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Effect of Gamma Rays, Electron Beams, and UV Radiation on Biopolymer Films for Food Packaging: A Comprehensive Review

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ABSTRACT

The escalating demand for sustainable and biodegradable food packaging materials has propelled intensive research into biopolymer-based films derived from polysaccharides and proteins. Radiation processing technologies—including ionizing radiations such as gamma rays and electron beams, alongside non-ionizing ultraviolet (UV) light—have demonstrated significant potential in modulating the physicochemical, mechanical, thermal, antimicrobial, and barrier properties of these biopolymer films. Ionizing radiation facilitates chain scission, crosslinking, and structural rearrangements within polymer matrices, leading to enhanced tensile strength, reduced water uptake, improved crystallinity, and extended shelf-life of packaged foods, while UV irradiation predominantly induces surface photochemical modifications, augmenting hydrophobicity and antimicrobial efficacy without substantially altering chemical functionalities. Synergistic effects are often observed when irradiation is combined with bioactive compounds or nanomaterials, resulting in superior film performance and microbial inhibition; nonetheless, optimizing irradiation parameters is critical to balancing beneficial modifications against potential adverse effects such as color changes, mechanical degradation, or compromised food quality. This review, by uniquely integrating mechanistic insights with comparative analysis of ionizing and non-ionizing radiation, highlights underexplored synergies with bioactive agents and nanomaterials and proposes future directions for dose optimization, intelligent packaging design, and industrial scalability, thereby offering a novel and comprehensive perspective beyond existing reviews on radiation-assisted biopolymer films.

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INTRODUCTION

Edible films and coatings have also emerged as an intriguing option in food packaging. These films are made from edible materials such as proteins, polysaccharides, and lipids, which can form a protective barrier around the food product. Edible films offer several advantages, including the potential for enhancing food safety, extending shelf life, and reducing the need for additional packaging materials. Moreover, these films can be customized to incorporate bioactive compounds that provide added health benefits (Mirzaee Moghaddam & Nahalkar, 2025).

In addition to biodegradable packaging and edible films, non-thermal methods are known as effective techniques for food storage and packaging. These methods, such as high pressure processing, pulsed electric fields, cold plasma, ozone, ultrasound, infrared rays, ultraviolet rays, and radiation rely on inactivating microorganisms, enzymes, and pests, thereby increasing the shelf life of food products (Guo et al., 2024). Non-thermal methods have advantages over traditional thermal processing methods by maintaining the sensory and nutritional characteristics of the packaged food.

Ionizing and non-ionizing radiation are two categories of electromagnetic radiation distinguished primarily by their ability to ionize atoms and molecules. Ionizing radiation has sufficient energy to remove tightly bound electrons from atoms, creating ions (charged particles) in the process. This type of radiation includes X-rays, gamma rays, and some high-energy ultraviolet (UV) radiation. Non-ionizing radiation, on the other hand, lacks the energy required to ionize atoms and typically includes radio waves, microwaves, infrared radiation, and low-energy UV radiation (Apte & Bhide, 2024).

Non-ionizing radiation, such as microwave and infrared radiation, plays a crucial role in modern food packaging technologies (Shojaei et al., 2025). Unlike ionizing radiation, which has higher energy and can ionize atoms, non-ionizing radiation is characterized by its lower energy levels that do not disrupt atomic structures or cause ionization (Chmielewski, 2023). This property makes non-ionizing radiation safer for direct application to food and food packaging materials, while still offering valuable functionalities in food processing and preservation. non-ionizing radiation offers versatile applications in food packaging, contributing to improved food quality, safety, and consumer convenience(Chaudhary et al., 2024). Its ability to provide efficient heating and other functional benefits makes it a valuable component in the evolution of modern food packaging technologies.

The use of radiation as a non-thermal process in food packaging has gained significant attention in recent years. Radiation-based techniques offer unique advantages in terms of food safety, preservation, and quality enhancement. Radiation-based processes, such as gamma irradiation, electron beam irradiation, and X-ray irradiation, involve the use of ionizing radiation to inactivate microorganisms, pests, and enzymes in food products. These techniques have been proven effective in extending the shelf life of packaged foods by reducing spoilage and preventing the growth of pathogens. Moreover, radiation can penetrate the packaging materials, reaching the food product directly, without affecting its quality or sensory attributes (Indiarto et al., 2023). When it comes to incorporating radiation into edible films and coatings, certain techniques are necessary to ensure the desired outcomes. Firstly, the selection of suitable packaging materials is crucial. These materials should be transparent or have low radiation absorption properties to allow the effective penetration of radiation (More et al., 2021). Secondly, the dosage and energy level of radiation must be carefully controlled. The appropriate dosage depends on various factors, such as the type of food product, desired shelf life extension, and the target microorganisms or pests (Pinto de Rezende et al., 2022). It is essential to conduct thorough research and determine the optimal radiation dosage to achieve the desired microbial reduction while maintaining the quality and safety of the packaged food. Furthermore, the packaging process itself plays a vital role in ensuring the successful irradiation of edible films and coatings. Proper sealing and packaging techniques are necessary to prevent the entry of contaminants and maintain the integrity of the packaging during irradiation (Chiozzi et al., 2022). Additionally, the handling and storage conditions of the packaged products after irradiation should be carefully managed to prevent recontamination and ensure the preservation of quality and safety (Mostafavi et al., 2012). In the production of polysaccharide-based films for perishable food items, UV radiation is utilized to ensure microbial safety and extend shelf life. UV-C light effectively penetrates the surface layers of these films, targeting and inactivating microorganisms such as bacteria and molds that could compromise food quality and safety during storage and transportation. This process not only reduces the microbial load but also helps maintain the integrity and freshness of the packaged food without the need for chemical additive (Ezati et al., 2023).

In this article, we will examine the use of radiation as a non-thermal process in edible films and coatings. We will examine the benefits and challenges associated with food packaging based on ionizing and non-ionizing radiation, the selection of appropriate packaging materials, and the techniques involved in irradiation. By understanding the complexities of combining ionizing and non-ionizing radiation in food films and coatings, we can harness the potential of these non-thermal processes to increase food safety, extend shelf life, and improve the overall quality of packaged food products.

Ionizing And Non-Ionizing Radiation

Non-ionizing radiation

Non-ionizing radiation encompasses a broad spectrum of electromagnetic waves, including radio waves, microwaves, infrared radiation, visible light, and UV radiation with longer wavelengths. In the food industry, these forms of radiation are utilized for a variety of purposes, ranging from processing and preservation to packaging and safety enhancement. Unlike ionizing radiation, which carries enough energy to ionize atoms and potentially damage biological molecules, non-ionizing radiation operates at lower energy levels that do not induce ionization but can still produce significant beneficial effects for food production and handling. Non-ionizing radiation technologies typically offer faster processing times and greater efficiency compared to conventional methods, resulting in increased throughput and reduced energy consumption (Guo et al., 2020). By minimizing heat exposure and preserving nutrients, non-ionizing radiation helps maintain the nutritional integrity and sensory characteristics of food products. These technologies are generally recognized as safe when used within established guidelines and standards, thereby contributing to food safety assurance and compliance with regulatory requirements. Non-ionizing radiation technologies often require fewer chemical additives and reduce the environmental footprint associated with food processing and packaging (Chen et al., 2024). Non-ionizing radiation technologies represent a versatile and essential component of modern food processing and packaging practices. Their applications continue to evolve, providing innovative solutions to enhance food safety, extend shelf life, and meet consumer demands for high-quality, nutritious, and safely packaged food products. As technological advancements and scientific understanding progress, these technologies are poised to play an increasingly significant role in shaping the future of the global food industry (Thavorn et al., 2022).

Ultraviolet (UV) radiation, a part of the electromagnetic spectrum with wavelengths ranging from 10 to 400 nanometers, has become an important tool in the food industry. UV radiation is classified into three types based on wavelength: UV-A, UV-B, and UV-C, each with distinct properties and applications. UV-C radiation (wavelengths between 100 and 280 nm) is highly effective in inactivating bacteria, viruses, and fungi. This property is utilized to disinfect surfaces, equipment, and packaging materials in food processing facilities. UV-C lamps are often installed in air ducts, on conveyor belts, and in storage areas to maintain a hygienic environment and reduce the risk of microbial contamination (Ramamurthy et al., 2010).

UV radiation is used to purify water in the food industry. UV systems are installed in water supply lines to eliminate pathogens and ensure the water used in food processing is safe. This method is chemical-free and does not alter the taste or quality of the water, making it an ideal choice for beverage production and other food processing applications. UV-C light is applied to decontaminate the surfaces of fruits, vegetables, and other food products. This process helps in reducing the microbial load on the surface without affecting the quality, flavor, or nutritional value of the food. It is particularly useful for minimally processed foods where maintaining freshness and safety is crucial. Exposure to UV-C radiation can extend the shelf life of certain food products by inhibiting the growth of spoilage microorganisms. For instance, UV treatment of fresh produce can slow down the ripening process and reduce decay, thus prolonging the shelf life and reducing food waste (Darré et al., 2022). UV radiation is effective in degrading mycotoxins, toxic compounds produced by molds that can contaminate food products such as grains, nuts, and dried fruits. UV treatment helps in reducing the levels of these harmful substances, ensuring food safety and compliance with regulatory standards. UV radiation can be used to generate ozone, a powerful oxidizing agent that is effective in sanitizing food processing environments. Ozone can be used to disinfect air, water, and surfaces, providing an additional layer of protection against microbial contamination (Quevedo et al., 2020). UV radiation is employed in the sterilization of food packaging materials. UV-C light can be used to treat the inner surfaces of packaging containers before filling them with food products, ensuring that the packaging is free from harmful microorganisms (Gürsu, 2024).

Ionizing Radiations

Ionizing radiation plays a crucial role in the food industry, offering numerous benefits and applications, including food irradiation, packaging sterilization, and crop improvement. Food irradiation, using controlled doses of gamma rays, electron beams, or X-rays, reduces spoilage and pathogenic microorganisms such as bacteria, viruses, and parasites, thereby enhancing food safety and extending shelf life, particularly for perishable products like fruits, vegetables, meat, poultry, and seafood. It also suppresses the growth of insects and pests, reducing the need for chemical pesticides. Additionally, ionizing radiation is applied to sterilize packaging materials, ensuring containers, films, and lids are free from harmful microorganisms and preventing contamination during storage and transport. In agriculture, controlled radiation doses can induce desirable mutations in seeds, bulbs, or other plant materials, leading to new crop varieties with improved yield, disease resistance, or nutritional content. Importantly, when applied within recommended dose ranges, food irradiation does not make food radioactive, significantly alter its nutritional value, or compromise sensory quality. Extensive research and regulatory frameworks ensure safety and proper labeling of irradiated foods. Nevertheless, concerns regarding potential risks and public acceptance highlight the need for comprehensive risk assessment, adherence to international standards, and clear communication with consumers to promote the responsible and effective use of ionizing radiation in food applications (Yang et al., 2024) . As a result, ionizing radiation has valuable applications in the food industry. Food irradiation helps enhance food safety, extend shelf life, and reduce dependence on chemical preservatives. Additionally, it can contribute to crop improvement and the development of new plant varieties. By implementing appropriate control measures and adhering to regulations, the food industry can harness the benefits of ionizing radiation while ensuring the safety, quality, and consumer acceptance of irradiated food products (Ahmad et al., 2021).

Gamma radiations

Gamma radiation, a form of ionizing radiation, has significant applications in the food industry. Gamma rays are high-energy electromagnetic waves emitted by certain radioactive materials, such as cobalt-60 or cesium-137. These rays possess excellent penetrating power, enabling them to pass through various materials, including food products and packaging. In the food industry, gamma radiation is primarily used for food preservation and sterilization. The process involves exposing food products to controlled doses of gamma rays. The high-energy gamma rays interact with the DNA and cellular structures of microorganisms, including bacteria, viruses, and parasites, effectively destroying them or rendering them unable to reproduce. This results in a reduction of spoilage organisms and pathogens, thereby enhancing food safety and extending shelf life. Food irradiation with gamma rays offers several advantages. Firstly, it provides a non-thermal means of preserving food, as the process does not involve excessive heat that could alter the sensory qualities or nutritional content of the food. (Chacha et al., 2021). This makes it particularly suitable for heat-sensitive products, such as fruits, vegetables, and certain spices. Secondly, gamma radiation helps in the control of pests and insects. By sterilizing or interrupting the reproductive cycle of pests present in stored grains, fruits, or vegetables, gamma irradiation reduces the need for chemical fumigation, safeguarding the quality and safety of the food while minimizing pesticide residues. Furthermore, gamma radiation can be used for the sterilization of food packaging materials. By exposing packaging containers, films, or caps to gamma rays, any potential microorganisms present on the surfaces can be effectively eliminated, ensuring the integrity and cleanliness of the packaging (Mondal & Akhtaruzzaman, 2024). It is important to note that gamma radiation does not make the food radioactive, as the energy source used for food irradiation is carefully selected and controlled (Joshua Ajibola, 2020). Extensive research and regulatory guidelines are in place to determine the appropriate dosage levels to achieve the desired microbial reduction while maintaining the safety and quality of the food.

Electron beams

Electron beams, a type of ionizing radiation, have significant applications in the food industry. Electron beam radiation is generated by accelerating electrons to high speeds using specialized equipment. These high-energy electron beams can effectively penetrate food products and packaging materials. In the food industry, electron beam radiation is primarily utilized for food sterilization and pathogen reduction. The process involves exposing food products to controlled doses of electron beams, which interact with the DNA and cellular structures of microorganisms, including bacteria, viruses, and parasites (Shahi et al., 2021). This interaction disrupts their ability to reproduce and renders them inactive, thereby reducing the microbial load and enhancing food safety. Electron beam radiation offers several advantages in food applications. Firstly, it is a cold process, meaning it does not involve the use of heat. This is particularly beneficial for heat-sensitive products, such as fruits, vegetables, and certain bakery items, as it minimizes any potential negative effects on the sensory qualities and nutritional content of the food. Secondly, electron beam radiation is highly efficient in microbial reduction. It can effectively eliminate a wide range of pathogens, including those responsible for foodborne illnesses. This contributes to the overall safety and quality of the food, reducing the risk of contamination and foodborne outbreaks. Furthermore, electron beam radiation can be employed for the sterilization of food packaging materials. By exposing packaging containers, films, or caps to electron beams, any potential microorganisms present on the surfaces can be effectively eliminated, ensuring the cleanliness and integrity of the packaging (Ansari & Datta, 2003)

. It is important to note that electron beam radiation does not make the food radioactive, as the process does not involve the use of radioactive materials. The equipment used for electron beam irradiation is designed to emit controlled doses of radiation, adhering to strict regulatory guidelines and safety standards. Figure 1 shows a schematic of the effect of different radiations on biopolymer-based films.

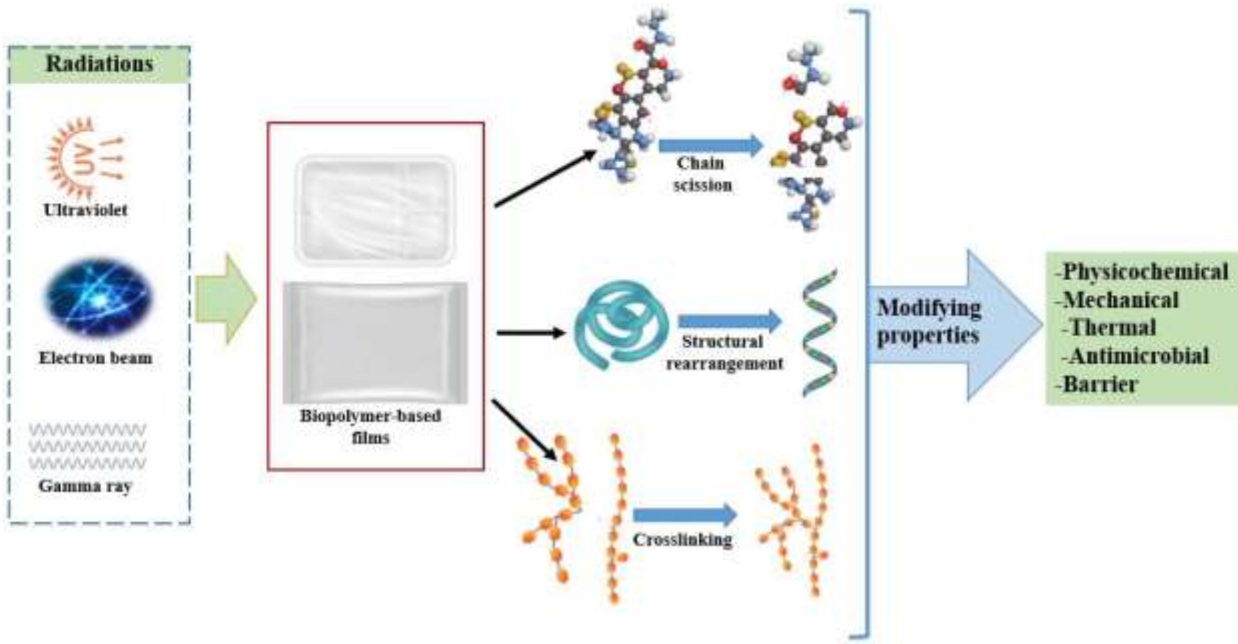

Figure 1. Schematic of the effect of different radiations on biopolymer-based films.

Different Doses of Radiation

The dosage requirements for irradiation in various food applications can vary depending on factors such as processing and harvest conditions, maturity of the food, and environmental factors. Therefore, the dosage ranges mentioned in the literature cannot be considered as precise indicators. Different dose ranges are utilized for specific purposes in food irradiation. Lower doses (10 Gy to 1 kGy) can be employed to inhibit germination and delay ripening. Medium doses (1-10 kGy) are effective in inactivating pathogens and spoilage microorganisms. Higher doses (>10 kGy) are utilized for sterilization and decontamination (Srinivasa et al., 2023). It is important to determine the appropriate dosage based on the specific requirements and considerations of each food application.

BIOPOLYMER FILMS

Polysaccharide Films

Polysaccharide films are thin, flexible films made primarily from polysaccharides, which are long chains of sugar molecules. These films are used in various applications, particularly in the food industry, as they are edible, biodegradable, and often derived from renewable sources. Polysaccharides commonly used to make these films include starches, cellulose, alginate, agar, and chitosan. In the food industry, polysaccharide films serve as an alternative to traditional plastic packaging materials (Nikbakht et al., 2024). They can be used to wrap individual food items or as a coating to protect and extend the shelf life of perishable products such as fruits, vegetables, and meats. Polysaccharide films can also serve as carriers for edible additives, including flavors, colors, and nutrients, providing functional benefits to food products. In addition to food packaging, polysaccharide films have applications in other industries as well (Mirzaee Moghaddam & Nahalkar, 2025). They can be used in pharmaceuticals for drug delivery systems, in agriculture for seed coatings or soil mulching, and in cosmetics for skincare products. Overall, polysaccharide films provide a sustainable and environmentally friendly solution for various packaging and coating applications, contributing to efforts to reduce plastic waste and promote a circular economy.

Protein Films

Protein films are thin, flexible films made primarily from proteins and can be either edible or non-edible. These films are typically derived from animal or plant proteins, such as gelatin, soy protein, and albumin. In the food industry, protein films can be used as packaging materials or applied as protective coatings on food products. They often possess protective and preservative properties and can serve as alternatives to traditional plastic packaging materials. In addition to packaging, protein films have various other applications in food processing, including encapsulating additives such as colors or flavors, or serving as protective coatings for dry or moist food products (Mirzaee Moghaddam & Nahalkar, 2025). In summary, protein films are an effective and sustainable alternative for packaging and protecting food products, offering biodegradable and consumable properties that contribute to environmental improvement.

EFFECT OF RADIATION ON BIOPOLYMER FILMS

Effect of Electron Radiation on Polysaccharide and Protein Films

The effect of electron radiation on polysaccharide and protein films refers to the impact of electron beams on films made from polysaccharides (such as starch, cellulose, or chitosan) and proteins used in food packaging and preservation. When applied to polysaccharide films and proteins, electron radiation can induce various changes, including chemical reactions, cross-linking, and degradation. One of the main effects of electron radiation on polysaccharide films is cross-linking. Cross-linking occurs when high-energy electrons break polymer chains and create new chemical bonds between them. This process forms a three-dimensional network within the film, resulting in improved mechanical strength, enhanced barrier properties (e.g., resistance to oxygen and moisture), and greater thermal stability (Li & Wu, 2020).

In addition to cross-linking, electron radiation can also cause chain scission or degradation of polysaccharide and protein molecules. This can result in a reduction in the molecular weight of the polymers, which may affect their mechanical properties and functionality (Manaila et al., 2021). Furthermore, electron radiation can induce chemical reactions and modifications in the functional groups of the polysaccharide and protein films. These reactions can lead to changes in the film's surface properties, such as hydrophobicity or hydrophilicity, which can impact its interaction with food products (Ashfaq et al., 2020). The application of electron radiation to edible polysaccharide and protein films can offer several advantages in the food industry. It can improve the mechanical and barrier properties of the films, extending the shelf life of food products by reducing spoilage and preserving their quality. Electron radiation can also be used as a sterilization technique, effectively eliminating pathogens and extending the safety and shelf life of food. However, it is important to note that the effects of electron radiation on polysaccharide and protein films are dose-dependent. The optimal radiation dose needs to be carefully determined to achieve the desired modifications without causing excessive degradation or undesirable changes in the film's properties (Fatehi et al., 2020). Table 1 shows some studies on the effect of electron beam radiation on polysaccharide and protein films.

Table 1. Some studies on the effect of electron beam radiation on polysaccharide and protein films

Edible film	Dose rate of electron beam	Observed Effects	References
Chitosan and fish gelatin with natural antioxidants (ferulic acid, quercetin and tyrosol)	60 kGy	• Increased tensile strength following the incorporation of antioxidants and/or irradiation. • Slight enhancement of thermal stability induced by antioxidants and irradiation. • Improved wettability and hydrophilicity of the film containing quercetin and tyrosol after irradiation. • Unchanged water barrier properties after irradiation. • Enhanced interactions between polymer chains and/or between polymer chains and antioxidants, promoted by both antioxidant addition and electron beam treatment.	(Benbettaïeb, Karbowiak, Brachais, et al., 2015)
Fish gelatin	60 kGy	• Electron spin resonance reveals free radical formation during irradiation, potentially leading to intermolecular cross-linking. • Significant increase in tensile strength of gelatin film following irradiation. • Minor effect of irradiation on vapor permeability. • Noticeable increase in surface tension and its polar component, consistent with enhanced wettability. • Possible reorientation of polar groups at the gelatin film surface and crosslinking of hydrophobic amino acids due to irradiation. • No observable change in film crystallinity. • Structural modifications, if any, likely confined to the amorphous regions of the gelatin matrix. • Enhanced thermal stability of gelatin film upon irradiation, marked by increased glass transition and degradation temperatures.	(Benbettaïeb, Karbowiak, et al., 2016)
Chitosan-gelatin with quercetin	40 and 60 kGy	• Irradiation led to a reduction in the release rate of quercetin, suggesting probable cross-linking during the process. • Electron beam irradiation enabled modulation of antioxidant retention and subsequent release within chitosan–gelatin matrices.	(Benbettaïeb, Chambin, et al., 2016)
Chitosan and fish gelatin	20, 40 and 60 kGy	• Significant increase in tensile strength (TS) of gelatin film with increasing irradiation doses. • No significant change in TS for chitosan and blend films after irradiation. • Irradiation led to a substantial reduction (up to 50%) in elongation at break (%E) for chitosan and blend films.	(BenBettaïeb, Karbowiak, Bornaz, et al., 2015)

		• Approximately twofold increase in Young's modulus for irradiated chitosan and blend films. • Slight improvement in moisture barrier efficiency of blend films following irradiation. • Decrease in oxygen permeability observed after 60 kGy irradiation in both chitosan and blend films. • Surface hydrophobicity tended to decrease post-irradiation. • Spectroscopic findings confirmed irradiation-induced modifications in intermolecular interactions, particularly involving hydrogen bonding and amide groups between polymer chains.	
Chitosan–gelatin	60 kGy	• Confirmation by enhanced mechanical properties, including a significant increase in tensile strength. • Accompanied by a reduction in permeability values.	(Benbettaïeb, Assifaoui, et al., 2016)
Soy protein concentrate and cassava starch	20 and 40 kGy	• Decrease in tensile strength observed after irradiation. • Intensification of yellow coloration with increasing irradiation dose. • No significant differences in thermal properties between irradiated and non-irradiated samples. • Reduced water vapor permeability and water absorption at higher irradiation doses, indicating improved barrier properties.	(Uehara & Mastro, 2017)
Fish gelatin with antioxidants of bamboo leaves	1 kGy, 3 kGy, 5 kGy and 7 kGy	• Positive impact of electron beam irradiation on tensile strength, denaturation temperatures, opacity, and microstructure of fish gelatin–bamboo leaf antioxidant films. • Maximum mechanical, thermal, and opacity values observed at irradiation doses of 5 and 7 kGy. • Decrease in contact angle and increase in water vapor permeability under high relative humidity (90–100%) after irradiation, indicating reorganization of hydrophilic surface groups. • FTIR and microstructure analyses confirmed that appropriate irradiation doses promoted crosslinking between fish gelatin and bamboo leaf antioxidants. • Formation of compact film structures due to irradiation contributed to reduced release rates of bamboo leaf antioxidants.	(Huang et al., 2020)
Chitosan/clay	10, 20, 30 and 40 kGy	• Increased water resistance, water contact angle, and water barrier properties observed up to 30 kGy irradiation, followed by a sharp decline at 40 kGy. • Enhanced crystallinity in the amorphous region of chitosan/clay nanocomposite with increasing doses up to 30 kGy. • Shift of chitosan's characteristic diffraction peak to lower angles, indicating increased interlayer spacing and effective nanoclay intercalation. • Improved tensile strength due to crosslinking of chitosan chains, especially at 30 kGy; strength decreased at 40 kGy due to chain degradation.	(Shahbazi et al., 2017)

		• Downward shift of cold-crystallization exothermic peak post-irradiation, suggesting accelerated crystallization. • FE-SEM analysis confirmed enhanced intercalation of chitosan chains between nanoclay platelets with increasing irradiation. • Atomic force microscopy revealed reduced surface roughness for films irradiated at 10–30 kGy, but increased roughness at 40 kGy.	
Waxy maize starch	2–30 kGy	• Marked decrease in starch molecular weight with increasing irradiation dose. • Slight reductions in branch chain length, melting temperature, melting enthalpy, and relative crystallinity, particularly at doses below 15 kGy. • Preferential cleavage of α-1,6-glucosidic bonds over α-1,4-glucosidic bonds at low irradiation doses, resulting in increased release of linear chains. • Films prepared from 10 kGy-irradiated waxy maize starch exhibited improved mechanical properties due to moderate increase in linear chains. • Increased solubility attributed to reduction in starch molecular weight.	(Zhou et al., 2020)

Irradiation, particularly electron beam treatment, induces notable structural and functional modifications in biopolymer-based films, often enhanced by the incorporation of antioxidants. These effects include significant improvements in tensile strength, thermal stability, and barrier properties, primarily due to the formation of free radicals that promote crosslinking between polymer chains and between polymers and antioxidants. Surface wettability and hydrophilicity tend to increase due to the reorientation of polar groups, while permeability to water vapor and oxygen generally decreases. Spectroscopic and morphological analyses (e.g., FTIR, UV-Vis, FE-SEM, AFM) confirm alterations in hydrogen bonding, molecular alignment, and film compactness, especially at moderate irradiation doses (10–30 kGy). Although crystallinity often remains unchanged or increases slightly in amorphous regions, excessive irradiation may lead to polymer degradation, reduced mechanical performance, and increased surface roughness. Additionally, irradiation modulates the retention and release of antioxidants, typically reducing their release rate by enhancing matrix binding (Benbettaïeb, Karbowiak, Brachais, et al., 2015; Benbettaïeb, Karbowiak, et al., 2016; Huang et al., 2020; Shahbazi et al., 2017; Uehara & Mastro, 2017).

Effect of Gamma Radiation on Polysaccharide and Protein Films

Gamma radiation plays a significant role in the treatment of polysaccharide and protein-based films. When applied to these products, gamma rays can have several effects. Sterilization: Gamma radiation is commonly used to sterilize polysaccharide and protein-based films. The high-energy gamma rays penetrate the films, effectively killing or inactivating microorganisms present on their surfaces. This process helps eliminate potential sources of contamination and extends the shelf life of the food products (Amin et al., 2021). Microbial Control: Gamma radiation can also control the growth of microorganisms within polysaccharide and protein-based films. By targeting and damaging the genetic material of bacteria, viruses, and fungi, gamma rays hinder their ability to multiply and cause spoilage. This helps maintain the quality and safety of the food products (Joshua Ajibola, 2020). Crosslinking and Modification: Gamma radiation can induce crosslinking and structural modifications in polysaccharide films and protein films. When exposed to gamma rays, the molecules within these materials undergo chemical changes, leading to improved mechanical properties, such as increased strength and flexibility. This can enhance the functionality and performance of the films. Allergen reduction: Gamma radiation has been shown to reduce the allergenicity of certain protein-based food materials. By altering the protein structure, gamma rays can potentially decrease the allergenic potential of proteins, making them safer for individuals with specific allergies or sensitivities (Pan et al., 2021).

It is important to note that the radiation doses used in the treatment of polysaccharide and protein-based films are carefully regulated and controlled to ensure product safety. Regulatory authorities, such as the Food and Drug Administration (FDA) in the United States, have established guidelines and safety standards for the use of gamma radiation in food processing. Furthermore, the irradiation process does not make the polysaccharide or protein-based films radioactive, nor does it significantly affect their nutritional value when applied correctly. Table 2 shows some studies on the effect of gamma radiation on polysaccharide and protein films.

Table 2. Some studies on the effect of gamma radiation on polysaccharide and protein films.

Edible film	Dose rate of gamma ray	Food Product Analyzed	Observed Effects	References
Cellulose nanocrystals/chitosan nanocomposite	5, 10, and 15 kGy	-	• Gamma irradiation increased surface hydrophobicity, water vapor permeability, and water sensitivity of the films. • Simultaneous increases in yellowness and opacity were also observed after irradiation. • Mechanical properties of films were significantly enhanced with increasing irradiation doses up to 10 kGy. • FTIR analysis showed no change in the chemical functional groups of the films during irradiation. • XRD results confirmed an increase in film crystallinity following irradiation. • The nanocomposite film irradiated at 10 kGy exhibited the highest thermal stability.	(Salari et al., 2021)
Chia seed gum	5 and 10 kGy	-	• A decrease in water uptake with increasing radiation dose. • Solubility remained nearly unchanged at a radiation dose of 5 kGy. • Moisture content also decreased as the radiation dose increased.	(Pandey et al., 2024)
Farsi gum-carboxymethyl cellulose (CMC) films containing *Ziziphora clinopodioides* essential oil and lignocellulose	2.5, and 5 kGy	Beef meat’s	• No significant effect on film thickness, tensile strength, swelling index, oxygen permeability, or water vapor transmission rate. • Chemical indicators such as thiobarbituric acid reactive substances, total volatile base nitrogen, and peroxide value also showed the most favorable results in irradiated packages.	(Bahari et al., 2020)

nanofibers				
Calcium caseinate (Ca-Cas) containing citrus extract, cranberry juice and essential oils	0.5 kGy	Carrot	• Irradiation of Ca-Cas coating effectively preserved the mechanical properties of the nanoemulsion-containing film. • The combined treatment of bioactive coating and irradiation exhibited a synergistic effect. • This combination showed higher efficiency in extending the shelf-life of carrots and maintaining their quality during storage compared to individual treatments.	(Ben-Fadhel et al., 2021)
chitosan and cumin essential oil	2.5 kGy	Beef loins	• Treatments effectively slowed the increase in total volatile basic nitrogen and pH over time. • Thus, combining active chitosan film with low-dose gamma irradiation is recommended to ensure microbiological safety and long-term preservation of beef under chilled storage.	(Dini et al., 2020)
Plasticized starch (PLST)/carboxymethyl cellulose (CMC)	10 and 50kGy	-	• The swelling properties of PLST/CMC blends increased with higher CMC content but decreased at higher irradiation doses. • PLST/CMC blends showed lower thermal stability than pure PLST; however, thermal stability slightly improved with increasing irradiation dose. • Mechanical testing demonstrated increases in both tensile strength and elongation at break with higher irradiation doses. • Gamma-irradiated PLST/CMC/chitosan blends exhibited enhanced antimicrobial activity compared to the unirradiated counterparts.	(Senna et al., 2016)
Corn-starch	10, 20, 30, and 40 kGy	-	• FTIR and XRD analyses indicated that irradiation had a slight effect on the molecular structure of corn starch, with crystallinity decreasing as the irradiation dose increased. • Particle size analysis revealed a reduction in granule size, with ≥ 8 μm particles decreasing from 59.1% in native starch to 24.1% after 40 kGy irradiation. • Irradiated-corn-starch films were produced by casting gelatinized, irradiated starch solutions. • Higher irradiation doses led to increased tensile strength but significantly decreased water vapor permeability.	(Li et al., 2018)
Pectin/silver nanoparticles	2.5 and 5 kGy	-	• FE-SEM micrographs showed that neat pectin films had a smooth surface, which became slightly rough after AgNP formation.	(Ardjoum et al., 2021)

			• Hunter color values of the nanocomposite films changed following AgNP synthesis. • No significant changes in structural or thermal stability after γ-irradiation-induced AgNP synthesis. • Mechanical properties and water vapor permeability improved after incorporation of AgNPs.	
Gelatin–riboflavin with essential oils and silver nanoparticle	5, 10, and 15 kGy	Meat	• 5 kGy irradiation positively affected the tensile strength, water insolubility, and water barrier properties of the composite gelatin film. • A reduction in film elongation (%) suggested the formation of a compact structure and crosslinking via radical generation. • Infrared spectroscopy indicated that appropriate irradiation doses promoted crosslinking bonds in gelatin, creating a denser network. • The film effectively extended meat shelf life by up to 21 days.	(Sarmast et al., 2024)
Chitosan/essential oils/silver nanoparticles	-	Strawberries	• SEM showed a smooth surface for the composite films. • FTIR analysis revealed structural changes in chitosan after blending with essential oils (EOs) and silver nanoparticles (AgNPs). • The flexibility of composite films increased with the addition of EOs, while tensile strength improved after incorporating AgNPs. • Water vapor barrier properties remained unchanged upon blending with EOs or AgNPs. • All composite films showed lower weight loss compared to control samples. • γ-Irradiation reduced firmness loss and decay over 12 days of storage.	(Shankar et al., 2021)
Chitosan-polyvinyl alcohol	40 and 60 kGy	-	• Irradiation decreased the water solubility of the films. • A 60 kGy dose reduced water vapor permeability and tensile strength without significantly affecting elongation at break. • Release tests showed that gamma irradiation lowered the release rate of catechin from the polymer matrix. • The release rate in high-fat simulant was approximately 2.5 times slower than in low-fat simulant.	(Sabaghi et al., 2020)

Gamma irradiation, often combined with bioactive additives such as silver nanoparticles, or essential oils, effectively enhances the mechanical, thermal, barrier, and antimicrobial properties of biopolymer-based films. Optimal irradiation doses typically increase tensile strength, crystallinity, and thermal stability by promoting crosslinking and structural reorganization, while reducing water uptake and solubility. Additionally, irradiation modulates the release rates of active compounds, improving controlled delivery in packaging applications. Surface characteristics and molecular interactions are altered, as confirmed by spectroscopic and microscopic analyses. Synergistic effects between irradiation and active coatings notably suppress spoilage and pathogenic microorganisms, extending the shelf life and safety of food products. However, excessive irradiation doses can lead to polymer degradation and diminished flexibility, underscoring the importance of dose optimization. Overall, gamma irradiation combined with nanocomposite or bioactive additives presents a promising approach for developing biodegradable films with improved functional performance for food and pharmaceutical packaging (Bahari et al., 2020; Dini et al., 2020; Sabaghi et al., 2020; Salari et al., 2021; Sarmast et al., 2024; Shankar et al., 2021).

Effect of Ultraviolet radiation on polysaccharide and protein films

Ultraviolet (UV) radiation has significant effects on both polysaccharide and protein films, influencing their structural and functional properties. Polysaccharide films are often used in food packaging due to their biodegradability and ability to form protective barriers. When exposed to UV radiation, these films can undergo several changes, including the breakdown of polysaccharide chains through photodegradation (Mendes et al., 2020). This process involves the absorption of UV energy, leading to the cleavage of glycosidic bonds, resulting in a reduction in molecular weight and changes in the mechanical properties of the film. The structural integrity of the film may decrease, making it more brittle and less effective as a barrier. UV radiation can induce oxidative reactions in polysaccharides, leading to the formation of new functional groups such as carbonyl and carboxyl groups (Kurdziel et al., 2022). These changes can affect the film's solubility, permeability, and overall stability. UV exposure can cause discoloration of polysaccharide films due to the formation of chromophores (colored compounds) as a result of photochemical reactions (Ezati et al., 2023). The tensile strength, elongation, and flexibility of polysaccharide films can be adversely affected. Typically, the films become more brittle and less elastic after UV exposure. UV radiation can alter the film's barrier properties against moisture, oxygen, and other gases, potentially reducing its effectiveness in preserving food quality (Liu et al., 2022).

Proteins are highly sensitive to UV radiation, which can lead to various structural and functional modifications. UV radiation can cause denaturation of proteins by disrupting hydrogen bonds, disulfide bridges, and hydrophobic interactions. This results in the unfolding of protein structures, leading to the loss of their native conformation and functionality (Kumar et al., 2020). Denatured proteins may aggregate due to exposure of hydrophobic regions, affecting their solubility and functionality. UV exposure can induce the formation of covalent cross-links between protein molecules, which can result in altered texture and functionality of food products. UV radiation can cause the oxidation of amino acid residues, particularly those containing sulfur (e.g., cysteine and methionine) and aromatic residues (e.g., tryptophan, tyrosine, and phenylalanine) (Reinmuth-Selzle et al., 2022). This can affect the protein's nutritional value and functionality. UV radiation can inactivate enzymes by disrupting their active sites or causing conformational changes that affect their catalytic activity. The nutritional quality of proteins can be compromised due to the loss of essential amino acids and the formation of non-digestible aggregates. UV-induced changes in proteins can alter the sensory properties of food products, such as flavor, texture, and color. Understanding the effects of UV radiation is crucial for developing effective edible films for food packaging. Manufacturers may need to incorporate UV stabilizers or antioxidants to enhance the UV resistance of polysaccharide films. Minimizing UV exposure during food processing and storage is important to maintain the quality and functionality of proteins in food products. This can involve using UV-blocking materials or packaging, as well as controlling environmental conditions (Ezati et al., 2023). Table 3 shows some studies on the effect of ultraviolet radiation on polysaccharide and protein films.

Table 3. Some studies on the effect of ultraviolet radiation on polysaccharide and protein films.

Edible film	Treatment	Time and Dose	Food Product Analyzed	Observed Effects	References
Whey protein concentrate	UV	12.0 Jcm^{-2}	-	• Ultraviolet treatment of pH 9 solutions increased free sulfhydryl groups. • Films formed at pH 9 showed higher solubility, tensile strength, elastic modulus, and puncture properties, with lower elongation at break. • UV radiation at pH 11 decreased free sulfhydryl groups. • Films formed at pH 11 exhibited higher solubility and elastic modulus, but lower puncture deformation and elongation at break compared to untreated films. • Film color was affected differently by UV treatment depending on the solution pH.	(Díaz et al., 2017)
Chitosan-gelatin	UV	0, 5, and 10 minutes.	-	• UV irradiation markedly reduced the darkness of the films. • UV treatment increased the release rate of gallic acid (GA). • Among non-irradiated samples, films with β-cyclodextrin (β-CD) showed the highest release rate, while those with ethanol had the lowest. • Incorporation of β-CD mitigated the UV-induced increase in release rate. • UV irradiation for 10 minutes reduced mechanical strength and water vapor barrier properties of the films. • Microscopic analysis revealed a consistent and uniform microstructure, though prolonged UV exposure caused cracks in the film network. • UV irradiation weakened the –OH bending vibration and enhanced the amide I and amide II bands in FTIR spectra.	(Rezaee et al., 2020)
whey protein concentrate	UV	0.12, 4.0 and 12.0 Jcm-2	-	• Ultraviolet treatment significantly affected most mechanical properties and solubility only when applied to the film-forming solution at the highest dose. • Films exhibited higher tensile strength, puncture strength, and puncture deformation, along with lower solubility compared to untreated films. • Films treated with the highest UV dose in solution showed tensile strength comparable to heat-treated films. • UV radiation caused films to become more yellow, greener, and darker, with a greater color change when applied to the film-forming solution. • High-dose UV treatment of solutions increased free sulfhydryl group concentration and induced aggregate formation, though changes were less pronounced than those from heat treatment. • Denaturation was greater in α-lactalbumin than in β-lactoglobulin. • No changes were detected in the secondary structure of proteins. • Microstructural differences were observed among the films.	(Díaz et al., 2016)
Aloe gel, cinnamon oil, chitosan	UV-C	3 and 5 min at 254 nm	Bell pepper	• UV-C application for 5 minutes and 1.5% Aloe gel delayed changes in firmness, titratable acidity (TA), ascorbic acid levels, soluble solids content (SSC), and fruit color development during storage. • These treatments also reduced weight loss, electrolyte leakage, and disease incidence. • Postharvest performance showed that UV-C for 5 minutes combined with 1.5% Aloe gel significantly	(Abbasi et al., 2015)

				preserved pepper quality compared to the control for up to 24 days.	
gelatin	UV-C	0, 0.5, 1, and 2 h	-	UV treatment applied for 2 hours significantly reduced water solubility (WS) but did not affect water vapor permeability (WVP). • Tensile strength (TS) and Young's modulus (YM) were affected by UV treatment. • For the longest UV exposure, TS increased from 1.56 MPa (control) to 2.85 MPa. • Young's modulus increased from 4.36 MPa (control) to 9.23 MPa after UV treatment.	(de Vargas et al., 2023)
***Salvia macrosiphon* seed gum**	UV-B	-	-	• UV-B treatment reduced the solubility and water vapor permeability of SSG films. • UV-B treatment increased the tensile strength of the films. • UV-B irradiation formed new connections between starch chains. • UV-B irradiation caused dissociation of the polymer chains. • The control film exhibited an uneven and coarse surface with lower thermal stability. • UV-B irradiation improved surface uniformity and thermal stability.	(Amininasab et al., 2024)
Fish gelatin	UV	30 min/ 365 nm	-	• Water contact angle of fish gelatin (FG) films improved significantly after riboflavin-mediated UV (RmUV) irradiation at 60 seconds compared to control films. • Water vapor absorption and water solubility of RmUV-irradiated FG films decreased relative to controls. • Tensile strength and Young's modulus of RmUV-irradiated FG films were significantly higher than those of control films in both dry and wet states.	(Wang et al., 2017)
Fish gelatin	ultraviolet-B	0, 3.4, 6.8, 14.9, 19.8, 24.8 and 29.7 J.cm−2	-	• Creating cross-linking of gelatin chains after radiation exposure. • UV-B treated samples showed increased gel strength, with cold-water fish gelatin rising from 1.39 to 2.11 N and warm-water gelatin from 7.15 to 8.34 N. • Both gelatin types exhibited increased viscosity at higher UV doses. • Cold-water fish gelatin films made from irradiated granules demonstrated greater tensile strength. • Warm-water gelatin films from irradiated granules had lower tensile strength but improved water vapor barrier properties. • The differences are likely due to UV-induced cross-linking in warm-water gelatin disrupting helical structures.	(Otoni et al., 2012)
Chitosan /carrageenan	UV-C	11.4 kJ/m2	longan fruit	UV treatment applied before coating (chitosan or carrageenan) resulted in lower polyphenol oxidase (PPO) and phenylalanine ammonia-lyase (PAL) activities and higher total phenolic content (TPC) in longan pericarp. • Enzymatic activity changes did not significantly affect surface lightness or browning index, which were more influenced by coating type.	(Lin et al., 2017)

				• Combination treatments with carrageenan showed higher surface lightness and lower browning index compared to those with chitosan. • When UV treatment preceded coating, UV plus chitosan combinations exhibited lower PPO and PAL activities and better-preserved cell structure with less damage than UV plus carrageenan combinations. • UV plus carrageenan coating led to higher weight loss and respiration rate, with cell structure showing larger intercellular spaces at the end of storage.	
Sesame protein isolate	UV-A, UV-B and UV-C	32.6 Jm−2 over 6 h	-	• XRD patterns showed an increased crystallinity index of the films after UV treatment. • FE-SEM observations revealed a more compact film structure without pinholes or cracks following UV exposure. • Moisture content, solubility, and water vapor permeability (WVP) decreased, while film density and hydrophobicity increased after UV treatment. • Mechanical properties improved, with UV-C irradiated film-forming solutions exhibiting the highest tensile strength (8.29 MPa) and Young's modulus (118.35 MPa).	(Fathi et al., 2018)
Carboxymethyl cellulose and polyvinyl alcohol	UV	11 and 22 J cm-2 /80 and 160 min	-	• Blend films containing sodium benzoate exposed to UV radiation showed lower moisture content, greater elongation at break, and rougher surfaces compared to untreated films. • The combination of sodium benzoate and UV treatment inhibited the growth of a broad spectrum of microorganisms, enhancing antimicrobial properties. • UV treatment altered the film morphology, increasing water insolubility.	(Villarruel et al., 2015)
fish gelatin	UV radiation	60 min/ 253.7 nm	-	• Tensile strength and elongation at break increased, especially in films without added sugars exposed to UV radiation. • Films containing ribose showed decreased solubility after UV treatment and higher swelling compared to films with lactose, which dissolved readily in water. • FTIR spectra of all films exhibited identical patterns, indicating no major changes in functional groups due to interactions between gelatin, sugars, and UV irradiation.	(Bhat & Karim, 2014)
Rice starch and fish proteins	UV radiation	250–400 nm/ 1, 5, and 10 min	-	• UV radiation for 1 minute increased tensile strength and modified the optical properties of the films. • It altered the polymeric matrix structure, as shown by microstructure and thermal analyses, consistent with changes in packaging properties. • Combining UV radiation with fish protein hydrolysates helps reduce lipid oxidation and enhances the performance of active bio-based films for food packaging.	(Romani et al., 2024)

Ultraviolet (UV) irradiation significantly modifies the physicochemical, mechanical, structural, and antimicrobial properties of biopolymer films and coatings, with effects influenced by factors such as irradiation dose, exposure time, pH, and the presence of additives. Generally, UV treatment enhances tensile strength, Young's modulus, and film crystallinity while reducing water solubility, moisture content, and water vapor permeability. Structural analyses reveal increased polymer chain cross-linking and alterations in functional groups without major changes in protein secondary structure, contributing to improved mechanical performance and thermal stability. Additionally, UV treatment combined with bioactive compounds or coatings enhances antimicrobial activity, delays quality degradation, and extends the shelf life of food products by inhibiting microbial growth and preserving key quality attributes. Despite these benefits, excessive UV exposure may induce microstructural damage, highlighting the importance of optimizing treatment conditions. Overall, UV irradiation is an effective, non-thermal method to tailor the properties of biodegradable films for advanced food packaging applications (Abbasi et al., 2015; Amininasab et al., 2024; Díaz et al., 2016; Otoni et al., 2012; Rezaee et al., 2020).

Comparison of different irradiations on biopolymer films

Irradiation, including electron beam, gamma, and UV treatments, significantly influences the structural, mechanical, barrier, and antimicrobial properties of biopolymer-based films, with each method exhibiting distinct mechanisms and outcomes. Electron beam irradiation is particularly effective for polymers with easily crosslinkable chains, promoting free radical-induced crosslinking that enhances tensile strength, thermal stability, and barrier performance while modulating antioxidant retention and release. Gamma irradiation, often applied in combination with bioactive additives such as nanoparticles, essential oils, or chitosan, not only strengthens mechanical and barrier properties but also provides antimicrobial activity and controlled delivery of active compounds, making it suitable for composite or additive-enriched films. In contrast, UV irradiation primarily modifies surface properties, improving surface tensile strength, crystallinity, and antimicrobial activity, especially in thin films and coatings, without significantly altering the bulk polymer structure. Despite these benefits, excessive irradiation—particularly at high doses—can cause polymer degradation, reduced flexibility, or microstructural damage, emphasizing the need for careful dose optimization. Overall, the choice of irradiation type and conditions must be tailored to polymer composition, film thickness, presence of additives, and intended functional outcomes, highlighting the complementary and application-specific roles of electron beam, gamma, and UV irradiation in the development of high-performance biodegradable films for food and pharmaceutical packaging.

FUTURE CHALLENGES AND PRIORITIES

Ionizing Radiations

Gamma rays and electron beams are widely applied for sterilization and functional modification of food packaging films due to their strong penetration capacity and ability to induce structural changes within polymers. However, several concrete gaps limit their broader adoption. Standardized irradiation protocols that ensure dose uniformity across different food matrices and packaging geometries are still lacking, complicating reproducibility and regulatory approval. Material compatibility remains insufficiently understood, as comprehensive databases mapping radiation–material interactions are not yet available, which hinders predictive design of radiation-resistant films. Although applications such as polymer cross-linking and barrier property enhancement have been demonstrated, integration with smart and active packaging systems—including sensor-enabled films and controlled-release antimicrobial coatings—has received minimal attention. Furthermore, harmonized international regulations for validation, traceability, and consumer labeling are absent, while robust life cycle assessments are needed to address the energy footprint and waste management of irradiation facilities. Addressing these gaps will be essential for scaling ionizing radiation technologies safely and sustainably in next-generation packaging.

Non-Ionizing radiations

Ultraviolet (UV) rays are primarily employed for surface disinfection and functional modification of films and food coatings, yet several critical challenges remain unresolved. Disinfection efficiency is limited by the absence of standardized UV dose–response curves for diverse microorganisms and packaging substrates, resulting in inconsistent industrial performance. UV exposure frequently induces negative effects such as discoloration, polymer degradation, and reduced mechanical stability, and systematic mitigation strategies—through stabilizers, protective nanocomposites, or optimized formulations—are still underdeveloped. Although LED-based UV systems have emerged as promising energy-efficient alternatives, issues of process scalability and cost-effectiveness persist. At the same time, consumer perception of UV-treated packaging has been insufficiently studied, underscoring the need for transparent labeling and communication frameworks to foster acceptance. Finally, occupational safety protocols tailored to continuous industrial UV operations remain vague and require further refinement. Future work should focus on developing standardized protocols, improving material stability under UV exposure, and integrating UV processing with active and intelligent packaging technologies to unlock its full industrial potential.

CONCLUSIONS

Gamma rays, electron beams, and UV radiation provide versatile strategies for improving the structural, mechanical, barrier, and antimicrobial properties of biopolymer-based films and coatings in industrial food packaging. Electron beam irradiation is particularly effective for polymers with easily crosslinkable chains, such as starch-, gelatin-, and protein-based films, enhancing tensile strength, thermal stability, and barrier properties through free radical-induced crosslinking and matrix stabilization. Gamma irradiation, especially when combined with bioactive additives such as nanoparticles, essential oils, or chitosan, improves mechanical, barrier, and antimicrobial performance while enabling controlled release of active compounds, making it highly suitable for composite or additive-enriched films. UV irradiation primarily modifies surface properties, making it most effective for thin films and coatings, enhancing surface tensile strength, crystallinity, and antimicrobial activity without significant alteration of bulk polymer structure. The effectiveness of each radiation type depends on polymer composition, film thickness, irradiation dose, exposure conditions, and the presence of additives, while practical limitations including dose uniformity, material compatibility, and process scalability must be carefully considered. Regulatory approval together with adherence to safety and environmental standards, is critical for industrial implementation. Overall, irradiation-based treatments represent a promising, safe, and sustainable approach for developing high-performance biodegradable packaging, with method selection guided by polymer characteristics, industrial objectives, and regulatory requirements.

REFERENCES

Abbasi, N. A., Ashraf, S., Ali, I., & Butt, S. J. (2015). Enhancing storage life of bell pepper by UV-C irradiation and edible coatings. *Pakistan Journal of Agricultural Sciences, 52*(2), 403-411.

Ahmad, M. I., Ab. Rahim, M. H., Nordin, R., Mohamed, F., Abu-Samah, A., & Abdullah, N. F. (2021). Ionizing radiation monitoring technology at the verge of internet of things.

Sensors, 21(22), 7629. https://doi.org/10.3390/s21227629

Amin, U., Khan, M. U., Majeed, Y., Rebezov, M., Khayrullin, M., Bobkova, E., Shariati, M. A., Chung, I. M., & Thiruvengadam, M. (2021). Potentials of polysaccharides, lipids and proteins in biodegradable food packaging applications. *International journal of biological macromolecules, 183*, 2184-2198. https://doi.org/10.1016/j.ijbiomac.2021.05.182

Amininasab, S. M. H., Hojjati, M., Noshad, M., & Soltani, M. (2024). Effect of UV-B irradiation and liquid smoke on physicochemical characterization of Salvia macrosiphon gum based edible films. *Colloids and Surfaces A: Physicochemical and Engineering Aspects, 682*, 132958. https://doi.org/10.1016/j.colsurfa.2023.132958

Ansari, I., & Datta, A. (2003). An overview of sterilization methods for packaging materials used in aseptic packaging systems. *Food and Bioproducts Processing, 81*(1), 57-65. https://doi.org/10.1205/096030803765208670

Apte, K., & Bhide, S. (2024). Basics of radiation. In *Advanced radiation shielding materials* (pp. 1-23). Elsevier.

Ardjoum, N., Shankar, S., Chibani, N., Salmieri, S., & Lacroix, M. (2021). In situ synthesis of silver nanoparticles in pectin matrix using gamma irradiation for the preparation of antibacterial pectin/silver nanoparticles composite films. *Food Hydrocolloids, 121*, 107000. https://doi.org/10.1016/j.foodhyd.2021.107000

Ashfaq, A., Clochard, M.-C., Coqueret, X., Dispenza, C., Driscoll, M. S., Ulański, P., & Al-Sheikhly, M. (2020). Polymerization reactions and modifications of polymers by ionizing radiation. *Polymers, 12*(12), 2877. https://doi.org/10.3390/polym12122877

Bahari, R., Shahbazi, Y., & Shavisi, N. (2020). Effect of gamma irradiation on physico-mechanical and structural properties of active Farsi gum-CMC films containing Ziziphora clinopodioides essential oil and lignocellulose nanofibers for meat packaging. *Journal of Food Science, 85*(10), 3498-3508. https://doi.org/10.1111/1750-3841.15456

Ben-Fadhel, Y., Cingolani, M. C., Li, L., Chazot, G., Salmieri, S., Horak, C., & Lacroix, M. (2021). Effect of γ-irradiation and the use of combined treatments with edible bioactive coating on carrot preservation. *Food Packaging and Shelf Life, 28*, 100635. https://doi.org/10.1016/j.fpsl.2021.100635

Benbettaïeb, N., Assifaoui, A., Karbowiak, T., Debeaufort, F., & Chambin, O. (2016). Controlled release of tyrosol and ferulic acid encapsulated in chitosan–gelatin films after electron beam irradiation. *Radiation Physics and Chemistry, 118*, 81-86. https://doi.org/10.1016/j.radphyschem.2015.01.035

Benbettaïeb, N., Chambin, O., Karbowiak, T., & Debeaufort, F. (2016). Release behavior of quercetin from chitosan-fish gelatin edible films influenced by electron beam irradiation. *Food Control, 66*, 315-319. https://doi.org/10.1016/j.foodcont.2016.02.027

BenBettaïeb, N., Karbowiak, T., Bornaz, S., & Debeaufort, F. (2015). Spectroscopic analyses of the influence of electron beam irradiation doses on mechanical, transport properties and microstructure of chitosan-fish gelatin blend films. *Food Hydrocolloids, 46*, 37-51. https://doi.org/10.1016/j.foodhyd.2014.09.038

Benbettaïeb, N., Karbowiak, T., Brachais, C.-H., & Debeaufort, F. (2015). Coupling tyrosol, quercetin or ferulic acid and electron beam irradiation to cross-link chitosan–gelatin films: A structure–function approach. *European polymer journal 67*, 113-127. https://doi.org/10.1016/j.eurpolymj.2015.03.060

Benbettaïeb, N., Karbowiak, T., Brachais, C.-H., & Debeaufort, F. (2016). Impact of electron beam irradiation on fish gelatin film properties. *Food Chemistry, 195*, 11-18. https://doi.org/10.1016/j.foodchem.2015.03.034

Bhat, R., & Karim, A. (2014). Towards producing novel fish gelatin films by combination treatments of ultraviolet radiation and sugars (ribose and lactose) as cross-linking agents. *Journal of Food Science and Technology, 51*, 1326-1333. https://doi.org/10.1007/s13197-012-0652-9

Chacha, J. S., Zhang, L., Ofoedu, C. E., Suleiman, R. A., Dotto, J. M., Roobab, U., Agunbiade, A. O., Duguma, H. T., Mkojera, B. T., & Hossaini, S. M. (2021). Revisiting non-thermal food processing and preservation methods—Action mechanisms, pros and cons: A technological update (2016–2021). *Foods, 10*(6), 1430. https://doi.org/10.3390/foods10061430

Chaudhary, S., Kumar, S., Kumar, V., Singh, B., & Dhiman, A. (2024). Irradiation: A tool for the sustainability of fruit and vegetable supply chain-Advancements and future trends. *Radiation Physics and Chemistry, 217*, 111511. https://doi.org/10.1016/j.radphyschem.2024.111511

Chen, B.-R., Roobab, U., Madni, G. M., Abdi, G., Zeng, X.-A., & Aadil, R. M. (2024). A review of emerging applications of ultrasonication in Comparison with non-ionizing technologies for meat decontamination. *Ultrasonics Sonochemistry, 108*, 106962. https://doi.org/10.1016/j.ultsonch.2024.106962

Chiozzi, V., Agriopoulou, S., & Varzakas, T. (2022). Advances, applications, and comparison of thermal (pasteurization, sterilization, and aseptic packaging) against non-thermal (ultrasounds, UV radiation, ozonation, high hydrostatic pressure) technologies in food processing. *Applied Sciences, 12*(4), 2202. https://doi.org/10.3390/app12042202

Chmielewski, A. G. (2023). Radiation technologies: the future is today. *Radiation Physics and Chemistry, 213*, 111233. https://doi.org/10.1016/j.radphyschem.2023.111233

Darré, M., Vicente, A. R., Cisneros-Zevallos, L., & Artés-Hernández, F. (2022). Postharvest ultraviolet radiation in fruit and vegetables: Applications and factors modulating its efficacy on bioactive compounds and microbial growth. *Foods, 11*(5), 653. https://doi.org/10.3390/foods11050653

de Vargas, V. H., Marczak, L. D. F., Flôres, S. H., & Mercali, G. D. (2023). Morphology and functional properties of gelatin-based films modified by UV radiation and bacterial cellulose nanofibers. *Journal of Food Process Engineering, 46*(9), e14399. https://doi.org/10.1111/jfpe.14399

Díaz, O., Candia, D., & Cobos, Á. (2016). Effects of ultraviolet radiation on properties of films from whey protein concentrate treated before or after film formation. *Food Hydrocolloids, 55*, 189-199. https://doi.org/10.1016/j.foodhyd.2015.11.019

Díaz, O., Candia, D., & Cobos, Á. (2017). Whey protein film properties as affected by ultraviolet treatment under alkaline conditions. *International Dairy Journal, 73*, 84-91. https://doi.org/10.1016/j.idairyj.2017.05.009

Dini, H., Fallah, A. A., Bonyadian, M., Abbasvali, M., & Soleimani, M. (2020). Effect of edible composite film based on chitosan and cumin essential oil-loaded nanoemulsion combined with low-dose gamma irradiation on microbiological safety and quality of beef loins during refrigerated storage. *International journal of biological macromolecules, 164*, 1501-1509. https://doi.org/10.1016/j.ijbiomac.2020.07.215

Ezati, P., Khan, A., Priyadarshi, R., Bhattacharya, T., Tammina, S. K., & Rhim, J.-W. (2023). Biopolymer-based UV protection functional films for food packaging. *Food Hydrocolloids, 142*, 108771. https://doi.org/10.1016/j.foodhyd.2023.108771

Fatehi, P., Alamouti, A., Behgar, M., & Norouzian, M. (2020). Effect of electron irradiation on some physical, chemical and digestion properties of pistachio by-products. *Radiation Physics and Chemistry, 174*, 108921. https://doi.org/10.1016/j.radphyschem.2020.108921

Fathi, N., Almasi, H., & Pirouzifard, M. K. (2018). Effect of ultraviolet radiation on morphological and physicochemical properties of sesame protein isolate based edible films. *Food Hydrocolloids, 85*, 136-143. https://doi.org/10.1016/j.foodhyd.2018.07.018

Guo, K., Baidak, A., & Yu, Z. (2020). Recent advances in green synthesis and modification of inorganic nanomaterials by ionizing and non-ionizing radiation. *Journal of Materials Chemistry A, 8*(44), 23029-23058. https://doi.org/10.1039/D0TA06742C

Guo, W., Mehrparvar, S., Hou, W., Pan, J., Aghbashlo, M., Tabatabaei, M., & Rajaei, A. (2024). Unveiling the impact of high-pressure processing on anthocyanin-protein/polysaccharide interactions: A comprehensive review. *International Journal of Biological Macromolecules, 270*, 132042. https://doi.org/10.1016/j.ijbiomac.2024.132042

Gürsu, H. (2024). Reusable Smart Lids for Improving Food Safety at Household Level with

Programmable UV-C Technology. *Sustainability, 16*(13), 5370. https://doi.org/10.3390/su16135370

Huang, T., Fang, Z., Zhao, H., Xu, D., Yang, W., Yu, W., & Zhang, J. (2020). Physical properties and release kinetics of electron beam irradiated fish gelatin films with antioxidants of bamboo leaves. *Food bioscience, 36*, 100597. https://doi.org/10.1016/j.fbio.2020.100597

Indiarto, R., Irawan, A. N., & Subroto, E. (2023). Meat irradiation: A comprehensive review of its impact on food quality and safety. *Foods, 12*(9), 1845. https://doi.org/10.3390/foods12091845

Joshua Ajibola, O. (2020). An overview of irradiation as a food preservation technique. *Novel Research in Microbiology Journal, 4*(3), 779-789. https://doi.org/10.21608/nrmj.2020.95321

Kumar, A., Rani, P., Purohit, S. R., & Rao, P. S. (2020). Effect of ultraviolet irradiation on wheat (Triticum aestivum) flour: Study on protein modification and changes in quality attributes. *Journal of Cereal Science, 96*, 103094. https://doi.org/10.1016/j.jcs.2020.103094

Kurdziel, M., Łabanowska, M., Pietrzyk, S., Pająk, P., Królikowska, K., & Szwengiel, A. (2022). The effect of UV-B irradiation on structural and functional properties of corn and potato starches and their components. *Carbohydrate polymers, 289*, 119439. https://doi.org/10.1016/j.carbpol.2022.119439

Li, L., Chen, H., Wang, M., Lv, X., Zhao, Y., & Xia, L. (2018). Development and characterization of irradiated-corn-starch films. *Carbohydrate polymers, 194*, 395-400. https://doi.org/10.1016/j.carbpol.2018.04.060

Li, R., & Wu, G. (2020). Preparation of polysaccharide-based hydrogels via radiation technique. In *Hydrogels based on natural polymers* (pp. 119-148). Elsevier. https://doi.org/10.1016/B978-0-12-816421-1.00005-7

Lin, M. G., Lasekan, O., Saari, N., & Khairunniza-Bejo, S. (2017). The effect of the application of edible coatings on or before ultraviolet treatment on postharvested longan fruits. *Journal of Food Quality, 2017*(1), 5454263. https://doi.org/10.1155/2017/5454263

Liu, J., Song, F., Chen, R., Deng, G., Chao, Y., Yang, Z., Wu, H., Bai, M., Zhang, P., & Hu, Y. (2022). Effect of cellulose nanocrystal-stabilized cinnamon essential oil Pickering emulsions on structure and properties of chitosan composite films. *Carbohydrate polymers, 275*, 118704. https://doi.org/10.1016/j.carbpol.2021.118704

Manaila, E., Craciun, G., Ighigeanu, D., Lungu, I. B., Dumitru, M., & Stelescu, M. D. (2021). Electron Beam Irradiation: A method for degradation of composites based on natural rubber and plasticized starch. *Polymers, 13*(12), 1950. https://doi.org/10.3390/polym13121950

Mendes, J. F., Norcino, L. B., Manrich, A., Pinheiro, A. C. M., Oliveira, J. E., & Mattoso, L. H. C. (2020). Development, physical-chemical properties, and photodegradation of pectin film reinforced with malt bagasse fibers by continuous casting. *Journal of Applied Polymer Science, 137*(39), 49178. https://doi.org/10.1002/app.49178

Mirzaee Moghaddam, H., & Nahalkar, A. (2025). Review on Enhancing the Physicomechanical Properties of Chitosan and Konjac Glucomannan Edible Films with Pickering Emulsions Containing Essential Oils for Sustainable Food Packaging. *Biomechanism and Bioenergy Research, 4*(2), 40-54. https://doi.org/10.22103/bbr.2025.24993.1118

Mondal, H. T., & Akhtaruzzaman, M. (2024). Food Irradiation for Food Safety. In *Food Safety* (pp. 183-196). CRC Press.

More, C. V., Alsayed, Z., Badawi, M. S., Thabet, A. A., & Pawar, P. P. (2021). Polymeric composite materials for radiation shielding: a review. *Environmental chemistry letters, 19*, 2057-2090. https://doi.org/10.1007/s10311-021-01189-9

Mostafavi, H. A., Mirmajlessi, S. M., & Fathollahi, H. (2012). The potential of food irradiation: benefits and limitations. *Trends in vital food and control engineering, 5*, 43-68.

Nikbakht, H., Rajaei, A., & Movahednejad, M. H. (2024). Investigation and Production of Thyme Essential Oil Nanoemulsion Using Chitosan-Zein Pickering Emulsion Method by Nano Spray Drying Mechanism. *Biomechanism and Bioenergy Research, 3*(1), 56-67. https://doi.org/10.22103/bbr.2024.22873.1077

Otoni, C. G., Avena-Bustillos, R. J., Chiou, B. S., Bilbao-Sainz, C., Bechtel, P. J., & McHugh, T. H. (2012). Ultraviolet-B radiation induced cross-linking improves physical properties of cold-and warm-water fish gelatin gels and films. *Journal of Food Science, 77*(9), E215-E223. https://doi.org/10.1111/j.1750-3841.2012.02839.x

Pan, M., Yang, J., Liu, K., Xie, X., Hong, L., Wang, S., & Wang, S. (2021). Irradiation technology: An effective and promising strategy for eliminating food allergens. *Food Research International, 148*, 110578. https://doi.org/10.1016/j.foodres.2021.110578

Pandey, S., Kumar, G., Tiwari, N. K., & Yadav, J. (2024). Gamma Irradiation Effects on Salvia hispanica L. seeds in M2 Generation: A comprehensive study of genetic variation and phytochemical responses. *Caryologia, 77*(4), 3-12.

Pinto de Rezende, L., Barbosa, J., & Teixeira, P. (2022). Analysis of alternative shelf life-extending protocols and their effect on the preservation of seafood products. *Foods, 11*(8), 1100. https://doi.org/10.3390/foods11081100

Quevedo, R., Bastías, J. M., Espinoza, T., Ronceros, B., Balic, I., & Muñoz, O. (2020). Inactivation of Coronaviruses in food industry: The use of inorganic and organic disinfectants, ozone, and UV radiation. *Scientia Agropecuaria, 11*(2), 257-266. https://doi.org/10.17268/sci.agropecu.2020.02.14

Ramamurthy, V. V., Akhtar, M. S., Patankar, N. V., Menon, P., Kumar, R., Singh, S. K., Ayri, S., Parveen, S., & Mittal, V. (2010). Efficiency of different light sources in light traps in monitoring insect diversity. *Munis Entomology & Zoology, 5*(1), 109-114.

Reinmuth-Selzle, K., Tchipilov, T., Backes, A. T., Tscheuschner, G., Tang, K., Ziegler, K., Lucas, K., Pöschl, U., Fröhlich-Nowoisky, J., & Weller, M. G. (2022). Determination of the protein content of complex samples by aromatic amino acid analysis, liquid chromatography-UV absorbance, and colorimetry. *Analytical and Bioanalytical Chemistry, 414*(15), 4457-4470. https://doi.org/10.1007/s00216-022-03910-1

Rezaee, M., Askari, G., EmamDjomeh, Z., & Salami, M. (2020). UV-irradiated gelatin-chitosan bio-based composite film, physiochemical features and release properties for packaging applications. *International journal of biological macromolecules, 147*, 990-996. https://doi.org/10.1016/j.ijbiomac.2019.10.066

Romani, V. P., Martins, P. C., da Rocha, M., Bulhosa, M. C. S., Kessler, F., & Martins, V. G. (2024). UV Radiation and Protein Hydrolysates in Bio-Based Films: Impacts on Properties and Italian Salami Preservation. *Antioxidants, 13*(5), 517. https://doi.org/10.3390/antiox13050517

Sabaghi, M., Maghsoudlou, Y., Kashiri, M., & Shakeri, A. (2020). Evaluation of release mechanism of catechin from chitosan-polyvinyl alcohol film by exposure to gamma irradiation. *Carbohydrate polymers, 230*, 115589. https://doi.org/10.1016/j.carbpol.2019.115589

Salari, M., Khiabani, M. S., Mokarram, R. R., Ghanbarzadeh, B., & Kafil, H. S. (2021). Use of gamma irradiation technology for modification of bacterial cellulose nanocrystals/chitosan nanocomposite film. *Carbohydrate polymers, 253*, 117144. https://doi.org/10.1016/j.carbpol.2020.117144

Sarmast, E., Shankar, S., Salmieri, S., Rahmouni, S. A., Mahmud, J., & Lacroix, M. (2024). Cross-linked gelatin–riboflavin-based film incorporated with essential oils and silver nanoparticle by gamma-irradiation: A novel approach for extending the shelf life of meat. *Food Hydrocolloids, 147*, 109330. https://doi.org/10.1016/j.foodhyd.2023.109330

Senna, M. M., Mostafa, A. E.-K. B., Mahdy, S. R., & El-Naggar, A. W. M. (2016). Characterization of blend hydrogels based on plasticized starch/cellulose acetate/carboxymethyl cellulose synthesized by electron beam irradiation. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 386*, 22-29.

Shahbazi, M., Rajabzadeh, G., & Ahmadi, S. J. (2017). Characterization of nanocomposite film based on chitosan intercalated in clay platelets by electron beam irradiation. *Carbohydrate polymers, 157*, 226-235. https://doi.org/10.1016/j.carbpol.2016.09.018

Shahi, S., Khorvash, R., Goli, M., Ranjbaran, S. M., Najarian, A., & Mohammadi Nafchi, A. (2021). Review of proposed different irradiation methods to inactivate food-processing viruses and microorganisms. *Food science & nutrition, 9*(10), 5883-5896. https://doi.org/10.1002/fsn3.2539

Shankar, S., Khodaei, D., & Lacroix, M. (2021). Effect of chitosan/essential oils/silver nanoparticles composite films packaging and gamma irradiation on shelf life of strawberries. *Food Hydrocolloids, 117*, 106750. https://doi.org/10.1016/j.foodhyd.2021.106750

Shojaei, M. H., Jafarinaeimi, K., Mortezapour, H., Maharlooei, M., & Asadi, M. (2025). Effect of Non-Thermal Methods on the Reduction of Pesticide Residues and Harmful Microorganisms in Food Products (A Review). *Biomechanism and Bioenergy Research, 4*(1), 1-18. https://doi.org/10.22103/bbr.2024.24212.1094

Srinivasa, U. M., Sruthi, P., Rastogi, N. K., & Naidu, M. M. (2023). Application of irradiation in the food industry. In *Non-thermal Food Processing Operations* (pp. 221-253). Elsevier.

Thavorn, J., Muangsin, V., Gowanit, C., & Muangsin, N. (2022). Research on Shelf Life Extension Technologies for Food Sustainability: An Assessment of Scientific Activities and Networks. *The Scientific World Journal, 2022*(1), 7120662

Uehara, V., & Mastro, N. d. (2017). Characteristics of biodegradable films based on cassava starch and soy isolate protein treated by electron beam radiation. *Academia Journal of Agricultural Research, 5*, 68-74.

Villarruel, S., Giannuzzi, L., Rivero, S., & Pinotti, A. (2015). Changes induced by UV radiation in the presence of sodium benzoate in films formulated with polyvinyl alcohol and carboxymethyl cellulose. *Materials Science and Engineering: C, 56*, 545-554. https://doi.org/10.1016/j.msec.2015.07.003

Wang, K., Wang, W., Wu, X., Xiao, J., Liu, Y., & Liu, A. (2017). Effect of photochemical UV/riboflavin-mediated cross-links on different properties of fish gelatin films. *Journal of Food Process Engineering, 40*(5), e12536. https://doi.org/10.1111/jfpe.12536

Yang, J., Pan, M., Han, R., Yang, X., Liu, X., Yuan, S., & Wang, S. (2024). Food irradiation: An emerging processing technology to improve the quality and safety of foods. *Food Reviews International, 40*(8), 2321-2343.

Zhou, X., Ye, X., He, J., Wang, R., & Jin, Z. (2020). Effects of electron beam irradiation on the properties of waxy maize starch and its films. *International journal of biological macromolecules, 151*, 239-246. https://doi.org/10.1016/j.ijbiomac.2020.01.287