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Electron beam irradiation in food processing: current applications and strategies for commercial scale implementation

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Electron beam irradiation (EBI) is a non-thermal processing technology that utilizes high-energy electron beams to eliminate microorganisms and extend the food storage period. Currently, EBI has demonstrated extensive application potential in food, agriculture, and medical fields, serving as a crucial technological means to ensure product safety and quality. Despite the many potential advantages of EBI technology, its large-scale application in the food industry remains underdeveloped compared to conventional processing methods. The main limiting factors are the limited penetration depth of electron beams and the potential adverse effects of high-dose irradiation on the texture and flavor of food. To overcome these limitations, more comprehensive studies of the mechanisms of EBI in microbial inactivation should be conducted. Furthermore, it is imperative to minimize the irradiation dose to the greatest extent possible based on the characteristics of different products. The integration of EBI with modified atmosphere packaging (MAP) techniques, the utilization of artificial intelligence (AI) to optimize irradiation parameters, and the development of natural antibacterial compounds (NAC) and aseptic packaging can enhance the microbial inactivation efficacy and product quality of EBI, thereby facilitating the large-scale implementation of EBI technology. This review examines the mechanisms of microbial inactivation induced by EBI, elucidates factors affecting its efficacy and explores the applications of EBI in various fields and the potential of combining EBI with other methods to ensure inactivation efficiency and ensure product quality. Finally, this review outlines the regulatory framework in the field of EBI to ensure the safety of the technology.

Sustainability spotlight

With the growing demand for safe and high-quality food, ensuring effective decontamination without compromising nutritional value has become a critical challenge. However, traditional thermal sterilization may result in high energy consumption and nutrient loss. Electron beam irradiation technology as one of the effective non-thermal sterilization methods can effectively inactivate microorganisms while preserving nutritional integrity. This review especially examines the application of electron beam irradiation in food decontamination and its synergistic effects in combination with other methods to improve inactivation efficiency of microorganisms, reduce environmental burdens and maximize the retention of nutritional value. It aligns with the UN Sustainable Development Goals, especially Goal 3 (Good Health and Well-Being) and Goal 12 (Responsible Consumption and Production).

1. Introduction

Advancements such as precision agriculture and biotechnology are reshaping modern agriculture, not only increasing crop yields and optimizing resource use but also driving sustainable agricultural development to effectively address global food security challenges.[1–3] Despite advancements in agricultural technology and production capacity, improper post-harvest processing leads to significant food waste. Data show that approximately 14% of global food is lost from harvest to retail.[4] Notably, the loss of fruits and vegetables accounts for a staggering 21.6%. 735 million people worldwide still face hunger due to insufficient access to food.[5] On the other hand, improper processing of post-harvest food not only leads to massive waste but also increases the risk of microbial contamination and foodborne diseases.[6] Data show that about 600 million people all over the world suffer from foodborne illnesses each year due to consumption of contaminated food, with major pathogens including *E. coli*, *Salmonella*, and *Listeria*.[7,8] Additionally, health

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concerns and changing lifestyles are raising consumers' expectations regarding food quality, nutritional content, color, and flavor of minimally processed foods.[9] Thus, the selection of the appropriate decontamination method can not only reduce food safety risks but also help preserve the original quality of the food to the greatest extent.[10] In this context, a range of emerging technologies have been exploited to mitigate food loss and improve the nutrient value and safety of food. Among them, electron beam irradiation (EBI) technology, as one of the effective non-thermal sterilization methods, has been receiving increasing attention.[11]

In the food industry, EBI is a non-thermal processing technology that uses high-energy electron beams to inactivate microorganisms and viruses.[12] It not only extends the storage period of food, but also preserves its nutrient value and sensory characteristics. In 1957, the first application of EBI in the food field was to enhance the hygienic quality of spices.[13] Before the advent of EBI technology, the food industry primarily relied on conventional thermal processing methods. These conventional techniques are extensively used in the food industry due to their broad applicability and cost-effectiveness.[14] However, the need for substantial thermal energy can lead to significant energy consumption and environmental burden. More notably, high-temperature can compromise food quality, particularly affecting fresh produce like fruits and vegetables.[15] To mitigate the negative impacts of thermal treatments, new non-thermal pasteurization technologies have been developed, such as the high pressure process (HPP), ultrasound, pulsed electric field (PEF), cold plasma (CP), and ionizing irradiation including EBI.[16]

The primary sources of ionizing radiation commonly used in the food sector include γ-rays, X-rays (with a maximum energy of 5 MeV or 7.5 MeV), and electron beams (with a maximum energy of 10 MeV).[17,18] γ-Rays are high-energy electromagnetic radiation emitted during the decay of radioactive isotopes, such as ^{60}Co or ^{137}C. X-rays are generated by high-speed electrons striking a metal target (*e.g.*, tungsten and platinum) in an X-ray tube.[19] Compared to γ-ray and X-ray irradiation, EBI seems to have distinct advantages. Although the isotopes used to produce γ-rays do not render the food itself radioactive, there is a need for substantial investment in regular source replenishment and radioactive waste disposal.[8,20] In contrast, EBI does not require radioactive isotopes, reducing safety concerns and offering economic benefits. Accelerated electrons have a high dose rate (kGy s^{-1}), allowing processing to be completed in just a few seconds to minutes, making it faster and more efficient compared to γ-rays and X-rays.[21] Additionally, the generation, disappearance, and dose of e-beams are easily controllable and they have been considered an ideal alternative to γ-ray and X-ray irradiation. EBI works by accelerating electrons and causing them to collide with the target molecules at high speed, resulting in ionization or changes in the molecular structure. Based on this energy transfer mechanism, electron beams can disrupt microbial DNA, induce genetic mutations, or alter material properties, making them widely applicable in decontamination, breeding and material modification.[22–25]

Although EBI has made promising achievements, some studies have indicated that it also has certain drawbacks. For example, EBI can accelerate oxidation reactions in food products, which may affect flavor and nutritional value. Arshad *et al.* found that irradiation at doses of 3 kGy and 7 kGy effectively reduced microbial contamination in frozen duck meat, significantly improving its hygienic quality.[26] However, higher doses of irradiation (7 kGy) can lead to marked increases in fat oxidation and protein degradation, as well as a reduction in vitamin content, which negatively affected the physicochemical properties of meat. Another limitation is that the electron beams have a limited penetration depth and typically only irradiate the surface of products, which makes them less effective on thicker or denser items. The study by Lucas *et al.* found that the thickness of dry-cured hams significantly impacted the effectiveness of electron beam inactivation, with thicker hams posing a risk of incomplete inactivation in its interior.[27] These challenges call for deeper investigations of the underlying mechanisms of EBI driving microbial inactivation to better understand the characteristics of this promising technology. Moreover, there is an urgent need for revolutionary methods to enhance the efficiency of EBI. Therefore, integrating EBI with other techniques is a promising strategy to ultimately achieve broader applicability.

In this review, we explore the principles and mechanisms of EBI inactivation of microorganisms, examine the key factors influencing its inactivation efficacy, and highlight the applications of EBI across various fields, with a particular focus on the food processing sector and its limitations. Additionally, we discuss the potential improvements of this technology, such as integration with modified atmosphere packaging (MAP), artificial intelligence (AI), natural antibacterial compounds (NAC) and aseptic packaging. These combined approaches aim to expand the commercial applications of EBI and enhance its effectiveness in food processing industries. The final section focuses on the regulatory measures and guidelines established by relevant authorities.

2. The composition of electron accelerators and different doses of electron beams

An electron accelerator is the core component of an EBI device, and its main function is to generate high-energy electron beams. Different types of electron accelerators vary in its acceleration methods and electron trajectories, but they are typically made up of an electron gun, accelerating cavity, magnetic scanning system, vacuum system, and beam output device.[28] First, the electron gun emits low-energy electrons from the cathode in a vacuum environment. These electrons are accelerated to high-energy states primarily by electric fields in the accelerating cavity.[29] After acceleration, the electrons are focused and guided by magnetic fields to precisely target the desired area. The vacuum environment prevents collisions between electrons and air molecules, reducing energy loss and

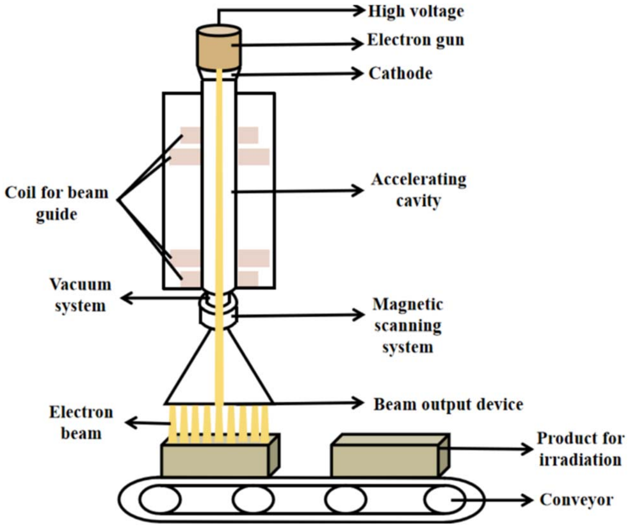

Fig. 1 Schematic diagram of the electron accelerator.

ensuring beam stability.[23] Fig. 1 presents a schematic diagram of the main structure of an electron accelerator.

Internationally, gray (Gy) is commonly used to quantify the amount of radiation energy absorbed in food processing. 1 gray represents the absorption of 1 kilojoule (kJ) of radiation energy per kilogram of material.[30] The management of the irradiation dose is crucial, as it highly influences the treatment efficiency and the product properties. Based on the different irradiation doses, electron beams used for inactivation can be categorized into low-dose (<1 kGy), medium-dose (1–10 kGy), and high-dose (>10 kGy).[31] Low-dose electron beams are primarily applied to prolong the shelf life of food, inhibit sprouting in agricultural products, and eliminate insects and pests in food.[32] Medium-dose electron beams are utilized for eliminating pathogens and parasites in food, as well as to reduce mycotoxin levels, thereby enhancing food safety.[33] High-dose EBI is widely used in space food preservation, material modification, medical waste treatment, virus inactivation and so on.[34,35] Additionally, high-dose irradiation is also used to break down harmful compounds, making them valuable in various industrial production processes. Achieving the optimal balance of dose based on the characteristics of the product and treatment objectives is a key challenge that must be addressed in the research.

3. Inactivation mechanisms of electron beam irradiation

To date, knowledge of the detailed mechanisms causing microbial cell death by EBI is relatively limited. Previous research has shown that EBI primarily kills microorganisms through two mechanisms: direct and indirect ionization, as illustrated in the upper part of Fig. 2.[36] Direct action involves high-energy electron beams directly damaging key biological macromolecules in microorganisms, such as DNA, proteins, and cell membranes, offering the advantages of fast and efficient inactivation. However, due to the limited penetration depth of electron beams, it is mainly effective for the surface or thinner materials. On the other hand, indirect action works by generating free radicals through the interaction of the electron beams with water molecules in the food matrix or microorganisms, which indirectly damages the key molecular structures of microorganisms. Therefore, when it comes to achieving deeper inactivation and disrupting the internal structures of

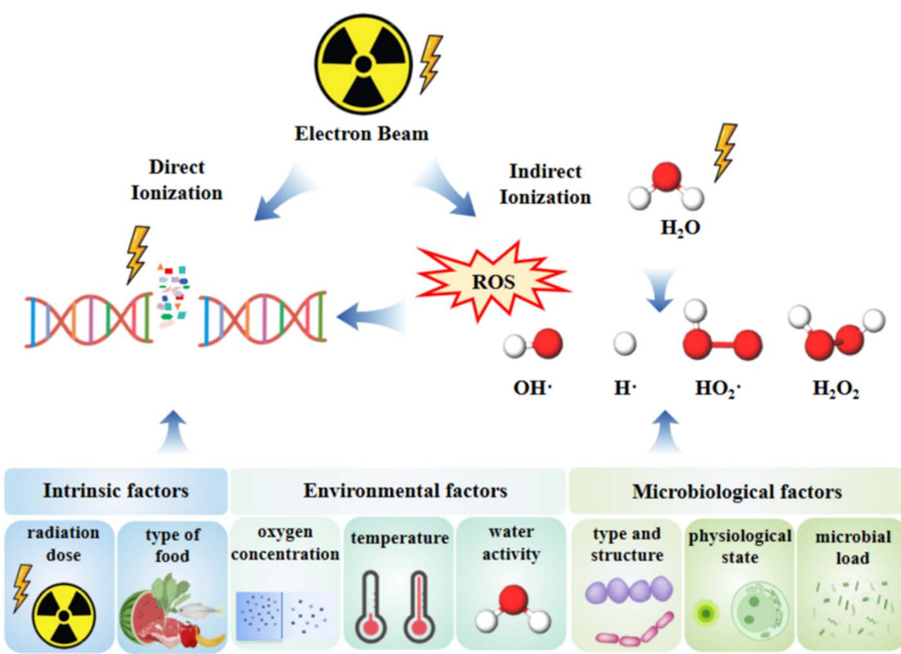

Fig. 2 The mechanism of EBI inactivation technology.

microorganisms, indirect ionization appears to be more effective than direct ionization.

3.1 Direct ionization

Direct action works by using high-energy electron beams to directly damage key molecular structures in microorganisms, such as DNA, proteins, and cell membranes, thereby inhibiting their growth or killing them. The energy transfer of high-energy electron beams generated by electron accelerators leads to inactivation of intracellular esterase and increased permeability of the cell membrane, resulting in the leakage of biomolecules such as nucleic acids and proteins from the cytoplasm.[37] However, Da Silva *et al.* found that low-energy pulsed electron beams do not disrupt bacterial morphology but trigger single- and double-strand DNA breaks and induce the formation of pyrimidine dimers, which restricts microbial DNA replication and ultimately results in microbial death.[38] Similarly, irradiation with a moderate dose (5 kGy) causes severe damage to the viral genome in the PBS, rendering it incapable of effective amplification.[39] Researchers found that repeated exposure to sublethal doses of EBI on beef increases the resistance of *E. coli* O157:H7 to electron beams.[40] Similarly, Tesfai *et al.* discovered that repeated EBI can induce a sublethal state in *S. typhimurium*, which adapts to the damage through mechanisms such as DNA repair, resulting in a significant increase in its radiation resistance in non-selective media.[41] In addition, research had shown that *E. coli* exposed to lethal doses retain relatively intact cell membranes and metabolic activity that phages are able to utilize for propagation, although their DNA cannot replicate.[42] Besides DNA, the structure of proteins is also damaged by EBI through direct ionization, leading to denaturation and inactivation. Luo *et al.* observed through SDS-PAGE electrophoresis that EBI can cleave high molecular weight proteins in bacteria into smaller fragments.[43] During this process, the primary structure of the proteins remained intact, while only their three-dimensional spatial structure was disrupted, which was consistent with the findings of Shi *et al.*[44] Due to the limited penetration depth of electron beams, which is usually reaching only a few millimeters to a few centimeters, direct action is less effective in eliminating microorganisms in thicker or denser objects. In addition, irregularly shaped objects may experience uneven irradiation, resulting in incomplete inactivation in certain areas. These factors limit the effectiveness of direct action in deep inactivation and applications involving complex structures.

3.2 Indirect ionization

Indirect action occurs when electron beams generate free radicals by interacting with water molecules in the food medium or microorganisms. These free radicals then damage the key molecular structures of the microorganisms, leading to inactivation. Electron beams can ionize water molecules in food or microorganisms, producing unstable reactive oxygen species (ROS), such as hydroxyl radicals ($OH\cdot$), hydrogen radicals ($H\cdot$), superoxide radicals ($HO_2^{\bullet}$) or hydrogen peroxide (H_2O_2).[8,12,45] ROS can induce bacterial death through multiple oxidative damage pathways.[46–48] ROS attack DNA bases, particularly guanine, leading to the formation of 8-hydroxy-2′-deoxyguanosine and may further cause tandem lesions, clustered sites, and DNA-protein cross-links (DPC), which severely interfere with critical bacterial physiological processes.[48–50] In terms of proteins, ROS preferentially attack amino acids containing sulfhydryl and amino groups, and impair protease function and disrupt bacterial metabolism by inducing abnormal disulfide crosslinking and carbonylation modifications.[51] Furthermore, the lipid peroxidation chain reaction induced by ROS generates lipid radicals ($H\cdot$) and lipid peroxides (LOOH), which ultimately degrade into malondialdehyde and other cytotoxic substances, significantly increasing membrane permeability.[43] Research demonstrates that ROS can inactivate spores in a water suspension by damaging their coat and inner membrane even at irradiation doses insufficient to cause significant DNA degradation.[52] In contrast, under very low-moisture conditions, the limited production and restricted diffusion of ROS markedly increase spore resistance to EBI. Although the antioxidant enzymes are able to reduce the accumulation of ROS, it had been found that the activity of antioxidant enzymes (*e.g.*, SOD and CAT) and 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging decrease in a dose-dependent manner during irradiation.[37] Their inactivation will lead to impaired microbial cell functions and accelerated cell inactivation.

Both inactivation mechanisms are useful in killing microorganisms and achieving excellent disinfection results. However, direct action requires uniform irradiation of the surface, while the free radicals generated by indirect action can diffuse through the medium and compensate for uneven surface coverage. Indirect action is more effective in high-moisture environments but less efficient under dry conditions. Combining both mechanisms enhances the overall inactivation effect, making EBI applicable to a broader range of scenarios.

4. Factors influencing the inactivation effect of electron beam irradiation

EBI disrupts the DNA, cell membranes and proteins of microorganisms, ultimately leading to the loss of their reproductive and survival capabilities. Its inactivation effectiveness is affected by various factors such as irradiation dose, food types, environmental conditions and the characteristics of the microorganisms themselves (Fig. 2, the bottom portion). The higher the EBI dose, the more evident the inactivation effect. At a dose of 5 kGy, the titer of HAdV-5 virus is reduced by 2-log levels; whereas at a dose of 13 kGy, the virus titer decreases by 4-log levels, effectively achieving inactivation.[39] Similar results were also obtained in previous studies.[53,54] Temperature, water activity (a_w), and oxygen concentration are critical environmental factors influencing EBI inactivation efficacy. Black *et al.* explored the role of temperature (such as −20 °C, 4 °C, and 22 °C) on the inactivation of *E. coli* O157:H7 by EBI in different types of meat, including beef, chicken, and trout.[55] Their study observed that *E. coli* O157:H7 exhibited significantly increased resistance at a temperature of −20 °C, which may be attributed to the frozen state of water limiting the generation and diffusion of free radicals, necessitating higher irradiation doses to attain the same level of microbial inactivation. Furthermore, the resistance of *E. coli* O157:H7 to EBI varied significantly among different food matrices, with chicken exhibiting the highest resistance to irradiation, while trout was more effective in inactivating the microorganism. This difference may be influenced by the varying physicochemical properties of the foods. Subsequent studies further demonstrated that a reduction in a_w significantly enhanced the resistance of *Escherichia coli* O157:H7 to EBI.[56] Even a slight decrease in a_w from 1.00 to 0.99 resulted in a marked increase in the D_{10} value. Additionally, the decrease in a_w may contribute to the "tails" effect, whereby certain microorganisms can survive even at higher irradiation doses. This phenomenon can be attributed to two aspects: first, when a_w decreases, the generation and diffusion of free radicals are limited.[56] Second, as a_w declines, the relatively increased proportion of solid components (such as proteins and fats) may absorb part of the irradiation energy, ultimately weakening the decontamination effectiveness of the indirect inactivation mechanism.[43,52] However, the secondary interference effect is highly dependent on their content and structural forms within the food. The existence of oxygen markedly boosts the microbial sensitivity to EBI. At the same irradiation dose, the log reduction of *Salmonella* in air-packaged almond samples was significantly greater than that in vacuum-packaged samples.[57] This may be because oxygen promotes the formation of free radicals, making DNA damage irreparable and further exacerbating the impairment of both DNA and bacterial structures.[58] The study also demonstrates that the inactivation efficacy of EBI is significantly influenced by pH levels, though with notable strain specificity. Generally, irradiation inactivation efficiency is higher under low pH conditions, but the sensitivity of different microorganisms to pH changes varies. Some show significantly reduced resistance at lower pH, while others remain largely unaffected by pH changes.[59,60] The type and structure of the microorganisms, and their physiological state and microbial load can also have a critical impact on the effectiveness of inactivation. In comparison, Gram-positive bacteria generally exhibit greater radiation resistance than Gram-negative bacteria. For instance, in cookie dough, the D_{10} values of EBI for *L. monocytogenes*, *S. typhimurium*, and *E. coli* O157:H7 were 0.63 kGy, 0.49 kGy, and 0.50 kGy, respectively.[61] *E. coli* O157:H7 and *S. typhimurium* exhibited higher sensitivity to EBI compared to *L. monocytogenes*. Different microorganisms exhibit varying sensitivities to EBI, and these differences arise from their biological characteristics, genetic repair mechanisms and other factors.[62] Therefore, when performing EBI decontamination, it is crucial to consider the characteristics of different microbial types and select the appropriate irradiation dose to ensure optimal inactivation efficacy. Van Gerwen *et al.* analyzed 539D_{10} values and found that the D_{10} values of spores were generally higher than those for nutrient cells, with mean values of 2.11 kGy and 0.42 kGy, respectively.[63] This indicates that the energy required to eliminate microorganisms is closely related to their physiological state, and that microorganisms in dormant or sporulating stages usually exhibit greater radiation resistance than actively growing nutrient cells. In addition, the higher the microbial load, the greater the dose of radiation needed to achieve the same inactivation effect. Espinosa *et al.* found that when lettuce was contaminated with more than 1000 PFU g^{-1} of poliovirus, a 4 kGy radiation dose did not significantly reduce the infection risk.[53] However, when the contamination level was below 10 PFU g^{-1}, a 3 kGy dose was sufficient to significantly lower the risk. The focus of future research should be on the mechanisms underlying these differences to provide important guidance for the practical application of EBI.

5. Application of electron beam irradiation in different fields

As illustrated in Fig. 3, EBI technology has achieved significant accomplishments in various fields, including food processing, agriculture, and medical sterilization.[64] In the food processing field, EBI effectively inactivates microorganisms in food, extends shelf life, and preserves the nutritional and sensory qualities of food, reducing reliance on chemical preservatives and significantly enhancing food safety (Table 1).[65] In agriculture, EBI is widely applied in seed treatment and crop mutation breeding, enhancing seed germination and vigor while controlling pathogens.[66] In the medical sector, EBI technology is primarily used for the sterilization of medical equipment, pharmaceuticals and other products to ensure their safety. However, EBI may also have certain drawbacks, such as the potential loss of some nutrients (Table 2). Additionally, the effects of EBI are dose-dependent, where excessive doses can damage product quality, while insufficient doses may not achieve effective inactivation. Therefore, when determining the appropriate radiation dose, it is vital to strike a balance between the minimum dose required to effectively eliminate pathogens

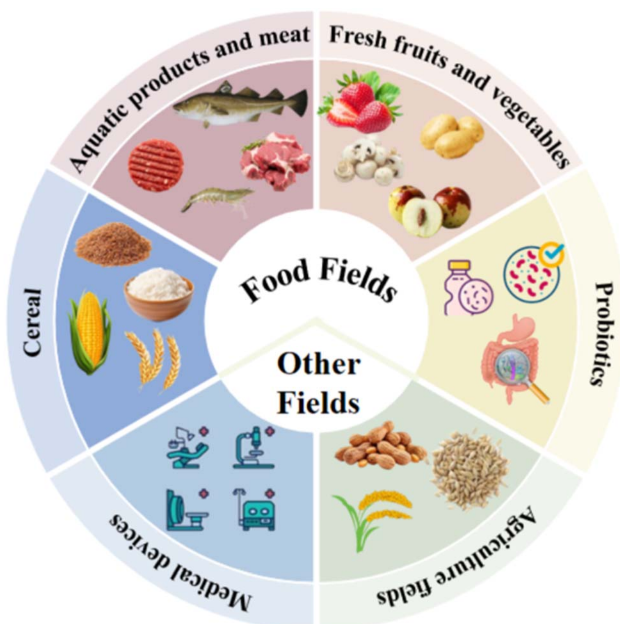

Fig. 3 The application of EBI technology in various fields.

Table 1 Investigation of the utilization of EBI in food decontamination

Product	Dose	Influence
Strawberries[79]	1–3 kGy	Reduced mold and yeast levels to undetectable Decreased mesophilic bacteria number by 2 log CFU g^{-1}
Raw ground beef patties[54]	2, 4 & 6 kGy	Dose-dependent reduction in microbial load with irradiation A 2 kGy dose can achieve an acceptable level of microbial reduction Optimal efficiency in batch processing of approximately 3.2×10^4 units No obvious sensorial quality variation from the non-irradiated samples
Raspberries[109]	2 & 3 kGy	Decreased the count of mesophilic bacteria by 2 log CFU g^{-1} and the filamentous fungi reduced by 3 log CFU g^{-1} at 3 kGy Inhibited bacterial and fungal growth in refrigerated raspberries at 3 kGy *Listeria monocytogenes* was the most radiosensitive and the D_{10} value is 0.41 kGy
Cherry tomatoes[80]	1.4 & 3.6 kGy	On exposure to 3.6 kGy, the level of mesophilic microbiota reduced by 4 log CFU g^{-1} and the filamentous fungi and coliforms were both detected
Ready-to-bake cookie dough[61]	1, 2&3 kGy	Reduction of *Escherichia coli* O157:H7 by 2.98, 5.07, and 6.13 log CFU g^{-1}; *Salmonella typhimurium* by 3.07, 4.98, and 6.35 log CFU g^{-1}; reduction in *Listeria monocytogenes* concentrations by 2.14, 3.77, and 4.84 log CFU g^{-1}
Black peppercorns[110]	0–14 kGy	High-energy EBI (10 MeV) requires 4.2 kGy to achieve a 5-log reduction of *Salmonella rissen* (equivalent to a 0.6-log reduction of *Enterococcus faecium*) Low-energy EBI (<300 keV) requires a higher dose of 8.13 kGy to attain the same microbial inactivation level Additional dose compensation is necessary in industrial applications
Ligusticum chuanxiong hort[111]	3, 5 & 7 kGy	TAC limit for *Ligusticum chuanxiong* should not exceed 3 log CFU g^{-1} Irradiation at 5 kGy induced a 2-log reduction in TAC, going below the detection level at 7 kGy Neither TYMC nor HRS was detected after 3–7 kGy irradiation

and the maximum dose to avoid undesirable changes to the product.[67]

5.1 Aquatic products and meat

In the fishing, slaughtering, transportation, processing and storage stages, aquatic products and meat are frequently exposed to bacterial and parasitic contamination, which makes them are prone to spoilage and poses a serious threat to human health.[68] In addition, the COVID-19 pandemic has disrupted the food cold chain supply and there was a potential threat of SARS-CoV-2 virus transmission even under freezing conditions, which further complicates and exacerbates the safety issues surrounding aquatic products and meat.[69,70] While traditional heat treatment is effective in killing pathogens, it has limitations when applied to frozen and fresh aquatic products and meat because it is difficult to meet safety standards while preserving the freshness of the products.[71] EBI, as an effective alternative approach, can effectively inactivate pathogens in aquatic products and meat without altering the texture.[72] Tolentino *et al.* studied the effects of EBI on the microbial quality and sensory characteristics of raw Philippine beef patties.[54] They found that a radiation dose of 2 kGy significantly reduced the aerobic plate counts, molds and yeast count, as well as total coliform in the beef patties, and that these reductions remained stable over the 7-month shelf life. Moreover, the irradiation had no notable effect on the color, flavor and overall acceptability of the beef patties. Annamalai *et al.* observed that EBI significantly decreased microbial counts and effectively extended the shelf life of vacuum-packed headless *Litopenaeus vannamei*.[73] Moreover, irradiation doses below 7.5 kGy had no noticeable influence on the sensory properties of the shrimp. On the other hand, the impact of EBI on aquatic products and meat quality had also attracted widespread attention. Zhao *et al.* analyzed the effects of EBI at different doses (0, 2, 4, 7, and 10 kGy) on shrimp quality.[74] The study demonstrated that irradiation significantly increased lipid oxidation in shrimp, while having little impact on protein oxidation and sensory quality. Yu *et al.* obtained similar experimental results using Atlantic cod.[75] It has also been observed that irradiation at doses of 5 kGy and 7 kGy accelerated protein oxidation in frozen weever fillets, while doses of 1 kGy and 3 kGy were more favorable for maintaining the quality and sensory properties.[67] Wahyono *et al.*, through a meta-analysis of 22 studies exploring the impact of EBI on pork, found that EBI effectively reduced the count of microorganisms and extended the storage period of pork.[76] However, the irradiation was also found to accelerate the oxidative degradation of lipids in the meat and decrease its overall acceptability. Therefore, it is essential to choose the appropriate irradiation dose based on the characteristics of different aquatic products and meat to ensure a balance between inactivation effectiveness and quality.

5.2 Fresh fruits and vegetables

Fresh fruits and vegetables may rot or mold if not handled properly after harvesting, and prolonged storage may also lead to the loss of some nutrients. EBI plays a positive role in inhibiting the physiological metabolism of fruits and vegetables while also maximizing the maintenance of storage quality during processing.[77] Hou *et al.* discovered that irradiation of winter jujube with 0.5 kGy electron beams extended the storage

Table 2 Impact of EBI on physicochemical and nutritional properties of different foods[a]

Product	Dose	Influence
Winter jujube[78]	0.5 kGy	Slowed down decay rate Maintained hardness and high levels of TP and TF Increased activities of antioxidant enzymes
Strawberries[125]	1–3 kGy	The TP content showed no significant variation and notably decreased after 15 days FRAP values decreased significantly at 1 and 3 kGy Induced decomposition of L-ascorbic acid content Increased antioxidant activity at 2 and 3 kGy without storage Dosage of 2 kGy is considered the most efficient
Actinidia arguta[126]	0.3, 0.4 & 0.5 kGy	0.4 kGy is the most effective in inhibiting weight loss, fruit senescence, TSS content increase and increasing PAL and POD activity Reduced respiration rate, ethylene production and content of vitamin C and MDA Maintained moisture and TA content Adverse restriction of PPO activity during the storage period
Mangoes[127]	0.5 kGy	Reduced the rate of respiration and TSS during storage Sustained fruit firmness No difference in vitamin C content from that of the control
Kiwifruit[128]	0.3, 0.4 & 0.5 kGy	Slowed down the decline in fruit firmness and the enhancement in TSS content Reduced the levels of WSP, H_2O_2, and MDA, and also decreased the production rates of ethylene and $O_2^{\bullet -}$ Enhanced the activity of antioxidant enzymes and LOX A dose of 0.5 kGy demonstrated the most significant effects
Goji-berry[129]	2.5, 5.0, 7.5&10.0 kGy	No change observed in the DPPH Improved the total antioxidant activity measured by the ORAC assay, especially 2.5 kGy Increased the TF and TP content
Dried wild mushrooms[130]	2, 6 & 10 kGy	Significantly reduced protein content and SFA Increased the levels of soluble sugars, fructose and tocopherol A dose of 6 kGy appears to be the optimal irradiation dose, achieving sterilization while maintaining nutritional components and antioxidant activity
Weever fillets[67]	1, 3, 5 &7 kGy	Maintained textural properties during storage at 1 and 3 kGy Enhanced carbonyl content oxidation rate of MPs (reduced sulfhydryl content and Ca^{2+}-ATPase activity) at 5 and 7 kGy
Beef steaks[131]	4, 8, 12 & 16 kGy	Improved color and did not increase lipid or protein oxidation at 4 and 8 kGy Reduced lightness and increased protein oxidation at 12 and 16 kGy
Shrimp[74]	2, 4, 7 & 10 kGy	The moisture, ash, and protein content remained stable, but the protein conformation and function were altered Significantly reduced the TVB-N level to 1.37 mg/100 g and decreased springiness, hardness, and chewiness at 10 kGy. The differences between the 2, 4, and 7 kGy irradiated samples and the control group will be magnified over time MUFA and PUFA levels showed reductions of 31.4% and 25.7%, respectively at 10 kGy. The extent of fat oxidation and ΔE values increases in a dose-dependent manner The vitamin E content decreased with increasing irradiation dose
Silver carp chunks[132]	4 & 8 kGy	Increased the level of lipid oxidation, significantly reduced the pH value and accelerated the decay at 8 kGy Increased the myofibrillar protein content, suppressed the degradation of actomyosin and has a minimal impact on lipid oxidation and pH levels at 4 kGy

[a] TP: total phenolic; TF: total flavonoid; FRAP: ferric reducing antioxidant power; TSS: total soluble solid; PAL: phenylalanine ammonia-lyase; POD: peroxidase; MDA: malondialdehyde; TA: titratable acid; PPO: polyphenol oxidase; WSP: water-soluble pectin; H_2O_2: hydrogen peroxide; O_2^-: superoxide anions; LOX: lipoxygenase; DPPH: 1,1-diphenyl-2-picryl-hydrazyl radical; ORAC: oxygen radical absorbance capacity; SFA: saturated fatty acid; MPs: myofibrillar proteins; TVB-N: total volatile basic nitrogen; MUFA: monounsaturated fatty acid; PUFA: polyunsaturated fatty acid.

period and improved the antioxidant capacity.[78] In another study, EBI treatment effectively extended the storage period of strawberries while ensuring the storage quality. Compared to non-irradiated strawberries, the 1 kGy EBI treatment reduced the total aerobic bacteria and yeast/mold counts of strawberries stored for 9 days from 4.7 and 5.4 log CFU g^{-1} to 3.8 and 4.0 log CFU g^{-1}, respectively. The decay rate was decreased from 85% to 38% and weight loss was reduced by 7%. Meanwhile, EBI had no noticeable influence on the total soluble solid (TSS) content, pH and titratable acidity (TA) of the strawberries.[32] Barkaoui *et al.* conducted a study that delved into the effects of medium doses (1, 2, and 3 kGy) of EBI on strawberries.[79] All doses significantly reduced microbial load, and while 1 kGy irradiation had minimal impact on sensory quality, it was less effective for long-term preservation. The 3 kGy dose, although highly effective in controlling microbes, may lead to degradation in the firmness and color of strawberries and accelerate their metabolism and ripening. In contrast, the 2 kGy doses demonstrated a better balance in controlling microbial load while maintaining the physicochemical and sensory qualities of strawberries. In addition, the study conducted by Madureira *et al.* demonstrated that EBI effectively eliminated the native microbiota and inoculated foodborne pathogens in cherry tomatoes while preserving the content of lycopene and antioxidant compounds.[80] However, it was observed that antioxidant activity reduced over time. Cardoso *et al.* found that EBI can effectively extend the storage period of button mushrooms and maintain the stability of the proteins and carbohydrates.[81] However, it is worth noting that this process may also result in vitamin degradation and fat oxidation. Apart from its application in extending shelf life, EBI had also demonstrated the capability to inhibit plant sprouting. Blessington *et al.* demonstrated that EBI at a dose of 200 Gy can effectively inhibit potato sprouting without negatively affecting the beneficial compounds within the potatoes.[82] EBI is also a promising technology for the degradation of pesticide residues. The study by Rodrigues *et al.* demonstrated that EBI can effectively degrade profenofos in aqueous solutions and peas, with degradation efficiency increased in a dose-dependent manner.[83] In peas, the highest dose (30 nnnnnnnnnnnnnn.4 kGy) removed approximately 47.9% of profenofos, while in the aqueous solution, the removal rate reached as high as 99.8%, which may be attributed to the complex composition of the vegetables. EBI shows great potential in extending the storage period of fruits and vegetables, inhibiting plant sprouting and degrading pesticide residues. Future research should focus on further optimizing EBI treatment parameters and exploring its underlying mechanisms to enhance treatment efficacy while minimizing nutrient loss, ensuring its safety and effectiveness in complex matrices.

5.3 Cereal

Grain processing is mainly faced with challenges such as biological contamination, pest infestation and mold growth. Traditional treatment methods rely on chemical agents or sealed storage, which can cause chemical residues or be energy-intensive.[84] EBI can inhibit microorganisms, eliminate pests and control mold growth through non-thermal sterilization techniques, while reducing or avoiding chemical residues.[85] Luo *et al.*'s research indicated that EBI had positive effects on the storage quality of brown and milled rice, effectively inhibiting lipase activity and preventing the increase in free fatty acid levels, while reducing microbial counts and slowing down quality deterioration.[86] They also found that doses of 1 kGy and 3 kGy had minimal impact on the color of both types of rice, whereas a 5 kGy dose significantly reduced the color quality of milled rice but had little effect on brown rice. Besides, irradiation slightly reduced the starch viscosity but had little impact on the crystal structure, resulting in some sensory changes in cooked rice, though the overall quality remained stable. The growth of mold in grains can produce harmful mycotoxins, such as aflatoxins, zearalenone (ZEN) and ochratoxin A (OTA), which pose risks to public health and lead to significant food loss and waste. EBI can efficiently suppress the growth and toxin production of *Aspergillus flavus* by damaging its morphology and cell wall structure to achieve the inactivation effect, with a D_{10} value of 0.9185 kGy. Luo *et al.* found that EBI can efficiently decompose ZEN and OTA in corn, with degradation efficiency positively correlated with the irradiation dose.[87] The degradation rates of ZEN and OTA under a dose of 50 kGy reached 71.1% and 67.9%, respectively. However, high-dose irradiation leads to a significant decrease in the redness and the yellowness values, causing the color to darken. Furthermore, EBI promoted fat oxidation in corn, increasing free fatty acid levels. Kottapalli *et al.* observed that EBI notably diminished the infection rate of *Fusarium* and the deoxynivalenol (DON) content in malt, with DON reductions ranging from 54% to 100% at doses between 4 and 10 kGy.[88] The irradiation had minimal influence on the quality of the malt, ensuring its value in beer brewing applications. These studies provide a theoretical and practical foundation for the utilization of EBI in the degradation of mycotoxins in cereal. In summary, EBI has demonstrated significant effectiveness in degrading harmful microorganisms and mycotoxins in cereals, and is poised to become a key technology for enhancing safety and storage stability of cereal, with considerable potential for broader application in a wide range of cereal crops.

5.4 Other fields

In the dairy industry, while traditional decontamination methods are effective at controlling pathogens, they often negatively impact the viability and beneficial properties of probiotics. Balayan *et al.* found that although EBI at doses of 50–150 Gy reduced the viability of *Lactobacillus rhamnosus* Vahe, and it did not affect its inhibitory effect on anti-*Klebsiella pneumoniae* (a foodborne pathogen).[89] Pepoyan *et al.* further demonstrated that low-dose EBI (50–100 Gy) significantly enhanced the biofilm formation ability of probiotics without affecting their cell surface hydrophobicity or antimicrobial activity.[90] The enhanced biofilm formation contributed to prolonged antimicrobial effects, which effectively eliminated pathogens in probiotic products while preserving the viability and functionality of the probiotics. EBI was also utilized in areas beyond the food industry. In the field of agriculture, EBI had gained increasingly widespread application as an efficient physical mutagenesis tool for crop breeding. Studies had shown that, compared to γ ray irradiation, EBI exhibited a higher mutation frequency and mutagenic efficiency, and helped in successfully cultivating high-yielding strains, opening new avenues for rice breeding.[91] In a study on peanut breeding, Mondal *et al.* found significant differences in sensitivity to EBI among different peanut genotypes, which may be attributed to variations in DNA repair mechanisms or cellular signaling pathways between the genotypes.[92] Besides its application in breeding, researchers have found that a 3 kGy dose of EBI not only increased the germination rate and growth force of barley seeds by 6% and 10%, respectively, but also successfully inhibited the spread of *Penicillium* spp. and *Fusarium* spp.[93] Although the 3 kGy dose had the positive effects on barley seeds, higher doses of EBI (such as 8 kGy and above) may cause root deformation and shortening in lentil seeds, reducing their ability to germinate.[29] The E-VITA technology is a successful application of EBI for seed treatment. It effectively eliminates seed-borne pathogens, enhances field emergence and reduces dependence on chemical treatments. This technology has been widely implemented in Germany, with each plant treating 25 metric tons of cereal seeds hourly, demonstrating its potential for agriculture.[66] EBI is used for sterilizing medical devices, effectively eliminating high radiation-resistant microorganisms such as *Bacillus pumilus* and *Deinococcus radiodurans*, while avoiding damage to sensitive materials or electronic components caused by high temperature.[94,95] Additionally, study has shown that compared to traditional formaldehyde inactivation of pathogens, low-energy electron beam treatment better preserved the antigen structure, thereby inducing a stronger and more efficient immune response.[21] In terms of material modification, the surface properties and composition of silver nanowires (AgNWs) can be modified through EBI, leading to an enhancement in the antibacterial activity of AgNW films.[35] EBI enhanced wear resistance, antibacterial properties and water repellency characteristics by inducing crosslinking, graft polymerization and curing reactions in textile materials.[23] This approach has higher efficiency and greater environmental benefits than conventional methods. In addition, EBI can induce severe damage to the cell morphology and active substances of *Microcystis aeruginosa*.[96] Its application in wastewater treatment can effectively reduce algal proliferation, thereby alleviating the ecological harm posed by algal blooms. Overall, EBI holds great potential for development, but further research is needed in practical applications to maximize its effectiveness and minimize potential adverse effects.

6. Strategies for promoting the large-scale commercial application of electron beam irradiation technology

6.1 Synergistic effects of modified atmosphere packaging in electron beam irradiation decontamination

The safety of packaging materials has received great attention in food irradiation processing. Existing research has shown that exposure to ionizing radiation can induce two major transformations in packaging materials: cross-linking and chain scission. Among this, chain scission degradation generates low-molecular-weight compounds, which may migrate into food and pose potential health risks. To mitigate the adverse effects of high-dose irradiation on packaging materials, the introduction of MAP technology offers a promising strategy.[97] MAP refers to a food preservation technique that adjusts the gas composition inside the package (such as nitrogen, oxygen and carbon dioxide) to inhibit microbial growth and lipid oxidation, thereby extending the storage period of food products.[98–100] However, the adoption of MAP alone to inhibit microbial growth has certain limitations. For example, in low-oxygen environments, while the growth of aerobic microorganisms is inhibited, certain anaerobic microorganisms and pathogens (such as anaerobes and *Clostridium botulinum*) can still grow or multiply slowly, posing a potential threat to food safety. McSharry *et al.* inoculated beef steaks with *Clostridioides difficile* spores and stored them in air, in low, medium and high barrier vacuum packaging, and under anaerobic conditions at 2 °C and 20 °C.[101] The results showed that at 20 °C, *C. difficile* concentrations significantly increased under medium and high oxygen barrier packaging and anaerobic conditions. It should be noted that low-oxygen environments may also create favorable conditions for certain anaerobic pathogens to thrive, further increasing food safety risks. Although MAP technology can effectively reduce the overall microbial load, especially the growth of aerobic bacteria, in practical applications, relying on MAP technology alone is not enough to ensure food safety.

Therefore, it is still essential to integrate MAP with other techniques to ensure efficient microbial inactivation. Increasing research indicated that low-dose EBI combined with MAP can achieve effective inactivation. Through the synergistic effect of this combination of technologies, the required irradiation dose can be reduced, lowering costs, while also achieving comprehensive inactivation of multiple microorganisms, overcoming the limitations of a single method. This combined approach effectively enhanced the overall quality and safety of food, further increasing its potential applications in food processing. A study by Smith *et al.* demonstrated that flushing the packaging bags with a mixed gas (5% oxygen, 10% CO_2, and 85% nitrogen) in conjunction with a low-dose electron beam treatment (approximately 1 kGy) significantly reduced the bacterial and fungal counts in freshly sliced watermelon compared to using low-dose irradiation alone.[102] Subsequently, the results confirmed that this combined method can also effectively maintain the quality of grapes, strawberries, and tomatoes.[103] According to the study by Ic *et al.*, appropriate doses of EBI can efficiently decrease the microbial load on the surface of nuts and dried fruits, thereby effectively enhancing food safety.[104] However, high doses of irradiation may adversely affect the sensory and chemical characteristics of nuts. The research by Sanchez-Bel *et al.* showed that the nutrient composition of almonds, such as lipids, proteins, and fiber, remained largely unchanged when the irradiation dose is below 7 kGy.[105] However, almonds exhibited noticeable rancidity and off-flavors at a dose of 10 kGy. This degradation not only affects the taste and flavor of the nuts but may also shorten their shelf life, reducing their market appeal. To address the negative effects caused by high-dose electron beams, combining EBI with MAP technology presents a feasible solution to reduce the irradiation dose. Karagoez *et al.*'s study revealed that, compared to vacuum-packed, both nitrogen-packed and 100% oxygen-packed reduced the D_{10} values for *S. typhimurium* LT2 and *E. coli* cocktail in pecan nuts.[106] Although the D_{10} values under the nitrogen-packed (0.38 kGy and 0.40 kGy) were slightly higher than those under the 100% oxygen-packed (0.34 kGy and 0.36 kGy), the nitrogen-packed ws effective in delaying the oxidation of lipids and reducing the risk of quality degradation in pecan nuts. In the same way, the experimental results of Mohammad *et al.* showed that combining EBI with air packaging can effectively reduce the D_{10} value of *Salmonella* on almonds.[57] This may be due to the existence of oxygen, which promotes the formation of ozone and free radicals, thereby enhancing the antimicrobial effect of the irradiation. Kudra *et al.* inoculated *L. monocytogenes* onto frankfurters and pork chops to study the integrated effects of EBI and MAP.[107] The results showed that the *Listeria* counts on non-irradiated, vacuum-packaged frankfurters significantly increased after 7 weeks of refrigeration, while the vacuum-packaged samples treated with EBI showed delayed bacterial growth. For cooked pork chops, the *Listeria* counts in non-irradiated, vacuum-packaged samples significantly increased after 4 weeks. However, under high-CO_2 MAP, no significant growth of *Listeria* was observed on either frankfurters or cooked pork chops after a 12-week refrigerated storage. Notably, this combined treatment can also effectively slow down changes in the color and texture of meat products, maintaining better visual quality throughout the shelf life.[108] However, the current research on processing parameters and mechanisms involved in the combined use of EBI and MAP to inhibit spoilage microorganisms is limited. Thus, future research should focus on refining these processing parameters and delving deeper into the mechanisms of microbial inhibition and inactivation, helping the industry to more effectively implement this technology.

6.2 Artificial intelligence-guided optimization of electron beam irradiation decontamination

EBI is an effective food decontamination technology, and the setting of irradiation dose and other parameters are crucial for food quality and safety. As mentioned previously, excessive irradiation may lead to degradation of food texture and development of off-flavors, negatively impacting taste and consumer acceptance. Conversely, insufficient doses may fail to effectively eliminate bacteria and viruses, increasing food safety risks. Therefore, optimizing EBI decontamination technology according to the specific physicochemical properties of food products is essential for ensuring food quality and safety and minimizing negative effects. Apart from that, this optimization process can decrease expenses and enhance the economic benefits of the business. However, the effectiveness of electron beam decontamination is impacted by multiple factors and extensive experimental studies are required to determine the optimal parameters. Consequently, optimizing the irradiation dose is a complex process. To address this challenge, the application of AI offers new opportunities for optimizing EBI. AI is currently applied in the food processing sector mainly in various areas such as automated production, quality control and new product development, reducing human errors and significantly enhancing efficiency.[112] Data mining and analysis, machine learning model development, optimization algorithms and real-time monitoring systems constitute the main drivers of AI applications in food decontamination and preservation.[113] These technologies have been utilized in preserving the freshness of fruits and vegetables to predict spoilage, monitor quality, estimate shelf life, and optimize storage and supply chain processes.[114] Current research has demonstrated that AI can be efficiently applied in non-thermal processing fields, such as PEF and cold atmospheric plasma, to predict inactivation effects and optimize process parameters. Machine learning and artificial neural network techniques can effectively predict the efficacy of pulsed electric fields in inhibiting *Aspergillus parasiticus* infestations and degrading aflatoxins in red pepper flakes while also optimizing the processing parameters for their treatment.[115] Cui *et al.* demonstrated that combining Fourier transform infrared spectroscopy (FTIR) with a machine learning algorithm (gradient boosting decision tree) can predict the microbial inactivation effects of cold atmospheric plasma exposure doses with an accuracy of up to 89%.[116] Similarly, Ozdemir *et al.* collected 33 different parameters related to plasma-activated liquid-microorganism interactions and found that the machine-learning model could accurately assess the antibacterial potential of cold atmospheric plasma-activated liquids.[117] In the future, AI could deeply mine and analyze historical data in EBI technology, integrating machine learning modeling to predict the optimal irradiation dose under various conditions. Additionally, the combination of Internet of Things (IoT) real-time monitoring techniques will ensure timely adjustments to irradiation parameters to adapt to changing production conditions. This intelligent adjustment will not only optimize the inactivation effect but also effectively ensure food quality, thereby driving food EBI decontamination in a more intelligent and efficient direction. The potential of AI in the food field is immense, and it will drive comprehensive innovations in production, processing and supply chain management.[118] The incorporation of AI in EBI technology has the potential to provide substantial economic benefits; however, its development is still hindered by several limitations. The diversity of food types and the multiple influencing factors in EBI increase the complexity of data collection and model development for AI systems.[101] The risks of data leakage and misuse, coupled with a lack of understanding of data and conflicts of interest, complicate effective data sharing and ultimately hinder the comprehensive utilization of data and the full realization of its potential value.[119]

6.3 Synergistic effects of natural antibacterial compounds and aseptic packaging in electron beam irradiation decontamination

With the escalating issue of antibiotic resistance in pathogenic microorganisms, there is a growing focus on the exploration and development of NAC. These compounds have a wide range of sources, including animals, plants, microorganisms, and algae.[120] Due to the broad-spectrum antimicrobial activity, antioxidant properties and high safety of NAC, they have been successfully applied in various fields, such as food preservation, agriculture, and medicine. These compounds exert their antimicrobial effects through various mechanisms, including disruption of microbial cell membranes, inhibition of protein and nucleic acid synthesis, interference with metabolic pathways, and induction of oxidative stress and programmed cell death.[121] It has been demonstrated in earlier studies that the joint use of antimicrobial coatings and ionizing radiation can reduce microbial load of pre-cooked shrimp under the same irradiation conditions.[122] With ongoing research, it has been found that NAC can enhance the microbial inactivation effect of EBI through a synergistic mechanism. This synergy not only improves the overall efficacy of inactivation but also allows for a reduction in the required irradiation dose, consequently mitigating the negative impact on product quality. For example, Kim *et al.* explored the combined use of EBI with leek extract.[123] Their results demonstrated that, after irradiation with the same dose of the electron beam, the group with leek extract exhibited a significantly stronger inhibitory effect on total aerobic bacteria in pork jerky compared to the control group. The incorporation of leek extract effectively reduced the required dose of the electron beam; however, it may also lead to the formation of undesirable odors and an increase in peroxide values, which could negatively impact the sensory properties and product quality. To mask the undesirable odor of NAC and enhance their solubility in food, Gomes *et al.* encapsulated these compounds with β-cyclodextrin and applied them to fresh spinach leaves inoculated with *Salmonella* and *Listeria* spp.[124] The study demonstrated that the addition of these compounds significantly increased *Salmonella* sensitivity to EBI. For example, irradiation alone required a dose of 0.95 kGy to reduce *Salmonella* by 5 logs, while only 0.54 kGy was needed after the antimicrobial compounds were applied. Currently, research on the synergistic bactericidal effect of combining NAC with EBI remains in the early exploratory stages and has several limitations. Future investigations should focus on elucidating the interaction mechanisms, enhancing the solubility and stability of NAC, and addressing potential adverse sensory characteristics to facilitate the practical commercialization of this combined technology.

Aseptic packaging refers to a technology that involves the sterilization of packaging materials and containers, followed by packaging and sealing the product under sterile conditions to ensure that the contents are free from microbial pollution. Additionally, in comparison to the hot filling system, the aseptic packaging systems reduce the weight of beverage packaging bottles, yielding more substantial long-term economic and environmental benefits.[133] It is worth noting that numerous studies have confirmed that recyclable multilayer aseptic packaging materials (such as paper, polyethylene, and aluminum foil) are suitable for further processing and application, reducing the emission of pollutants.[134,135] The aseptic packaging technique is applied in a wide range of industries, including food, chemical, and pharmaceutical sectors. In the food industry, the purpose of aseptic packaging is to extend the storage period of products without the use of chemical preservatives, while maintaining its safety, original nutritional value and flavor. Hydrogen peroxide is a commonly used disinfectant to achieve aseptic packaging, often in combination with heat treatment. However, potential chemical residues from this process may pose a risk to food safety. EBI, as a decontamination technique, is capable of effectively sterilizing a variety of packaging materials such as polyethylene and polypropylene without significantly altering their physicochemical or functional characteristics. At the same time, aseptic packaging prevents external factors from interfering with the effectiveness of EBI inactivation, providing a stable and sterile environment for the process. Studies have demonstrated that ohmic heating technology combined with sterile packaging can produce high quality vegetable soups and chicken.[136,137] The integration of blanching treatment with near-aseptic packaging technology effectively extends the preservation period of potato fries while improving the color and texture after frying.[138] Future research should focus on the integration of aseptic packaging and EBI technology; and more importantly, the integration of NAC into aseptic packaging materials could provide continuous antimicrobial protection, enhancing microbial control during storage and preventing secondary contamination. The synergistic effect of these technologies and EBI will more be effective in extending the shelf life of food, preserving nutritional contents and ensuring its safety, potentially offering more sustainable packaging and decontamination solutions for the food processing industry.

7. Barriers and progress in the adoption of electron beam irradiation in food

While EBI has been employed in food preservation for over half a century, its further penetration across the food industry faces significant challenges, particularly in terms of economic costs, regulatory barriers, and consumer acceptance. Economically, the initial investment in irradiation infrastructure and the ongoing maintenance costs may discourage small- and medium-sized food industries.[139] The divergent regulatory policies between countries and regions have largely hindered the international trade and commercial adoption of food EBI technology.[140–142] Firstly, there are notable differences in the approved categories of irradiated foods. For instance, the United States has approved a wider range of irradiated food items, while the European Union countries have approved fewer types, mainly focusing on dried spices and seasonings.[143] Secondly, labeling requirements for irradiated foods differ between countries. In 1985, the FAO approved the General Standard for Labelling Prepackaged Foods, which has undergone several amendments to require irradiated foods to have treatment information near the name of product. The use of the international food irradiation label is voluntary; if used, it should be placed next to the food name to uphold the consumers' right to know.[144] In a few countries, like the United States, the Radura symbol is mandatory for irradiated foods, whereas the European Union and certain others require labeling with "irradiated" or "treated with ionizing radiation" but do not enforce the use of the Radura symbol.[145] Moreover, maximum permitted irradiation doses lack harmonization even for the same food category. Beyond financial and regulatory considerations, consumer acceptance plays a critical role. Consumer concerns about the safety and efficacy of EBI technology mainly stem from fear of radiation and a lack of sufficient understanding of the technology. Many confuse EBI with nuclear radiation, primarily due to misleading terminology.[146] Additionally, the instinctive wariness toward novel food technologies and the dissemination of misinformation similarly impede the adoption of EBI technology in the food industry.[147,148] In fact, the EBI of food is fundamentally different from radioactive foods; irradiated foods are subject to permits and strict supervision from relevant authorities and do not contain radioactive contaminants.[149] In 1980, the joint expert committee of the WHO, FAO and IAEA concluded, based on extensive scientific research and assessments, that an average irradiation dose less than 10 kGy is safe and does not cause specific nutritional or microbiological issues.[150,151] In 1983, the Codex Alimentarius Commission (CAC) adopted the General Standard for Irradiated Foods, which was revised in 2003 to detail the hygienic codes, food standards and transportation requirements for irradiated foods.[152] Additionally, the Manual of Good Practice in Food Irradiation and the Code of Practice for Radiation Processing of Food provide guidelines to prevent irradiated foods from being contaminated by pathogenic microorganisms.[153,154] With the continuous improvement of regulatory frameworks, a variety of technologies have been exploited to identify irradiated food products. Khan and Shahid demonstrated that electron spin resonance (ESR) spectroscopy can be used to distinguish irradiated samples of nuts, beans, and foods with low molecular weight sugar.[155] Irradiated samples exhibited complex ESR signals with a dose-dependent increase in signal intensity with increasing irradiation dose. Notably, these signals were still detectable even 10 months after irradiation. In contrast, non-irradiated samples either displayed a single ESR signal or showed no detectable signal at all. In addition, ESR spectroscopy, electronic sensing, and calibrated photostimulated luminescence (PSL) technologies were capable of detecting whether fruits such as grapefruit and lemons had been subjected to EBI.[156] Nevertheless, these techniques showed limited effectiveness in distinguishing fruits exposed to low-dose irradiation. Similarly, these methods were also applicable for identifying dried spice mixtures irradiated with electron beams.[157] Future efforts should focus on optimizing detection methods to enhance both the sensitivity and accuracy of these techniques. Although the existing regulatory framework for EBI mitigates potential side effects to consumers, harmonized international standards are urgently needed to establish to facilitate global trade and consumption. However, as technology advances and global cooperation strengthens, it is feasible to establish maximum permissible doses and to develop unified regulatory standards for EBI.

8. Conclusion

EBI decontamination technology, with its advantages of high efficiency, residue-free characteristics, and excellent preservation of food nutrients and texture, has become a feasible alternative to traditional thermal and chemical sterilization methods. However, despite these notable advantages, EBI technology still faces several challenges in practical application. First, the underlying mechanisms driving microbial inactivation have not been fully elucidated. Additionally, constraints related to penetration depth and optimal irradiation dose hinder its commercial viability. Adoption is further complicated by the fact that studies have suggested that repeated EBI may induce bacteria to enter a sublethal state, posing a potential threat to public health. To facilitate the advancement and broader application of electron beam decontamination, future research should prioritize elucidating the mechanisms of microbial response to electron beams, optimizing irradiation parameters, and exploring synergies with other technologies to enhance inactivation efficacy. With ongoing research and technological innovation, EBI decontamination technology is expected to have a growing impact on the food industry and beyond, providing strong support for food safety and public health.

Data availability

No primary research results, software or code have been included and no new data were generated or analyzed as part of this review.

Conflicts of interest

The authors declare that they have no conflict of interest.

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