative technology; food safety; sustainable packaging

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1. Introduction

Food safety is a key priority of the food industry [1]. Post-process contamination of food products due to inappropriate handling, packaging, and storage can lead to the spread of food-borne diseases and to increased food waste [2]. Hence, it is important to decontaminate foods before packaging and then ensure that microbial contamination does not occur after packaging [3]. The nature of the packaging materials used to protect foods is important because it affects their effectiveness as well as consumer perceptions. Ideally, any packaging material should not adversely affect the sensory appeal, quality, affordability, and health of a food product [4]. Moreover, it should ideally be produced and disposed of in an environmentally friendly manner. The use of synthetic compounds as film-forming substances (such as petroleum-based plastics) or as additives (such as sorbic acid, benzoic acid, propionic acid, and sulfur dioxide) can lead to packaging materials that can protect foods but that are often perceived negatively by consumers [5,6]. Consequently, there is interest in developing alternative kinds of food packaging materials that are more environmentally and consumer-friendly.

Microbial contamination can also be eliminated or reduced by using various thermal treatments of foods, such as pasteurization or sterilization. However, these processes often cause appreciable reductions in the sensory and nutritional profiles of foods. Consequently, there is interest in identifying alternatives to traditional thermal processing technologies that are able to improve product safety and shelf life without reducing product quality or nutrition [7]. For instance, natural antimicrobial compounds, such as essential oils (EOs), bacteriocins, and herbal extracts, are being explored for their potential application as additives in food packaging materials, such as films and coatings [8]. Non-thermal technologies, such as high hydrostatic pressure, pulsed light, ultrasound, and radiation technologies, are another food preservation method suitable for improving the safety and shelf life of foods [9,10]. Foods can also be preserved by using edible coatings, which consist of a thin and continuous layer of food-grade materials deposited around the food surfaces [11,12]. These coatings are often applied onto the surfaces of fresh produce by spraying, dipping, or brushing to enhance their safety, shelf life, and quality [13,14]. Edible coatings can be prepared from natural film-forming materials such as polysaccharides, proteins, lipids, and their blends [15]. Edible coatings are commonly applied to foodstuffs to inhibit their deterioration through oxidation, microbial spoilage, and gas exchange, as well as to improve their physical, tactile, and visual properties [16,17]. The functional performance of coatings can often be improved by incorporating active compounds into them, such as antimicrobial, antioxidant, or anti-browning agents [18]. However, the use of these any of these methods alone is typically unable to reduce pathogenic or spoilage microorganisms to a suitably low level.

A recent trend in food preservation has been the utilization of hurdle technologies, which use a combination of different approaches to increase the overall effect [19]. Indeed, combined treatments often exhibit synergistic effects, i.e., they lead to a greater effect than expected from the sum of the individual treatments. Previous studies have reported that coatings combined with non-thermal treatments have had an appreciable lethal effect on several microorganisms [20]. Consequently, there is interest in combining these two technologies together to improve their overall efficacy [9]. This review paper therefore describes the combined use of non-thermal technologies and edible coatings for the preservation of food products. It begins by describing different kinds of biodegradable packaging materials that can be used as edible coatings. It then discusses different types of non-thermal processing methods that can be used to treat foods. Finally, it provides examples of the use of combined methods to enhance the shelf life, safety, and quality of foods. Figure 1 presents a schematic of combining non-thermal methods with edible coatings as a new approach to food preservation.

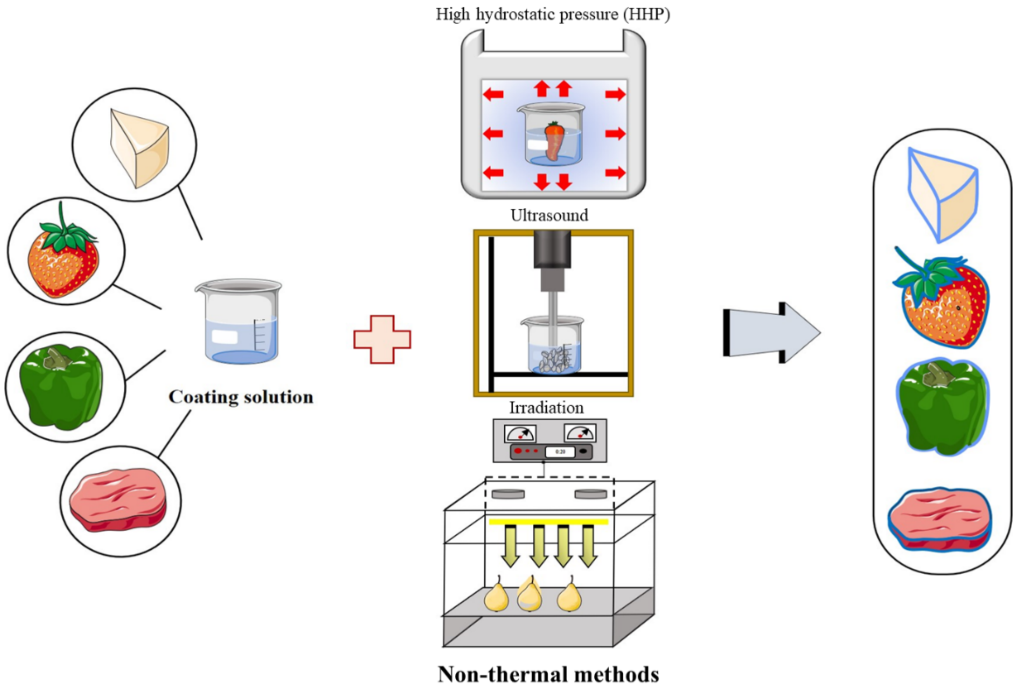

Figure 1. Schematic of combining non-thermal methods with edible coatings as a new approach to food preservation.

2. Food Packaging Materials

During recent decades, the expectations of consumers for food products with high quality, safety, and shelf life led to the emergence of many advancements in packaging systems. Active packaging materials are being designed that contain functional additives that can extend the shelf life of foods, including oxygen scavengers, moisture absorbers, antioxidants, and antimicrobials [21]. These active packaging systems often extend the shelf life of foodstuffs by decreasing their deterioration rates. In some cases, the active ingredients (such as antimicrobials or antioxidants) are designed to be released from the packaging materials into the food product or its head space during storage [22]. Smart packaging materials are also being produced that contain indicators such as temperature, pH, or gas indicators [21]. This type of packaging material is usually designed to provide visual information about the safety, quality, or freshness of packaged food in real time [23,24]. Indicators are typically attached to the interior or exterior of the packaging material to monitor, record, and communicate information to food producers, distributors, and consumers along the whole supply chain [25,26]. In the remainder of this review, we focus on the utilization of active packaging materials to form coatings that are designed to preserve foods, as well as the combination of non-thermal processing methods.

2.1. Biodegradable Packaging Materials

Due to the environmental problems associated with the production and disposal of petroleum-based plastic packaging materials, there has been growing interest in the development of more sustainable biodegradable packaging materials assembled from renewable natural resources. Edible film-forming substances, such as proteins, polysaccharides, and lipids, are commonly used to assemble this kind of packaging material.

2.2. Functional Additives for Active Packaging

The functional performance of biodegradable packaging materials can often be improved by including functional additives. Antioxidants, antimicrobials, light blockers, barrier enhancers, and mechanical modulators are often added to coatings for this purpose.

2.2.1. Preservatives: Antioxidants and Antimicrobials

Free radicals and reactive oxygen species (ROS) have deleterious effects on food quality and nutrition due to their ability to promote the oxidation of major food ingredients, such as lipids and proteins. Antioxidants can be incorporated into edible coatings to inhibit oxidation reactions in foods. Natural botanically derived antioxidants have received special attention recently because of consumer demand for greener labels [27]. The effectiveness of antioxidant compounds to scavenge free radicals is frequently determined using in vitro assays, such as the DPPH, FRAP, and ABTS assays [28]. These assays often measure the effectiveness of a coating material to scavenge free radicals.

Several kinds of antioxidants have been used to increase the antioxidant activity of edible films, including essential oils, phytochemicals, organic nanoparticles, and inorganic nanoparticles. For instance, López-Mata et al. (2018) reported that incorporating α-cinnamaldehyde into chitosan films increased their antioxidant properties. Qin et al. [29] showed that adding betacyanins to PVA/starch-based packaging films increased their radical scavenging activities in a dose-dependent manner. Moreover, Sholichah, Nugroho [30] reported that including quercetin in packaging films increased their antioxidant activity. The antioxidant activity of phytochemicals is closely attributed to the presence of numerous hydroxyl (-OH) groups in their structures and their electron-donating capacity to reactive free radicals during oxidation, which can neutralize free radical chain reactions [30].

The antimicrobial activity of food packaging materials is another important factor to consider when developing edible coatings. Natural substances that exhibit good antimicrobial activity, such as essential oils, phytochemicals, organic nanoparticles, and inorganic nanoparticles, can be incorporated into biodegradable packaging materials. For instance, Mohamad, Mazlan [31] showed that the antimicrobial activity of poly (lactic acid) films was increased by incorporating thymol, kesum, and curry essential oils. In another study, Chen, Zong [32] reported that the incorporation of cinnamaldehyde into PVA/starch films increased their ability to inhibit *Salmonella putrefaciens*. In addition, other kinds of active additives have also been incorporated into packaging materials to enhance their antioxidant activity, such as ZnO nanoparticles in chitosan/CMC films [33], ε-poly lysine in sodium lactate/whey protein films [34], anthocyanins in chitin/methylcellulose films [35], and silver nanoparticles in PVA/starch films [36].

2.2.2. Light Blockers

Many foods contain ingredients that are susceptible to degradation when exposed to light, especially electromagnetic radiation in the ultraviolet region. For instance, the chemical degradation of carotenoids, curcuminoids, or omega-3 fatty acids is accelerated in the presence of light [37]. Consequently, it is often important to design packaging materials that can block light from entering the food. Light absorbers and scatterers are substances that can block light, thereby protecting food components from photodegradation reactions [38]. Light scatterers are particulate materials with dimensions close to the wavelength of light, so they scatter light strongly, thereby blocking the ability of light to enter the packaging material and damage the food. However, these materials also make the packaging material appear cloudy or opaque. Light absorbers are chromophores that selectively absorb light waves over certain wavelength ranges and that can also be included in packaging materials to protect packaged foods from photodegradation. A wide variety of UV-protective chromophores have been studied for this purpose, including proteins, natural pigments, anthraquinone, lignin, flavonoids, tannin, curcuminoids, chalcones, and bixin [37–39]. As an example, lignin has chromophore functional groups (e.g., aromatic rings, conjugated carbonyl groups, and C=C bonds) that can absorb a broad spectrum of UV light (250–400 nm) [37]. Consequently, they can be used as light blockers to protect photo-labile substances from degradation when exposed to light.

2.2.3. Barrier Enhancers

The safety, quality, and shelf life of packaged foods are mainly influenced by the transfer of certain molecules, such as gases (such as O_2, CO_2, water vapor, or organic vapor) or liquids (such as water or oil), between the packaging materials and the surrounding environment as well as by the diffusion of other ingredients through the packaging film, including nanoparticles [40]. Consequently, additives are required to control the movement of different substances through packaging materials and to control the rate of oxidation reactions, microbial growth, enzymatic browning, and other processes responsible for changes in the look, feel, taste, and nutrition of foods. Controlling the oxygen and water vapor permeability (WVP) of films is critical for many applications due to the important role oxygen and water play in various chemical reactions and in microbial growth. Therefore, low oxygen and water vapor permeability are generally required for food packaging materials to minimize oxygen and moisture transfer between the food and the surrounding environment [41,42].

The permeability of natural or synthetic polymer-based films depends on their thickness, porosity, integrity, and rheology. Therefore, it can be modified and controlled by incorporating various kinds of additives into the films, such as blockers, plasticizers, or crosslinking agents [40]. These substances may either decrease or increase a film's permeability depending on their effects on the polymer chain interactions, the ratio between any crystalline and amorphous zones, the degree of porosity, and the hydrophilic/hydrophobic ratio. Recently, Tanwar, Gupta [43] reported that the addition of coconut shell extract increased the WVP of PVA/starch films, which may have been because of the hydrophilic nature of the components of the prepared films. In contrast, Ceballos, Ochoa-Yepes [44] reported that incorporating yerba mate extract into starch films decreased their permeability to water vapor and oxygen. Consequently, an appropriate additive must be selected for the required application.

2.2.4. Mechanical Modulators

A food packaging material is expected to possess certain mechanical properties including flexibility, stretchability, integrity, and strength to protect the food throughout the distribution chain. The mechanical properties of packaging materials can be assessed by various parameters such as their tensile strength (TS), elastic modulus (EM), and elongation at break (EAB) [40,45]. Various kinds of additives incorporated into packaging materials may either positively or negatively influence their mechanical properties. In addition, several factors including the type or nature of biopolymer, as well as the number and strength of the interactions between the polymer molecules, can impact the mechanical properties of packaging systems [45]. As an example, it was reported that adding grapefruit seed extract and TiO_2 nanoparticles reduced the TS and EM of corn starch–chitosan films, while the EAB increased significantly ($p < 0.05$) [46]. In another study, the TS of CMC films was reported to decrease from 37 to 23 MPa, the EM to decrease from 114 to 41 MPa, and the EAB to increase from 32 to 53% after adding α-tocopherol nanocapsules [47]. Chen, Zong [32] reported that incorporating cinnamaldehyde into PVA/starch-based films decreased the TS and increased the EAB of the films. This change in TS can be partially related to the heterogeneous film structure with a discontinuous phase created after adding the cinnamaldehyde. The increase in EAB can be partially attributed to the plasticizing effect of this essential oil [32].

3. Non-Thermal Methods in Combination with Food Coating Materials

3.1. High Hydrostatic Pressure (HHP)

HHP is a non-thermal process in which a pressure of 100 to 1000 MPa is applied to a food, which can be either liquid or solid food [48]. Typically, the temperatures used are below those normally utilized in traditional thermal processing operations. However, the temperature does increase as the pressure increases, by almost 3 °C per 100 MPa, which has to be taken into account [49]. A commercial-scale high-pressure processing time is around

20 min. HHP is a simple, flexible, and reliable process that does not require the use of additives; as a result, it has been successfully applied to food products [50,51]. This process has been used commercially in various products such as fruit juice, jam, jelly, sauces, meat, fish, ready-to-eat products, and yogurts [52]. In addition, new applications of HHP are being developed in the pharmaceutical and medical fields [53]. HHP can be applied to products that are packaged into flexible containers (high-pressure-resistant packaging). The pressure is applied to a chamber containing a liquid medium (commonly water), causing it to be uniformly and instantly transmitted all over the sample, independent of its shape, size, and composition [54].

HHP can be used for various purposes in food applications, including inhibiting bacterial growth, inactivating enzymes, prolonging shelf life, maintaining natural nutrients, improving sensory attributes, and increasing desirable properties (digestibility) [55,56]. It has been reported that HHP can inactivate microorganisms by breaking non-covalent bonds and damaging cell membranes [57]. The pressure applied in this process has a very small effect on covalent bonds. The combined use of HHP and an edible coating can be applied as a two-hurdle factor approach to reduce the survival of microorganisms, inactivate enzymes, and enhance the quality of food products [58].

Table 1 summarizes recent studies related to the combined use of HHP and edible coating on various products. Gómez-Estaca, López-Caballero [59] applied high-pressure processing (250 MPa) and an edible film composed of gelatin, chitosan, and clove essential oil on vacuum-packed salmon carpaccio. The combined approach reduced the total viable bacteria (TVC), *pseudomonads*, H_2S-producing organism, and enterobacteria content. Donsì, Marchese [60] studied the effects of combining a modified chitosan coating with an HHP treatment on the color, firmness, and microbial (*Listeria innocua*) count of green beans during storage for 14 days at 4 °C. The green beans were coated by spraying a modified chitosan solution containing a nanoemulsion of mandarin essential oil for 10 s, and then they were inoculated with 10^7 cfu/g of *L. innocua*. The coated green beans were packed in multilayer polymer/aluminum/polymer film and then exposed to HHP treatment at pressure levels of 200, 300, or 400 MPa for 5 min at 25 °C. According to the results, combining the coating with 200, 300, and 400 MPa pressure declined the population of *L. innocua* by 1.6 to 3.5 logs. This combined treatment improved the firmness of the green beans due to the ability of the pressure to thicken the cell walls. This treatment also led to a significant color change: the L* (darkness) and b* (yellowness) values of the green beans decreased, while the a* (greenness) values increased. This may be due to the disruption of the chloroplasts and leakage of chlorophyll, which was indicated by a bright green color on the surface. Gonçalves, Gouveia [61] produced cellulose acetate films with oregano essential oils using a casting method and then subjected the films to an HHP treatment at pressures of 300 or 400 MPa for 5 or 10 min. The ability of the films to inhibit *L. monocytogenes*, *S. aureus*, and *E. coli* on Coalho cheese was measured during 3 weeks of storage at 4 °C. At the end of storage, the microbial count for the three types of microorganisms was reduced by using the combined treatment.

Table 1. The effects of non-thermal processes combined with edible coating on food product quality and safety.

Product	Type of Food	Type of Process	Process Conditions	Polymer	Concentration of Polymer (%*w*/*v*)	Active Packaging Materials	Significant Results	Ref
Meat	Rainbow trout fillets	High hydrostatic pressure (HHP)	220 MPa, 15 °C, 5 min	Chitosan	1.5	-	Slight change in major bond of sarcoplasmic and myofibrillar muscle fractions	[62]
	Rainbow trout fillets	HHP	220 MPa, 15 °C, 5 min	Chitosan	1.5	-	Extend the shelf life by about 24 days	[63]
	Trout fillets	HHP	300 MPa, 12 °C, 10 min	Chitosan	1.5	Clove EO	Strong additive antimicrobial effect against mesophilic aerobic and coliform bacteria	[64]
	Cured Iberian ham	HHP	600 MPa, 8 min	Chitosan	2	Nisin, Rice bran extract	6 Log CFU/g of *L. monocytogenes* reduction	[65]
	Fermented sausages	HHP	600 MPa, 12 °C, 5 min	PVOH	13	Nisin	No extra protection on *L. monocytogenes*	[66]
	Chicken	γ-irradiation	2.5 kGy	Chitosan	2 0.1	Grape seed extract	Reduction of bacterial growth Increasing shelf life	[67]
	Minced chicken thigh	γ-irradiation	0, 2, 4, and 6 kGy	Pectin	~3	Papaya leaf extract	Improving the quality and safety of minced chicken thigh meat Reduced the initial total bacterial count, psychrophilic bacteria, and LAB Prolonged shelf life	[68]
	Carp fillets	Irradiation	3 kGy	Chitosan	2	Rose polyphenols	Extending the shelf life of fish Preserving sensory quality Preventing bacterial growth, oxidation, and changes in color	[69]
	Carp fillets	γ-irradiation	0, 1, 3, and 5 kGy	Calcium caseinate	4.7	Rosemary Oil	Increasing in the bacterial inhibitory effect Improving the quality and safety Extending the refrigerated shelf life	[70]
	Minced meat	γ-irradiation	3 kGy	CMC Chitosan PC	3 0.5 3	ZnO	Improving microbiological, chemical, and sensory quality Increasing the chilling life of minced meat	[71]
	Carp fillets	Ultrasound	40 KHz	Chitooligoaccharides	1	-	High score of sensory properties for coating and ultrasound Increased shelf life by 11 days 1.40 Log CFU/g of TVC reduction Applying coating with ultrasound led to reduction of TVB-N by 37%	[72]

Table 1. *Cont.*

Product	Type of Food	Type of Process	Process Conditions	Polymer	Concentration of Polymer (%*w*/*v*)	Active Packaging Materials	Significant Results	Ref
Fruit & vegetable	Fresh-cut Apple	Pulsed light (PL)	12 J/cm^2	Gellan	0.5	Ascorbic acid	Delayed the microbiological spoilage Preserved the sensory quality Decreased softening and browning of apple slices	[73]
	Fresh-cut Apple	PL	0.4 J/cm^2 per pulse	Pectin	2	Ascorbic acid	Reduced browning and softening of apple slices Led to 2 log CFU/g decline of microbial papulation Preserved sensory characteristics	[74]
	Fresh-cut cantaloupe	PL	0.9 J/cm^2 every 48 h up to 26 days	Sodium alginate	1.86	-	Compared with PL, alginate coating revealed more effectiveness in preserving high pectin content in cantaloupe slices. PL treatment was more effective than alginate coating in maintaining hemicellulose The combination of PL treatment with alginate manifested a synergistic effect on maintaining the overall cell wall fractions and cell wall integrity of cantaloupes	[75]
	Fresh-cut cucumber slices	PL	4, 8, and 12 J/cm^2	Chitosan	2	Carvacrol EO	Coating was less effective on *E. coli ATCC 26* reductions. PL treatments showed more effectiveness on microbial inactivation The inactivation of *E. coli ATCC 26* increased by increasing PL fluences Applying chitosan coating containing 0.08% carvacrol in combination with PL treatment (12 J/cm^2) led to reduction of more than 5 log cycles in the *E. coli* population	[76]
	Tomatoes	PL	2, 4, and 8 J/cm ^{2}	Sodium alginate	0.5	Oregano EO	Applying coating containing 0.17% Oregano EO in combination with PL treatment (4 J/cm^2) led to reduction in the TVC, yeast, and mold	[77]
	Apple cubes	HHP	400 MPa, 35 °C, 5 min	Alginate	2	Vanillin	Reduction of *E. coli* by >5 log Reduced color changes Maintain firmness Increased phloridzin concentration (17%)	[78]
	Fresh-Cut Kiwifruit	Ultrasound	40 KHz, 350 W, 10 min	Chitosan	1	ZnO	Reduced ethylene, carbon dioxide production, and water loss with combination treatment with 1.2 g/L ZnO	[79]
	Fresh-Cut Cucumber	Ultrasound	20 kHz, 400 W, 10 min	Chitosan	1	Carbon dots	5.18 log CFU/g of microbial papulation reduction 3.45 log CFU/g of mold and yeast reduction Reduced respiration rate and weight loss Increased TSS, brix, and ascorbic acid amount Maintain flavor and taste	[80]

Table 1. *Cont.*

Product	Type of Food	Type of Process	Process Conditions	Polymer	Concentration of Polymer (%*w*/*v*)	Active Packaging Materials	Significant Results	Ref
	Pumpkin	Ultrasound	40 KHz, 150 W	Sodium alginate	3	-	Reduced processing time and solid uptake Increased water removal rate Improved texture	[81]
	Bell pepper	UV-C irradiation	254 nm, at 8 ± 1 °C, 24 days, 80%–85% RH	Aloe gel cinnamon oil chitosan	(1.5 and 2.5) (0.30 and 0.40) (1 and 1.5)	Cinnamon oil	Improving the quality of fruit Reduction in softening, weight loss, and electrolyte leakage	[82]
	Plum	γ-irradiation	1.5 kGy, 25 ± 2 °C, RH 70% and 3 ± 1 °C, RH 80%	CMC	0.5–1.0	-	Maintaining the storage quality Delaying the decaying Reduction in yeast and mold count	[83]
	Cherry	γ-irradiation	1.2 kGy, 25 ± 2 °C, RH 70% and 3 ± 1 °C, RH 80%, at 28 days	CMC	0.5–1.0	-	Maintaining the storage quality Delaying the decaying Delaying the onset of mold growth	[84]
	Jujube	Ultraviolet irradiation	253.7 nm, 4, 6, 8, and 10 min	Chitosan	1, 1.5, 2, and 2.5	-	Reduction of decay incidence Restraining increase in respiration rate, weight loss, malonaldehyde content, and electrolyte leakage Maintaining the activities of superoxide dismutase, peroxidase, and catalase at higher level Restraining decrease in ascorbic acid and chlorophyll	[85]
	Green beans	γ-irradiation	0.25 kGy	Chitosan	3	Mandarin EO	Reduction in microbial population and controlling their growth	[86]
	Carrot	γ-irradiation	0.5 kGy	Calcium caseinate	5	Cinnamon, citronella, lemongrass, and oregano EOs	NO significant effect on weight loss, color, or firmness Decreased the TMF and yeast and mold count after 7 days	[87]
	Peanut	Ultrasound	25, 40, and 80 kHz	WPI Zein CMC	11 15 0.5	-	Delayed hexanal formation (11% for CMC, 48% for WPI)	[88]

3.2. Ultrasound

Ultrasonic technologies involve the use of oscillating pressure waves with frequencies typically in the range from about 20 kHz to 10 MHz in most industrial applications [89]. Based on the magnitude of the intensities employed, ultrasound can be classified as high intensity (destructive), which is used to change the properties of foods, or low intensity (non-destructive), which is used to measure the properties of foods [90]. Two essential requirements of this method are a source of ultrasound and a condensed medium [91]. Ultrasonic waves are typically applied to liquid, semi-solid, or solid systems [92]. Samples can be treated with ultrasound irradiation by immersing them within an ultrasonic bath or by directing the pressure waves generated by an ultrasonic probe onto them [93]. In some cases, ultrasonic waves are directly applied to the surfaces of samples, whereas in other cases, they may pass through the air first [94].

Ultrasonic treatments can inactivate bacteria and enzymes, which is useful for improving the shelf life and safety of foods [95]. The high-intensity ultrasound technologies used in food processing can cause physical and/or chemical changes in foods through cavitation, which involves the formation and rapid collapse of gas bubbles in fluids in the presence of fluctuating pressure waves [96]. Cavitational forces can break up structures within foods as well as accelerate mass transfer processes. Coating foods with edible films alters the effects of ultrasound on mass transfer processes [97].

Edible coatings and ultrasound can be used in combination to minimize quality deterioration in foods. For instance, the peanut samples were first subjected to ultrasonic treatments (25, 40, and 80 kHz/10 min) and subsequently dipped in carboxymethyl cellulose (CMC) solution containing α-tocopherol, rosemary, and tea extracts, after which there was a striking increase in the oxidative stability of peanuts stored for 12 weeks at 35 °C [98]. This effect was attributed to the ability of sonication to remove some of the surface lipids from the peanuts, as well as to the barrier properties provided by the coatings. Reducing the amount of surface lipids available to react with oxygen reduced lipid oxidation. A combination of sonication and a CMC coating has also been shown to improve the quality and nutritional profile of banana slices [99]. In this case, the banana slices were first coated by immersion in CMC solutions, and then they were sonicated.

Researchers have evaluated the effects of combining sonication with chito-oligosaccharide (COS) coatings on the microbial and chemical properties of grass carp fillets during 12 days of storage at 4 °C [72]. The combined treatment was shown to reduce the chemical and microbial deterioration of the fish, thereby extending its shelf life considerably. Moreover, no deleterious effects of the combined treatment on the sensory properties of the fish were observed.

3.3. Pulsed Light

Pulsed light (PL) treatment is a non-thermal processing method that can be used for the rapid inactivation of microorganisms on food surfaces and packaging materials [100]. PL technology involves the use of intense light pulses of short duration and a broad wavelength spectrum [101]. The PL generation system comprises one or more inert-gas flash lamps (e.g., xenon lamps), a power unit, and a high-voltage connection. When a high-current electric pulse passes through the gas chamber of the lamp, the inert gas molecules are excited and collide with each other, leading to the emission of short intense pulses of light with wavelengths ranging from around 200 to 1100 nm [101–103]. This range includes ultraviolet (200–400 nm), visible (400–700 nm), and infrared (700–1100 nm) light [102]. In food applications, PL usually involves applying 1 to 20 flashes per second with an energy density ranging from 0.01 to 50 J/cm^2 at the surface [100].

Microbial decontamination by PL treatments has mainly been attributed to UV light [103]. Conjugated carbon–carbon double bonds in proteins and nucleic acids absorb ultraviolet radiation, which leads to structural changes in enzymes, receptors, transporters, membranes, and genetic materials, thereby causing disruption of key biochemical pathways that lead to cell death [100,103]. Moreover, applying ultraviolet light on the target surface stimulates the generation of reactive oxygen species (ROS) such as H_2O_2, single oxygen, and hydroxyl radicals that affect the cell membranes and cell walls [104,105].

The application of PL technology for food preservation has some benefits over conventional methods, such as efficient inactivation of microorganisms, no need for chemical disinfectants or preservatives, low operation costs, the capability of either continuous or batch operation, short processing times, and high throughputs [100]. Nevertheless, it does have some limitations. Foods with smooth surfaces, such as many fresh fruits and vegetables, cheeses, and meat slices are suitable for PL treatment, while foods with uneven or porous surfaces are unsuitable because shadow effects reduce the ability of the light waves to interact with all of the surfaces [106]. Because PL technology is a surface decontamination technique, it is affected by the light scattering and absorption properties of foods, which means that it is unsuitable for the treatment of grains, cereals, and spices due to their opaque nature [100,106]. Other potential drawbacks of this technology are the high initial investment costs, the short lifetime of lamps, the potential for changes in pH and color at high intensities, and overheating [22].

Combining edible packaging and PL treatments has been shown to have synergistic benefits on food preservation by increasing microbial decontamination [23]. Studies on the combination of PL and edible packaging are summarized in Table 1, and a few examples are provided here.

Researchers have evaluated the effects of various combinations of alginate coating, malic acid dipping, and PL treatment on the quality of fresh-cut mango during 14 days of storage at 4 °C [24]. Fresh mango slices inoculated with *L. innocua* were dipped in sodium alginate solution (2% *w*/*v*) and then dipped in a calcium chloride solution (2% *w*/*v*) containing malic acid (2% *w*/*v*) or in a malic acid solution (2% *w*/*v*). The PL treatment involved applying 20 pulses with a fluence of 0.4 J.cm^2/pulse. This study showed that combined treatments led to around a 4 log reduction in *L. innocua* in the mango. Coating the mango pieces prior to the PL treatment helped to avoid tissue softening during storage.

Koh, Noranizan [26] assessed the effects of an alginate coating followed by a PL treatment on the sensory properties of fresh-cut cantaloupes during 36 days of storage at 4 °C. The fresh-cut cantaloupes were coated by dipping them in an alginate solution containing glycerol and sunflower oil. The coated cantaloupes were then packed in polypropylene bags and exposed to the PL at a fluence of 0.9 J/cm^2 every 48 h for up to 26 days. Combining the alginate coating with the PL treatment reduced the decrease in the sugar content of the cantaloupes during storage. The alginate coating was more effective than the PL treatment when they were used alone in preventing changes in the organic acid content of the cantaloupes. However, the combination of the alginate coating and PL treatment reduced the formation of lactic acid and helped preserve the desirable aroma profile of the cantaloupes.

Researchers have assessed the effects of combining a PL treatment with starch films containing preservatives (sodium benzoate and/or citric acid) on microbial growth and the quality of Cheddar cheese slices during refrigerated storage [2]. The surfaces of the cheese slices were first inoculated with *L. innocua* at a level of 7 log CFU/cheese slice, which were then coated or not coated before being exposed to the PL treatment. The results showed that combining the coatings and PL treatments greatly reduced the number of *L. innocua* on the cheese surfaces during storage. However, there were some undesirable changes in the quality attributes of the cheese caused by the treatments. After 7 days of storage, the pH value of cheese reduced to 4.0, which resulted in increased cheese hardness.

3.4. Irradiation

Food irradiation involves exposing foods to a controlled level of ionizing radiation, which has the ability to break chemical bonds and deactivate microorganisms [107]. Irradiation has been used to kill harmful microorganisms in poultry, meat, seafood, and spices; extend the storage time of fresh vegetables and fruits; and control the sprouting of tubers, onions, and potatoes. The dose of radiation used depends on the application: low dose (1 kGy) to delay ripening and prevent germination, medium dose (1–10 kGy) to kill pathogens, and high dose (>10 kGy) for disinfection and sterilization [108]. According to the World Health Organization (WHO), there is no risk of applying irradiation to foodstuffs at the levels normally used, and it may even help maintain the nutritional content [109]. Irradiated food products must comply with strict international regulations with regard to safety [110]. Three types of ionizing radiation are commonly used for this purpose: ultraviolet light, gamma rays, and electron beams.

UV light, which has a wavelength ranging from 100 to 400 nm, is that part of the electromagnetic spectrum that falls between visible light and ionizing radiation. The nucleic acids of microorganisms absorb UV light strongly between 250 and 260 nm. Microorganisms are destroyed when they are exposed to sufficiently high intensities of UV light due to changes in the molecular structure of nucleic acids and proteins that disrupt their metabolism [87]. Ultraviolet light can also directly damage the ester bonds in key molecules in microorganisms, either by directly absorbing UV energy or by generating reactive species, such as oxygen-free or hydroxyl radicals, which react with them [111]. For instance, it has been reported that the antimicrobial activity of UV light towards various microorganisms is due to the formation of pyrimidine dimers in the DNA strands [20,112]. Researchers have reported that applying low doses of UV-C light (254 nm) to fruits and vegetables can reduce their tendency to rot during storage, thereby increasing their quality and shelf life [113].

Electron irradiation involves creating an electron beam using a cathode, which is then directed at the sample to be treated. At sufficiently high energy, the electron beam is capable of breaking molecular bonds or releasing electrons from atoms, which can lead to the deactivation of microorganisms [114]. The radiation dose required to have a beneficial effect depends on the nature of the food being treated, so it must be optimized for each product. A major benefit of electron irradiation is that no pretreatment of the samples is required and the processing times are relatively short [108].

Gamma rays are electromagnetic radiation with a relatively short wavelength and high frequency that can easily penetrate foods with little or no heat generation [115]. This method is already used commercially to sterilize a variety of foods. Cesium (137) or cobalt (60) radionuclides are gamma ray sources that have been used in biological applications for decades [116]. A commonly used gamma ray supply consists of cobalt 60 rods contained within rustproof steel tubes. These tubes are raised within a concrete irradiation crate containing the food. Studies have shown that irradiating foods with bioactive coatings or in modified atmospheric packaging helps to enhance the radiation sensitivity of food pathogens without negatively impacting the sensory properties of the food products [117].

Several studies have examined the combined impact of irradiation and coatings on the quality attributes of food products. For instance, combining alginate coatings (containing essential oils, sodium diacetate, and natamycin) with γ-radiation (0.4 and 0.8 kGy) was shown to be effective in decreasing the viability of several spoilage and pathogenic microorganisms (*A. niger*, *E. coli*, *L. monocytogenes*, and *S. Typhimurium*) on broccoli florets under refrigeration conditions, thereby increasing their shelf life [117]. In another study, it was shown that a combination of an edible coating and γ-irradiation (0.5 kGy) was effective in reducing *E. coli*, *Salmonella enteric*, and *L. innocua* on green peppers without adversely affecting their quality attributes [10]. Other researchers have shown that combining a chitosan coating (loaded with a mandarin essential oil nanoemulsion) with a UV-C irradiation treatment decreased the levels of *L. innocua* contamination on green beans while also improving their firmness and color retention [20]. Similarly, combining CMC coatings with UV-C or γ-irradiation inhibited the growth of *L. innocua* in pears, thereby extending their shelf life and quality attributes [118]. A combination of an alginate coating (loaded with essential oils and citrus extract), ozonation, and irradiation has also been shown to increase the shelf life of fish fillets (Figure 2) [119]. Similarly, combining a chitosan coating (loaded with cumin essential oil) and γ-irradiation (2.5 kGy) was shown to reduce the growth of *L. monocytogenes*, *E. coli* O157:H7, and *Salmonella Typhimurium* on beef [120].

Salem, Naweto [121] showed that a combination of γ-irradiation (0.5 and 1.0 kGy) and a paraffin oil coating reduced the levels of blue mold (*Penicillium expansum)* on apples during cold storage. The coated and irradiated apples had the lowest weight loss, highest firmness, highest calcium levels, and longest shelf life. Similarly, a combination of electron beam radiation (0, 0.5, and 1 kGy) and a shellac coating was shown to reduce changes in the color, chlorophyll levels, and chlorophyllase activity of pears during storage at 13 °C for 30 days while increasing the rate of respiration and vitamin C concentration (Figure 3) [108]. Other researchers showed that combining an ultraviolet light treatment with a chitosan coating improved the quality and nutritional content of strawberries during storage of 15 days at 1 °C and 90% relative humidity [114]. Although irradiation methods (pulsed light or UV) in combination with food coatings have successful effects on the preservation of coated food, some bioactive compounds or nanomaterials such as anthocyanins, quercetin, some essential oils, nanoparticles, etc., have the property of blocking the irradiated rays. Therefore, there may be a need to use a higher dose of antimicrobial or irradiated radiation, which should be considered in future studies.

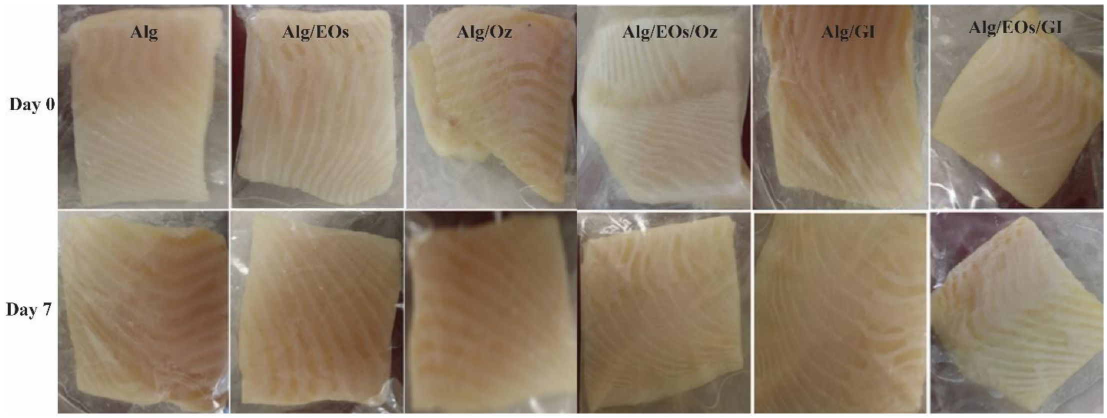

Figure 2. Effect of alginate coating with ozonation or gamma irradiation on *Merluccius* sp. fillets. Reprinted from [96], copyright 2019, with permission from Elsevier.

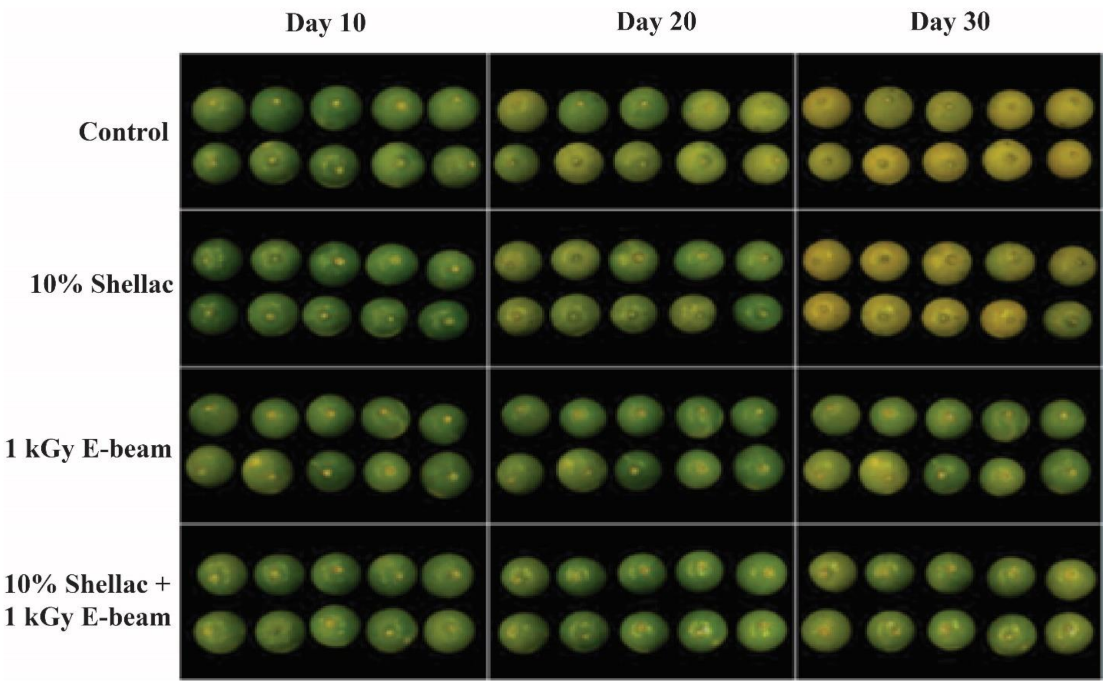

Figure 3. Effect of shellac coating with E-beam irradiation on lime. Reprinted from [83], copyright 2021, with permission from Elsevier.

4. Conclusions

In this review article and according to the reported results, it was concluded that a combination of biodegradable coatings and non-thermal processing methods can be used to improve the quality, safety, and shelf life of various kinds of food products. The utilization of this approach may reduce the need for plastic packaging materials and synthetic chemicals, which can adversely affect human health and the environment. However, further research is required to ensure that these technologies are safe and efficacious to employ under realistic usage conditions and that they can be performed economically at the large scale required for industrial applications. If these hurdles can be overcome, then combining biodegradable coatings and non-thermal processing methods may be a means of improving the sustainability and reducing the negative environmental impact of the food supply chain.

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