# Research Progress on the Impact of Nuclear Radiation in Food on Human Health

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**Abstract.** This review provides a detailed overview of two types of nuclear radiation-related foods – radioactive foods and irradiated foods. Despite the maturity of irradiation technology and its widespread application in food processing and preservation, there is still public resistance to nuclear radiation in food, partly stemming from irrational fears. The main focus of this paper is on the impact of nuclear radiation on the quality of food itself. It explores the effects of nuclear radiation in food on human health, addresses relevant laws, regulations, and labeling of nuclear radiation in food. Additionally, key measures and recommendations to ensure the safety of nuclear radiation in food are proposed, aiming to provide references and insights for future in-depth research.

**Keywords:** Nuclear Radiation; Food; Human Health; Radioactive.

## 1. Introduction

Nuclear radiation in food can be broadly categorized into two main types: radioactive food and irradiated food. Radioactive food refers to situations where a large number of radioactive substances accumulates in food due to nuclear leaks following a nuclear accident, resulting in nuclear contamination. Such foods pose a higher safety risk, as consuming food contaminated by nuclear radiation may lead to the accumulation of radioactive substances in the body, significantly increasing the risk of illness [1]. Irradiated food, on the other hand, is a method of processing food using ionizing radiation to induce physical, chemical, and biological effects [2]. The processing of irradiated food is a purely physical process in which the food receives the energy of the radiation, without coming into contact with radioactive substances or producing radioactive residues [1].

Irradiated food is favored for its advantages, including food preservation, controllable sterilization, lower cost, and good application effects. Although irradiation technology is still in the early stages of development, its overall trend and potential are enormous, with the application scope gradually expanding [3]. However, there is a general public aversion to nuclear radiation in food. Concerns exist not only about radioactive food, with anxiety related to radioactive contamination and actively avoiding food from affected areas, but also about irradiated food to some extent [4]. Despite decades of evidence demonstrating the safety and effectiveness of food irradiation, there still exists some irrational silence and misunderstanding. Some radical organizations create irresponsible fears through irrelevant associations, such as Hiroshima, Chernobyl, or cancer [5]. Surveys indicate that the public is concerned about the safety and effectiveness of food irradiation [6]. In this context, providing accurate information is expected to encourage wider acceptance of irradiated food by consumers [5].

This review aims to systematically and comprehensively discuss the latest research progress on nuclear radiation in food. It focuses on the impact of nuclear radiation on food quality, its effects on human health, relevant laws and regulations, and provides some suggestions and reflections, serving as a reference and guide for future in-depth research on nuclear radiation in food.

## 2. Impact of Nuclear Radiation on the Intrinsic Quality of Food

When studying the effects of nuclear radiation on the intrinsic characteristics of food, one must consider changes in the physicochemical properties and nutritional quality of the food. The following is a detailed discussion of the impact of nuclear radiation on the intrinsic quality of food:

### 2.1. Impact of Nuclear Radiation on the Physicochemical Properties of Food

The use of radiation in food processing operations is known for its high safety and efficiency. It is essential to differentiate between nuclear-contaminated food, where residual radioactive elements are present, and irradiated food, which undergoes processing using radiation without leaving residues in the food [7]. Therefore, nuclear radiation treatment is widely employed in food processing and preservation.

Microbial Load: The microbial contamination of food typically leads to an increase in the bacterial count in the food. The application of nuclear irradiation can effectively reduce the microbial load in food, thereby extending the shelf life of the food. Taking fresh beef and frozen beef as examples, both contain a significant amount of foodborne pathogenic microorganisms. The growth of foodborne pathogenic microorganisms is the primary cause of beef spoilage. Some foodborne pathogenic microorganisms, such as Escherichia coli, Shigella, and Clostridium botulinum, can infect humans, leading to severe infections and even death. Therefore, methods like Plasma-Activated Water (PAW) have the potential to eliminate local microbial contamination on fresh beef [8].

Similarly, nuclear irradiation is applicable to fruits and vegetables. Microbiological analysis results suggest that gamma irradiation is indispensable for the disinfection of grape seeds, and an irradiation dose of 10 kGy (within the range specified by food irradiation regulations) is sufficient to completely eliminate bacteria [9].

Genetic Material: Low-dose nuclear radiation can activate enzymes in organisms, promoting metabolism and accelerating the growth and development process. This method helps enhance the organism's disease resistance and increase yield. For instance, using low-dose neutron irradiation to treat young shrimp significantly accelerates their growth and development, resulting in a 10% to 20% increase in yield. This method has been widely promoted in the Bohai Bay region of China [10].

Nuclear radiation can also disrupt plant deoxyribonucleic acid (DNA) and interfere with plant hormone metabolism, thus inhibiting the germination of agricultural products. Sprouting is another major reason for the decline in the quality of agricultural products during preservation, making nuclear radiation treatment effective in maintaining their freshness [11].

The widely recognized advantages of food irradiation technology include no chemical residues, the ability to treat fresh, packaged, or frozen foods, and lower energy requirements [12]. However, it also has some disadvantages.

Color: Irradiation treatment may alter the color of food, often leading to discoloration, which can be observed in meat, fruits, and vegetables. For example, irradiating a pigment solution with a dose of 6.5 kGy (a moderate intensity of radiation required for irradiation sterilization) completely fades the pigment solution, turning it into a colorless transparent liquid [13].

Odor: Nuclear radiation can sometimes cause changes in the odor and taste of food, especially in some high-fat foods like nuts. This is because high-fat foods undergo lipid oxidation and fatty acid degradation after irradiation, resulting in the production of "radiolysis products." Undesirable odors mainly originate from these "radiolysis products" [14].

Texture: Irradiation treatment can also make food softer or harder. This is due to changes in the activity of water molecules in food after irradiation, leading to the formation of substances such as hydrogen peroxide or hydroxyl radicals, altering the water content of the food and affecting its texture [14].

While changes in color, odor, and texture typically do not affect the safety of food, they may have a negative impact on consumer acceptance.

### 2.2. Impact of Nuclear Radiation on the Nutritional Quality of Food

Radiation treatment may also affect the nutritional quality of food, particularly vitamins, fats, and proteins.

#### 2.2.1 Vitamins

The sensitivity of vitamin molecules to irradiation is influenced by various factors, including irradiation dose, temperature, oxygen concentration, and the specific type of food. Studies indicate that irradiation conducted at low temperatures or under anaerobic conditions can reduce the loss of vitamins. This is because the destruction of water-soluble vitamins by radiation mainly occurs through the interaction of radiation with the aqueous solution, leading to indirect effects such as the generation of free radicals. Specifically, different types of water-soluble vitamins exhibit varying degrees of loss after irradiation. Vitamin C (VC), in particular, is considered one of the most sensitive vitamins to radiation [14]. The untreated raspberry's VC content is 125±5 mg/100 g. Electron beam treatment significantly reduces the VC content [15]. The loss of VC can significantly impact the nutritional value of food.

#### 2.2.2 Fats

Irradiation treatment may accelerate the oxidation of fats. When food is irradiated with 3~7 kGy gamma rays, a significant increase in the peroxidation value of fats is typically observed, indicating that radiation can accelerate the oxidation process of food fats.

Cobalt-60 gamma irradiation significantly accelerates the oxidation of food fats. Under storage conditions of 30°C and 35°C for 120 days, the peroxidation values of control group and 7 kGy group of walnut kernels were 3.97 meq/kg, 68.52 meq/kg, and 5.77 meq/kg, 80.02 meq/kg, respectively, with the irradiation group showing significantly higher peroxidation values than the control group [15]. The loss of fats in food may have adverse effects on human health.

#### 2.2.3 Proteins and Amino Acids

Some studies suggest that nuclear radiation may lead to changes in the amino acid and protein content of food, potentially affecting its nutritional quality.

Research has found that the use of 0.02-0.04% propyl gallate (PG) can inhibit protein aggregation after undergoing 0.5 and 1.0 megarad radiation treatment and subsequent storage at -20°C for 3-6 months [17].

Similarly, U(VI) interacts with serum proteins. Fourier-transform infrared spectroscopy (FTIR) shows that uranium ions can change the conformation of bovine serum albumin (BSA) under different pH conditions, indicating interaction between them [18].

#### 2.2.4 Other Substances

Irradiation may also cause changes in other components of food. Radiation-induced coumarin increase mainly occurs in plant products naturally rich in coumarin. The chemical changes caused by the radiolysis process in theoretical food can be estimated. In a study, it was found that the content of scopolin increased from 2 mg/kg to 60 mg/kg after irradiation at 3 kGy [19]. Excessive coumarin can cause damage to the skin, liver, and other organs in the human body.

In summary, the impact of nuclear radiation on food is a complex issue, widely used in areas such as mutagenesis, breeding, and food preservation. While some changes may affect the appearance, taste, and texture of food, they typically do not have a significant impact on the safety of food consumption. However, further research is needed on the effects of nuclear radiation on the nutritional quality of food to better understand its potential impact and formulate relevant regulatory and food safety policies.

## 3. Impact of Nuclear Radiation on Human Health

Firstly, it is essential to clarify the types of nuclear radiation in food, which can be categorized into two main groups: radioactive food and irradiated food.

### 3.1. Radioactive Food

Radioactive food refers to food contaminated with radioactive substances from production to acquisition. The contamination pathways typically include three aspects: direct contamination, indirect contamination, and food chain transfer [20].

Direct Contamination: Direct contamination primarily results from early-stage nuclear events, including the operation of nuclear power plants and the discharge of nuclear industrial wastewater. Additionally, it is noteworthy that radioactive isotopes are widely used in medical, scientific, and agricultural fields, and their waste may eventually be released into the marine system. While the concentrations of these wastes are generally low, the sheer global volume may contribute to the pollution of seafood products to some extent [21].

Indirect Contamination: Indirect contamination occurs in the environment, such as in the air, water, and soil, leading to the absorption of radioactive isotopes by plants and animals [20]. For instance, on cultivated land, cesium-137 may be uniformly distributed in the cultivation layer. Simultaneously, cesium-137 can enter plants in two ways: directly absorbed from the plant's surface or absorbed through the plant's roots from the soil, resulting in plant contamination [22].

Food Chain Transfer: Food chain transfer is the process of radioactive isotopes being transmitted through the food chain [20]. Farm animals raised in a natural environment may be contaminated with cesium-137, occurring in their gastrointestinal, respiratory, and skin systems. Cesium-137 can be absorbed by the digestive and respiratory organs of these animals. Furthermore, an increase in potassium content in food may contribute to the accumulation of cesium-137 in the tissues of these animals [22].

### 3.2. Irradiated FoodK

Irradiated food refers to food affected by nuclear radiation during production, processing, or packaging, which typically includes X-rays, gamma rays, and beta rays [23]. Irradiated food is subject to strict food safety standards, and while it is safe to consume, attention should still be paid. For example, irradiation may impact packaging materials, affecting the migration of substances into the food. Studies have been conducted to assess the levels of radiation dissolution products in irradiated packaging materials. The research covers various packaging materials, types of irradiations, and doses, revealing that irradiation can cause changes in substances. Therefore, evaluating the safety of finished packaging materials remains crucial [23].

### 3.3. Impact of Nuclear Radiation on the Nutritional Quality of Food

#### 3.3.1 Radiation Dose

The radiation dose is a crucial factor in determining the impact of nuclear radiation in food on human health. High doses of radiation may lead to acute radiation syndrome, a severe radiation illness. However, low doses of radiation present in food pose relatively minor risks, primarily manifesting as chronic and long-term effects. Prolonged consumption of contaminated products, especially those containing isotopes with long half-lives, may result in their accumulation in the human body, thereby increasing health risks [24]. For instance, radioactive isotopes in fish are primarily absorbed through the gills and body surface, particularly accumulating in the digestive tract after ingestion. This leads to significantly higher radioactive activity in their bodies compared to seawater. Long-term, substantial consumption of contaminated products, especially those with long half-lives and prone to accumulation, such as the radioactive isotope 137Cs, can lead to the accumulation of these isotopes in the human body. For example, the accumulation rate of 137Cs in human muscle can be as high as 80%, while in bones, it is 8% [21].

#### 3.3.2 Individual Sensitivity

Individual sensitivity is a crucial factor, with pregnant women, infants, and young children being more susceptible to nuclear radiation due to their faster cell division rates, which can result in greater

DNA damage. Nuclear radiation may inflict more significant harm on children, as they exhibit higher absorption rates for certain isotopes.

According to studies by Lapins, children absorb strontium-90 at much higher rates than adults, indicating that the harmful effects of nuclear radiation on children are significantly greater than on adults [25]. Research also suggests that prolonged, substantial consumption of seafood contaminated with radioactive isotopes may cause radiation damage to the human body, potentially leading to radiation-related illnesses. This impact is particularly pronounced in infants, young children, pregnant women, and the elderly [21].

### 3.4. Impact of Nuclear Radiation on the Nutritional Quality of Food

#### 3.4.1 Cancer Risk

Long-term consumption of food contaminated with nuclear radiation may increase the risk of cancer, especially with prolonged exposure. Certain isotopes can lead to the carcinogenesis of different tissues, such as strontium-90, radium-226, and polonium-239. The damage to DNA by nuclear radiation may initiate the development of cancer [24].

#### 3.4.2 Genetic Mutations

Nuclear radiation in food may induce DNA mutations, which could be passed on to offspring, raising concerns about genetic toxicity and mutagenesis. These mutations may increase the risk of cancer and potentially lead to various health issues in future generations. When the human body is exposed to gamma radiation, increasing radiation doses may trigger malignant tumors. Simultaneously, it could cause genetic mutations and chromosomal aberrations in the human genetic material [26].

#### 3.4.3 Immune System

Various parts of the human body are susceptible to radiation damage. The lymphatic system and gonads are particularly sensitive to radiation and may adversely affect the immune system, making the body more vulnerable to threats of diseases [25].

#### 3.4.4 Other Hazards

Acute radiation syndrome, local radiation injuries, and long-term exposure to low-dose radiation may lead to various diseases and adverse effects. Individuals significantly affected by nuclear power plant accidents, exposed to low-dose radiation over an extended period, may experience genetic effects and adverse impacts on various aspects, including mental, psychological, and social well-being [27].

In conclusion, nuclear radiation in food has complex implications for human health, necessitating a deeper understanding of potential risk factors. The formulation of rational food safety policies and further research efforts can help mitigate the potential risks that nuclear radiation in food may pose to public health.

## 4. Regulatory Framework and Labeling of Nuclear Radiation in Food

The management and regulation of irradiated foods are crucial to ensuring public safety and food quality. This section will explore regulatory agencies, laws, regulations, and labeling issues related to irradiated foods.

### 4.1. Impact of Nuclear Radiation on the Nutritional Quality of Food

Regulatory agencies play a crucial role in the field of irradiated foods, both at the international and domestic levels. These agencies, through the formulation of policies, setting irradiation standards, and issuing regulations, are dedicated to ensuring the safety and compliance of irradiated foods.

Internationally, a series of projects and committees have ensured the smooth international trade of irradiated foods through rigorous investigations, promoting the widespread application of food irradiation. Projects supported by countries and organizations such as the Food and Agriculture Organization, the Atomic Energy Agency, and the World Health Organization have formulated policies and schemes related to food irradiation processing. The aim of these measures is to conduct thorough health, technical, and economic feasibility studies on food irradiation. Simultaneously, efforts are made to ensure the unimpeded international circulation of irradiated foods, thereby promoting the widespread acceptance and practical application of food irradiation [28].

In 1980, the International Joint Expert Committee on Irradiated Food confirmed that "for storage purposes, no toxicological testing is required for food irradiated at doses below 10 kGy (radiation absorbed dose)." Subsequently, in 1983, the Codex Alimentarius Commission (CAC) of the Food and Agriculture Organization (FAO) and the World Health Organization (WHO) officially issued the "General Standard for the Irradiation of Food," providing the basis for countries to formulate health regulations related to irradiated food [29].

At the national level, specific regulatory agencies are typically established to oversee nuclear radiation in food. These agencies are responsible for detecting and monitoring radiation levels in food to ensure compliance with national and international standards. For example, in China, the Ministry of Health issued the "Regulations on the Hygiene Administration of Irradiated Foods" on April 5, 1996. This regulation stipulates that the irradiation of food must be strictly controlled within the national permissible range and specified dose standards. If exceeding the allowable range, producers must submit applications for approval before production. Additionally, since June 1, 1998, China has mandated that irradiated food must bear the designated irradiation label on its smallest packaging, and irradiated food without this label is strictly prohibited from entering the domestic market [29].

In the United States, the Food and Drug Administration (FDA) is responsible for regulating food radiation levels. The FDA has established a series of regulations and standards to ensure the safety of irradiated food. These regulations and standards aim to protect the public from potential hazards, ensuring that appropriate measures are taken during food irradiation to maintain food quality and safety. The FDA plays a crucial role in overseeing these aspects to ensure that food in the U.S. market undergoes proper irradiation and complies with relevant safety standards [30].

At the EU level, the management of food safety risks throughout the entire food chain is overseen by the Health and Food Safety Directorate-General under the European Commission, and the Food and Veterinary Office, led by this directorate, serves as the main executive body for this task. The European Food Safety Authority is the agency responsible for conducting risk assessments in this system. The Food and Veterinary Office plays a crucial executive role, assisting in the enforcement of standards and regulations that ensure the safety of food in the European Union [31].

## 4.2. Relevant Laws and Regulations

Each country has its own regulations and legal framework to supervise and control the production and sale of food irradiated with nuclear radiation. These regulations typically stipulate the upper limits of radiation levels, food labeling requirements, and penalty provisions.

### 4.2.1 Types of Foods

The International Consultative Group on Food Irradiation (ICGFI) recommends that countries approve irradiated foods in seven categories: legumes, cereals and their products, dried fruits and fruit preserves, processed meat and poultry, frozen packaged meat and poultry, spices, fresh fruits, vegetables, and aquatic products. Many countries, including China, have adjusted their irradiated food regulations based on these categories. In China, approval has been granted for irradiated foods in six categories, excluding aquatic products. This classification and adjustment aim to standardize and manage the production and distribution of irradiated foods, ensuring consumer food safety [32].

### 4.2.2 Purposes of Irradiation

Countries such as the Codex Alimentarius Commission (CAC), the European Union (EU), the United States, and China specify the purposes of food irradiation, including:

(1) Killing insects in cereals, dehydrated legumes, and dehydrated vegetables, as well as parasites in meat and aquatic products.

(2) Inhibiting sprouting in foods like potatoes and onions.

(3) Delaying the ripening of fresh fruits and vegetables, extending their shelf life.

(4) Eliminating pathogenic microorganisms and other spoilage bacteria in food, reducing the incidence of foodborne diseases.

(5) Extending the shelf life of food to ensure its quality and safety during production, transportation, and sale [32].

#### 4.2.3 Definition Standards

Countries such as the CAC, EU, the United States, and China all specify that the use of irradiation technology should not "replace hygienic health standards or good manufacturing practices." This provision aims to ensure that the application of irradiation technology enhances food safety and quality without substituting for other fundamental hygiene and production standards. In China, it is particularly emphasized that the use of irradiation processing methods on substandard or unqualified foods is strictly prohibited to safeguard consumer rights. These regulations aim to integrate the use of irradiation technology to maximize the quality and safety of food [32].

The FDA's authority to approve irradiated food and packaging before market launch originates from the Food Additives Amendment of 1958. This amendment defines food additives as substances that "directly or indirectly affect any component of food or otherwise affect any characteristic of food and are reasonably expected to become a component of food." While there are exceptions, the use of radiation sources for treating food still requires FDA approval. According to section 409, all food additives, including radiation sources, must comply with general safety and procedural rules, meaning they require FDA approval before market entry. If food is intentionally irradiated and this use does not comply with regulations or obtain an exemption, the FDA considers it adulteration. The purpose of this regulation is to ensure the safety and compliance of irradiated food to protect public health [33].

#### 4.2.4 Dosage Usage

According to the current standards GB 14891.1—GB 14891.8 issued by the Ministry of Health, the application of irradiation technology to treat food in China is currently subject to certain limitations. Numerous studies typically use low irradiation doses (≤1 kGy) to treat fresh fruits, fresh vegetables, dried fruits and fruit preserves, pork, legumes, cereals, and their products to achieve effects such as insect elimination, sterilization, sprout inhibition, and delayed ripening. Medium irradiation doses (1–10 kGy) are mainly used to treat fresh meat, aquatic products, processed foods, pollen, dehydrated vegetables, and other processed products to achieve sterilization and mold prevention. High irradiation doses (10–50 kGy) are primarily applied to sterilize meat, poultry, seafood, and food additives.

The selection of these irradiation doses depends on the characteristics of different foods and processing requirements, ensuring that food can maintain its quality during the irradiation process while meeting hygiene and safety standards [34].

**Table 1.** Foods permitted to be irradiated under FDA's regulations [30]

| Food | Purpose | Dosage |
|---|---|---|
| Fresh pork | Control Trichinella spiralis | 0.3 kGy min.–1 kGy max. |
| Fresh foods | Growth and maturation inhibition | 1 kGy max. |
| Foods | Arthropod disinfection | 1 kGy max. |
| Dry enzyme preparations | Microbial disinfection | 10 kGy max. |
| Dry spices/seasonings | Microbial disinfection | 30 kGy max. |
| Poultry | Pathogen control | 3 kGy max. |
| Frozen meats (NASA) | Sterilization | 44 kGy min. |
| Refrigerated meat | Pathogen control | 4.5 kGy max. |
| Frozen meat | Pathogen control | 7 kGy max. |
| Shell eggs | Pathogen control | 3 kGy max. |
| Seeds for sprouting | Pathogen control | 8 kGy |
| Fresh pork | Control Trichinella spiralis | 0.3 kGy min.–1 kGy max. |

The FDA has determined that irradiated food is safe under certain conditions. Authorized regulations have been issued based on petitions and FDA initiatives, as shown in Table 1.

### 4.3. Relevant Laws and Regulations

Food labeling is crucial for consumers to make informed choices about their food. In the case of food treated with nuclear radiation, specific labeling is necessary to clearly indicate that these foods have undergone radiation treatment. This helps consumers have a clear understanding of the radiation history of the food they are purchasing.

These labels typically include information such as the product's origin, radiation dosage, production date, and certification from relevant regulatory authorities. Through such labeling, consumers can obtain key information, enabling them to make decisions about food choices based on their individual needs and beliefs.

In China, CAC, the European Union, the United States, and the Australia-New Zealand region, regulations and standards for food labeling stipulate that the labeling of irradiated food on pre-packaged food labels is mandatory. An internationally recognized symbol for irradiated food is shown in Figure 1.

However, specific regulations on the manner of irradiation labeling may vary by region, and detailed provisions can be referenced in the relevant regulatory documents. See Table 2 for a comparison of specific regulations on irradiation labeling on food labels in different countries or organizations [35].

**Fig. 1** International Irradiated Food Labeling

**Table 2.** Comparison of specific regulations on irradiation labeling on food labels in different countries or organizations

| Country/Organization | Specific Regulations |
|---|---|
| China | Foods treated with ionizing radiation or ionizing energy must be labeled as "Irradiated Food" near the food name. Any ingredients treated with ionizing radiation or ionizing energy should be indicated in the ingredient list. |
| CAC | Foods treated with ionizing radiation or ionizing energy must be labeled as "Irradiated Food" near the food name and can use the International Irradiated Food Labeling (Fig.1), this labeling should be placed in close proximity to the product name. |
| European Union | According to the input country's requirements, it is necessary to include the words "Treated with Ionizing Radiation" in the food's name. In the case of bulk sales, these words should appear together with the product name on a display or notice near or above the container where the product is placed. If irradiated products are used as ingredients, the corresponding words should be included in the ingredient list. In the case of bulk sales, these words should be displayed with the product name on a notice near or above the container. |
| America | On irradiated foods, affix a label with the International Irradiated Food Labeling (Fig.1) and include "Processed by Irradiation" or "Irradiation Treatment" on it. If non-irradiated food contains irradiated components, no special label is required on retail packaging since the processed nature is evident. However, for products not in the retail market and potentially subject to further processing, a special label is necessary to ensure they aren't irradiated multiple times. |

Regulation and labeling of irradiated food are integral components in ensuring food safety and public health. Through rational regulations and standards, coupled with increased international collaboration, we can better manage and control the risks associated with irradiated food. Future regulations and oversight should place a greater emphasis on cooperation and information sharing to ensure the safety of irradiated food. Additionally, enhancing consumer education and raising awareness about food safety are crucial to assist the public in making informed choices regarding food and understanding associated risks.

## 5. Recommendations and Reflections on Irradiated Food

The development of irradiated food has raised concerns about public health and food safety. In this section, taking China as an example, recommendations to improve irradiated food and related industries, as well as reflections on their future development, are presented to mitigate potential risks to human health from irradiated food.

### 5.1. Relevant Laws and Regulations

Survey data indicates a low level of trust among people regarding irradiated food, particularly in terms of safety, legality, and concerns about residual radioactivity. Among respondents, 59% believed irradiation was legally permitted, but only 20% considered irradiated food to be reliable and safe. Additionally, over 70% of respondents expressed concerns about potential harm to human health from residual radioactivity after irradiation [32].

To effectively manage the risks associated with irradiated food, the public needs more education and heightened awareness. This includes:

Providing information about irradiated food, its effects, potential risks, and how to identify labeling.

Communicating information about food safety through various media channels to ensure consumers can make informed food choices.

Initiating educational programs, with a focus on specific groups such as pregnant women and children, who are more sensitive to radiation.

### 5.2. Improve Regulation and Legislation

To ensure the safety of irradiated food, regulatory frameworks and legislation need continuous improvement. Strict enforcement of regulations, including inspections and monitoring of radiation levels in irradiated food, is crucial. Currently, regulatory efforts are relatively weak, and according to health regulations, businesses can produce irradiated food only after obtaining sanitary permits from disinfection service agencies and complying with health management requirements. However, there is a significant presence of unlabeled irradiated food in the market due to unlicensed operations, pushing legal boundaries and causing market confusion [32].

Moreover, for enhanced international cooperation, coordination of regulations and standards among different countries is essential to guarantee the safety of food in the international market. China currently has fewer and slower-updating regulations, making it challenging to timely align with international regulatory standards. For instance, the EU and the US require certification for irradiation facilities, a requirement not yet implemented in China [32].

Lastly, to better manage and monitor the production and sale of irradiated food, improvements in the capabilities of regulatory agencies are necessary. Currently, China lacks certification requirements for the qualifications of irradiated food and production enterprises in imports and exports. There is also a lack of clear regulations in health science identification, quarantine, and assessment [32]. Improvements in these areas will contribute to enhancing the regulatory standards and safety compliance of irradiated food in the market.

### 5.3. Continuous Research and Monitoring

Research and monitoring of irradiated food should be ongoing. Firstly, in terms of research, there is a need to delve into the impact of different types of irradiated food on the human body to determine which foods require stricter regulation. Design entities in this regard not only need to hold corresponding qualifications but should also rigorously assess their technical reliability, safety, and implementation feasibility. After design, they should be responsible for installation, debugging, and even modification. For early-built facilities, systematic upgrades should be gradually implemented, and consideration could be given to introducing or collaborating with foreign entities to quickly align China's irradiation facilities with international standards [36].

Secondly, in terms of monitoring, relevant projects should be conducted to ensure the compliance of irradiated food. Health supervisory departments in provinces, cities, and autonomous regions need to carry out strict approval, supervision, and inspection work. Training and examination of operators should be conducted to ensure certified personnel are on duty, placing irradiated food processing production under national unified control. Additionally, irradiation units need to establish a reporting and review system to ensure the strictness of doses and monitoring, guarantee the uniformity of irradiation doses, and implement pre- and post-irradiation microbial inspections and sample retention procedures [36]. These measures will contribute to ensuring the safety of irradiated food and compliance with regulatory requirements.

### 5.4. Continuous International Cooperation

The management of irradiated food requires international cooperation because the food supply chain typically involves multiple countries. To ensure the safety of irradiated food, the international community should strengthen cooperation.

Taking the formulation of relevant regulations as an example, China should actively participate in the formulation and review of various standards in the field of food irradiation by the Codex Alimentarius Commission (CAC). Through participation, China can gain a deep understanding of the formation process of CAC food irradiation standards, thereby better formulating and adjusting its own regulatory system [35]. This proactive international engagement will help ensure the international consistency of domestic irradiated food management and alignment with global standards.

In conclusion, raising public awareness and education, improving regulation and legislation, continuous research and monitoring, and international cooperation are crucial aspects to ensure the safety of irradiated food. By providing relevant information to the public, strengthening regulatory efforts, and conducting in-depth research, we can gradually address people's concerns about irradiated food. Simultaneously, international cooperation is indispensable to ensure the global consistency of irradiated food management, further enhancing safety and controllability, and providing consumers with wiser food choices. These measures will contribute to advancing the development of the irradiated food sector, providing the public with a safer and more transparent food market.

## 6. Conclusion

Nuclear radiation affects the physicochemical properties and nutritional quality of food. In terms of physicochemical properties, nuclear radiation treatment enhances food safety by reducing microbial loads, and its impact on genetic material contributes to improved resistance to diseases. However, changes in color, odor, and texture may negatively impact consumer acceptance. In terms of nutritional quality, vitamins, fats, and proteins are all influenced by irradiation.

Irradiated food has an impact on human health, with high doses often causing acute illnesses and low doses potentially leading to chronic diseases through accumulation. Pregnant women, infants, and children are more sensitive to nuclear radiation. Additionally, irradiated food may pose health risks, including cancer, genetic mutations, and immune system effects.

The relevant laws, regulations, and labeling of irradiated food are crucial to ensuring public safety and food quality. International and domestic regulatory agencies formulate policies and standards in the field of irradiated food to ensure its safety and compliance. National regulations typically specify maximum radiation levels, food labeling requirements, and penalty provisions. Labeling includes information such as product origin, radiation dose, and production date, providing consumers with crucial information to make informed choices. Future regulations and oversight should emphasize collaboration, information sharing, and consumer education to better manage the risks associated with irradiated food.

Raising public awareness and education, improving regulation and legislation, continuous research and monitoring, and international cooperation are key aspects of ensuring the safety of irradiated food. These measures contribute to alleviating public concerns about potential risks associated with irradiated food, ensuring the effective operation of regulatory bodies, promoting scientific research and technological development, and advancing global standard consistency. Through these efforts, a more transparent and safe market for irradiated food can be established, enhancing public trust in food safety.

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