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Food Irradiation Technology: A Review of The Uses and Their Capabilities

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Abstract *- Irradiation is the process of exposing several radiation beams to food to sterilize and extend their shelf-life. The radiation principle is excitation, ionization, and food components change when the radiation source touches the food. Irradiation aims at making food safer for consumption by killing pathogenic microorganisms. The irradiation process is like the pasteurization process but without heat, causing freshness and texture changes. The irradiation process will interfere with rot-causing biological processes and prevent shoot-growth. Food irradiation uses gamma radiation energy sources, electron beams, and X-rays to eliminate pathogenic microorganisms, insects, fungi, and pests. This process is safe and does not cause food to be radioactive. Chemical, nutritional, microbiological, and toxicological aspects of irradiated products are used as food safety parameters. The irradiation consists of three dose levels: low, medium, and high. Each of these ingredients was exposed to varying radiation doses based on the specific properties of the materials. There are advantages and disadvantages to the irradiation process: the radiation process doesn't use heat to prevent food from changing its features. However, there is still public fear that the irradiation process will have a radioactive influence on the material.*

Keywords — *Dose, food, excitation, irradiation, quality, pathogenic*

I. INTRODUCTION

Food is one of the most important basic human life needs [1]. Food stored for a long time can decompose or deteriorate [2]. Therefore, preservation is needed to extend these foodstuffs' storage capacity but still meets the nutritional criteria and quality of food suitable for the body [3]–[5]. The protection of food widely practiced in ancient times was salting, smoking, blanching, and others [6]. The modern era's development has created several new technologies capable of preserving food products [5], [7], [8]—one of the food preservation technologies using irradiation [9], [10].

Irradiation is the processing of food by applying electromagnetic waves to reduce damage and decay [11]. The irradiation process can kill pathogenic microorganisms because it will attack directly into the DNA so that microorganisms cannot reproduce and live in food [12]. In general, irradiation is described as a beam of light that penetrates a food material with different strengths, depending on the wavelength and inversely proportional to the frequency. The shorter the wavelength, the higher the penetrating power [13]. One of the requirements for food irradiation is the dose used. It is because each dose of irradiation has a different purpose [14]. The irradiation dose given to a food item exceeds the limit; it will cause damage to the materials [15]. The ionizing radiation penetrates a material; it will absorb part or all of the radiation energy. The unit absorbed dose measured in gray or kilo gray (Gy or kGy) [16]. This review discusses irradiation as a food preservation technology, the principles, doses, and purpose of food irradiation, and its efficacy for products. Besides these advantages and disadvantages, irradiation product characteristics are also discussed. The laws governing the use of food irradiation technology are also studied.

II. IRRADIATION TECHNOLOGY

A. Definition

Irradiation was the preservation method wherein food is exposed to radiation. Irradiation is a safe, healthy, and clean technology applied to the food industry. The irradiation process can maintain the nutrition, freshness, and sensory properties of food ingredients (texture, color, taste, and aroma). It is because the irradiation treatment does not apply high temperatures to maintain product quality. If the source of irradiation hits the foodstuff, there will be excitation and ionization, which will inhibit DNA synthesis in living things. This effect is used to inhibit the growth of pathogenic microorganisms and suppressor. Thus, this technique also plays its part in the shelf-life extension of food products. If the source of irradiation hits foodstuffs, there will be excitation and ionization, which will inhibit DNA synthesis in living things. This effect is used to stop the growth of bacterial pathogens. Thus, this technique also plays a role in extending food shelf life [17].

Food irradiation is a non-chemical food processing method that is energy efficient and can help reduce significant losses due to spoilage or contamination from bacteria or other parasites. It involves exposure of foodstuffs to ionizing radiation before packaging or in large quantities to reduce the risk of foodborne diseases, prevent or remove budding or ripening [11].

Food irradiation technology is green technology, which is used without chemicals and does not produce pollution. This technology can be applied sustainably in the food sector, which is in line with the increasing human population, limited agricultural land, globalization, and international trade issues requiring quality and food safety [18].

B. Irradiation principles

Irradiation food preservation uses high energy, known as ionizing radiation [11]. It is because the material in its path can be ionized. When irradiation sources such as X-rays, gamma rays, and electron beams touch the material, these foods' components will be excited, ionized, and altered [19]. An excitation is an event where living cells become sensitive to external conditions. Ionization is the process by which macromolecules are broken into free radicals. Changes in living cells' components will inhibit DNA synthesis, disrupting microbial cell division, and biological effects. This effect inhibits microbial growth in food [20].

III. SOURCES OF IRRADIATION AND ITS USE IN FOODS

A. Electron beam

The electron beam is like X-rays; it is a flow of electrons that have high energy. The waste is pushed from the electron accelerator into food products [21]. The electron beam is generated by machinery, not by radioactive material. They have by speeding up the flow of electrons targeted on the narrow point of light. Food moves perpendicular to the light; at this point, the electrons will pass through the food [22]. Electron ray radiation is different from gamma rays. The need to carry radioactive material can be removed when it is not needed, and the electron beam is characterized by a low level of penetration with a high dose. Electron beams perform very well at low density and with consistent results. So it's effective against pathogens on the food surface [10]. The electron beam can be applied to foods, shown in Table 1.

Table 1. Application of electron beams to various food products and their characteristics

Food products	**Dose**	**Findings**	**Ref.**
Fish gelatin film with bamboo leaves antioxidants	5 and 7 kGy	Antioxidant release rate decreases; can improve the film's physical characteristics	[23]
Rice starch	0, 1, 2, 4, 8, and 10 kGy	Lipase activity decreased in rice, and it did not significantly affect the quality of cooked rice at low doses; however, at higher doses, lipase activity caused the degradation of starch molecules	[24]
Mango	0,5 kGy	Suppressing post-harvest diseases; also stimuli increased H_2O_2 production, respiration, and C_2H_4, retaining firmness, slowing the increase in total soluble solids, but not affecting ethylene production or vitamin C content during storage	[25]
The waxy maize starch and its films	2–30 kGy	The molecular weight, branching, and thermal properties of the starch were reduced. At low doses, α-1,6-glucosidic bonds were present at higher levels than α-1,4-glucosidic bonds, and at high doses, a film with high mechanical properties and good solubility was formed	[26]
Egg white protein	1.0, 1.5, 2.0, and 2.5 kGy	S-S bond breakage and exposure to hydrophobic amino acid residues; the antioxidant activity of egg white protein increases and causes oligomerization; egg white protein microstructure becomes a "honeycomb" microstructure	[27]
Goji-berry	2.5, 5.0, 7.5, and 10.0 kGy	Does not affect DPPH radical scavenging activity; generates higher total flavonoids than without irradiation; there was a gradual decrease in ORAC results at doses above 5.0 kGy	[28]

B. Gamma rays

Gamma rays are used for food processing, whose light source is obtained from a ^{60}Co radionuclide source. This type of radiation is essentially monoenergetic [29]. Using analytical methods such as the kernel point or the Monte Carlo method, it is straightforward to calculate the spread of irradiation doses in food products. The resulting dose depth distribution will resemble an exponential curve [30]. Irradiation from two sides, obtained by rotating the processing load, is often used to enhance dose uniformity in system loads [31]. Its applications on food were widely used, as shown in Table 2.

Table 2. Application of gamma rays to various food products and their characteristics

Food products	Dose	Findings	Ref.
Brown rice	0, 2, 4, 6, 8, and 10 kGy	With improved irradiation dose, the rehydration ratio and browning index decrease while the total phenolic, antioxidant activity, β-carotene content, and microbiological stability increase	[32]
Kimchi seasoning mixture	0-10 kGy	As the irradiation dose increased, the microbial population decreased, slowed the changes in pH, acidity, sugar reduction, and headspace gases, and did not change the color values	[33]
Pomegranate	1, 3, and 5 kGy	Increase pomegranate shelf-life; decrease the microbial load on pomegranate aryl; decrease polyphenol oxidase activity	[34]
Wheat	0–5 kGy	Rheological properties and dynamic module decrease; antioxidant activity increased significantly	[35]
Beef loins	2.5 kGy	Improve microbiological safety and meat quality	[36]

C. X-ray

X-rays are generated by reflecting high-energy electrons into the food from the target substance. X-rays are also frequently shown in medical applications to create images of internal structures [37]. A machine generates X-rays, and it could be turned off. Therefore, the electrons will be speeded up at the target metal (e.g., tungsten or gold) to produce X-rays. In this process, the energy of the electric rays is dissipated as heat. However, with the atomic number of the target material and an increase in the electron beam, X-ray efficiency can be improved [38]. Several food products using X-rays are currently shown in Table 3. As technology advances, the use of X-rays will be widely used in the future.

Table 3. Application of X-rays to various food products and their characteristics

Food products	Dose	Findings	Ref.
Strawberry	0–1 kGy	It can reduce fruit weight loss and spoilage at 1 kGy during storage; delay fruit discoloration; increase sensory characteristics during storage	[39]
Spinach leaf	Combination of 0.3 kGy, 1% citric acid	There was an improved bactericidal effect due to X-ray irradiation combined with 1% citric acid; the combined effect of treatment did not cause quality degradation	[40]
Sliced cheese	0, 0,2, 0,4, 0,6, and 0,8 kGy	Increasing the dose of irradiation can inactivate the pathogenic microbes, including *Escherichia coli, Salmonella typhimurium,* and *Listeria monocytogenes* but does not affect the quality of the cheese	[41]
Lettuce	Combination of 0.05-0.3 kGy and 0.5% gallic acid	The combined effect of X-rays 0.3 kGy and gallic acid at 0.5 % effectively inactivates *Escherichia coli*, *Salmonella typhimurium*, and *Listeria monocytogenes* but has no negative impact on lettuce quality	[42]
Rice	0-1.5 kGy	Irradiation with essential oregano oil increases microbicidal efficacy	[43]

IV. FOOD IRRADIATION DOSES AND INTENDED USE

A. Low dose (0 to 1 kGy)

Low doses of irradiation can be applied to several types of food products such as tubers, fresh fruit and vegetables, cereals or nuts and seeds, dried vegetables and spices, and dry food of animal origin [44]. Irradiation aims to delay ripeness, eradicate insects, and control quarantine for some fresh fruits and vegetables. Irradiation of tubers seeks to inhibit the germination process. In cereals or nuts and seeds aims to eliminate insects. Meanwhile, irradiation of dry vegetables, spices, or dry herbs and tea herbs is intended to eradicate insects [10], [45]. Dry food derived from animals also has the same goal, namely, to eliminate insects.

Recommendations or regulations regarding irradiation in low doses of food products are available based on the BPOM

Republic of Indonesia [46]. The minimum dose is 0.2; 1.0; 1.0; 1.0; and 1.0 kGy, respectively found in tubers; fresh vegetables and fruits; cereals, beans and seeds; dry vegetables and spices; and dry food from animal sources. The different purposes of using low-dose irradiation in food products are shown in Table 4.

Table 4. The purpose of using food irradiation at low doses at various study

Food products	Dose	Purposes	Ref.
Strawberries	0, 0.3, 0.6, and 0.9 kGy	Analysis of chemical and nutrient composition during post-harvest storage	[47]
Fish meat	0.25, 0.5, 1, 3, 5, 7, and 9 kGy	Determine the level of irradiation and distinguish whether the material is irradiated or not	[48]
Onion and potato	0.15, 0.5, and 1 kGy	Analyzed the effect of storage on light emissions by irradiating	[49]
Lettuce	0.02, 0.03, 0.04, and 0.05 kGy	Increase percentage growth by using irradiation effects on plant seeds	[50]
Milk and eggs	0.75 kGy on wheat flour	Determine the efficacy of irradiation and thermal processes able to influence the immunochemical diagnosis of allergens	[51]

B. Moderate dose (1 to 10 kGy)

Under moderate doses of irradiation, some fresh fruits and vegetables, some kinds of cereals and nuts and seeds, fresh seafood, poultry, and other fresh meat, dried fruits, spices, dried herbs, some herbal products, and dried animal products can be applied [52]. Some fresh fruits and vegetables are irradiated to extend shelf-life [10]. In some cereal types, nuts and seeds, its process decreases the number of microbes. Fresh seafood irradiation eliminates certain pathogenic microorganisms, control infection due to parasites, so improve shelf-life. Poultry and other fresh meats can also significantly reduce specific pathogens, control parasite infection, and eliminate harmful organisms like salmonella. Irradiation in dried fruits and vegetables, herbs, dry herbs, and some herbal products reduces certain pathogenic microorganisms. Meanwhile, eradicate microbes, molds, and yeasts for dried animal products [46], [53]. The purpose of using moderate dose food irradiation has been extensively studied, as shown in Table 5.

Table 5. The purpose of using food irradiation at moderate doses at various study

Food products	Dose	Purposes	Ref.
Seafood	3, 5, 7, and 10 kGy	Reduces norovirus in Korean dried seafood storage	[54]
Herbal/spice	1 kGy	Detects compounds in irradiated herbal/spice mixtures	[55]
Carrot and lettuce	2 kGy	Studying gamma radiation and its effects	[56]
Acacia, apricot, and gum-karaya	2.5 and 5 kGy	Investigate the impact of irradiation on the physicochemical characteristics	[57]
Rubber seed	2.5 and 5 kGy	Evaluating the structural effects and physiochemical characteristics of gamma irradiation on materials	[58]
Lettuce	0, 0.5, 1, 1.5, 2, 2.5, and 3 kGy	Inquiry of the effects of radiation on *Salmonella typhimurium* and *Staphylococcus aureus*	[59]
Fish myofibrillar proteins	2, 4, 6, 8, and 10 kGy	To determine whether gamma irradiation alters the physicochemical and structural characteristics of a sample	[60]
Saengshik (healthy cereal food)	0, 1, 3, 5, and 10 kGy	Identifying the chemical effects of irradiation and functional quality	[61]
Spinach and fresh iceberg lettuce	0, 1, 2, 3, and 4 kGy	Analyze the quality of spinach and fresh iceberg lettuce exposed to irradiation	[62]
Squid	3 and 5 kGy	The bacterial population was drastically reduced; stabilizes the squid's biochemical characteristics	[63]

C. High dose (>10 kGy)

High levels of irradiation can be applied to food items, such as dried spices and animal-based ready-to-eat food. Each irradiation process that is carried out has a different purpose (Table 5). Irradiation of some dried herbs has the aim of reducing certain pathogenic microorganisms. Meanwhile, animal-based ready-to-eat processed food products have the objective of sterilizing and eradicating pathogenic microbes, including microbes with spores and extending shelf life. There are regulations regarding irradiation in high doses of food, including some dry spices with a minimum dose of 10.0 kGy. In animal-based ready-to-eat food products, the dose is the minimum is 65.0 kGy [53]. The use of high-dose food irradiation for diverse research purposes is shown in Table 6.

Table 6. The purpose of using food irradiation at high doses at various study

Food products	Dose	Purposes	Ref.
Boletus Edulis (Mushrooms)	2, 6, and 10 kGy	Analysis of gamma-ray irradiation effects on the chemical component and antioxidant activity during storage	[64]
Milk and Egg	10 kGy on allergen antigens	To investigate the impact of irradiation and thermal processes on the immunochemical detection of food allergens	[51]
Sorghum and Potato Starch	0, 5, 10, 15, and 20 kGy	Identification of physicochemical and functional properties of sorghum and potato starch irradiated with gamma rays	[65]
Oleic acid of methyl oleate, beef, and olive oil	0-60 kGy	Examined the influence of gamma radiation on oleic acid in methyl oleate and its effect on food	[66]

V. FOOD QUALITY IRRADIATED: BENEFITS AND DRAWBACKS

Some of the benefits of using irradiation in food are little or no heating process, so the material doesn't change its characteristics. Also, irradiation can suppress microorganisms that live in food. Irradiation can be carried out on packaged foods, frozen foods, and fresh food through one operation and do not use chemical additives. Irradiation requires only a small amount of energy, nutrition changes can be compared with other preservation methods, the automatic process is controlled, and the operating costs are low [67].

The drawbacks of using irradiation in foods include killing large amounts of bacteria to make food unfit for food selling; consumers cannot see indications of pathogenic bacteria that have not been destroyed in food. Food will become dangerous to health if the pathogenic bacteria are destroyed after contaminating food [68]. The irradiation process also allows the development of microorganisms' resistance to radiation, loss of nutritional value in food, and analytical procedures that detect whether food has been irradiated inadequately and public fear of radioactive effects [67]. As shown in Table 7, the use of irradiation in food has several advantages and disadvantages.

Table 7. Benefits and drawbacks of food irradiation

Benefits	Drawbacks
The variation of irradiation and other treatments would cause food to remain on the shelf-life longer [69]	The biological effect of irradiation occurs in DNA or RNA disruption in the cell nucleus [22]
Combining heating irradiation can inactivate the virus [70]	Irradiation can have a direct effect caused by oxygen-centered reactive radicals from water radiolysis. Water is a large part of the food, and harmful microorganisms are present [71]
Irradiation can be used as direct insect control in spices [72]	During the process, irradiation forms free radicals causing lipid oxidation [73]
An organism's pathogenicity can be reduced by irradiation [74]	Irradiated chicken with 1 kGy reduced thiamine by 16% compared to the non-irradiated product [73]
Nutrition in foods with irradiation tends not to change [75]	Food irradiation showed no increased threat due to mycotoxin formation [76]

The quality of irradiated food includes aspects of chemistry, nutrition, microbiology, and toxicology. Chemical characteristics; irradiation using ionizing radiation is a process without using hot materials called a "cold" method [77]. The energy absorbed by food will be much lower than that of heated food. The changes in chemical elements that occur will be less quantitatively. Chemical compounds will be formed depending on the material's composition, and the amount will increase if the dose used is added. Chemical changes can be suppressed by regulating the material's temperature and moisture content and removing oxygen from the air around the irradiated material [78].

Irradiation can change the chemical compounds in food to change these products' nutritional value in nutritional aspects. The study results showed that nutrient loss in food irradiated with 1 kGy dose had no significant impact. In comparison, moderate-dose irradiation (1-10 kGy) may reduce its nutritional components unless the irradiation process's temperature and air are adjusted in this way [79]. Proper treatment, such as combined radiation conditions with packaging techniques, will maintain processed food products' quality and nutrition [80].

In the microbiological aspect, exposed ionizing radiation causes DNA damage in living cells, including microbial cells, explicitly targeting pathogenic bacteria [81]. However, applying moderate doses did not cause radiation-resistant or pathogenic microbe mutations. Vegetative, non-spore, and gram-negative pathogenic bacteria are generally very radiation-sensitive. Meanwhile, bacteria with spores usually are more resistant, except if high-dose irradiation [82].

Although the chemical analysis did not find any compounds that could endanger health, toxicological tests were still conducted, especially new products. Food safety testing is done on animals and humans. It tests performed with a more complete and accurate procedure than conventional methods. Research by experts from the International Food Irradiation Project (IFIP) has shown that the radiation technique used to process food is much safer than other conventional methods [83].

VI. IRRADIATION LEGALITY

Government legality of food irradiation is one of the essential and central aspects of implementing food irradiation technology. Food irradiation regulations that must be adhered to by nearly 40 countries refer to the international CODEX Alimentarius standards and internal standards issued by each member country. Indonesia is a member of the International Atomic Energy Agency (IAEA). Food label no. 69/1999 became the international regulatory standard for irradiated foods. Regulations regarding food irradiation in different countries are outlined in Table 8.

Table 8. Food irradiation regulations in different countries

Regulation number	Country	Regulatory content
Republic of Indonesia's Government Regulation, No. 69, 1999	Indonesia	Food labeling
Republic of Indonesia Health Minister's Regulation, No.826/MENKES/PER/XII/1987	Indonesia	Irradiated food
Republic of Indonesia Health Minister's Regulation, No.152/MENKES/SK/II/1995	Indonesia	Irradiated food
Republic of Indonesia Health Minister's Regulation, No.701/MENKES/PER/VIII/2009	Indonesia	Irradiated food
The Indonesian Food Law, No.7, 1996	Indonesia	Food
Republic of Indonesia's Government Regulation, No. 28, 2004	Indonesia	Food Safety, Quality, and Nutrition
Directive 1999/2/EC	Uni Eropa	Foods and food ingredients that have been treated with ionizing radiation
Council Regulation (Euratom) No 3954/87; No 944/89; No 2218/89; No 770/90; and (EEC) No 2219/89	Uni Eropa	The placement of maximum permitted levels of radioactive contaminants in foodstuffs after a nuclear accident or any other instance of a radiological emergency
U.S. Regulatory Requirements for Irradiating Foods, 1986	The U.S.	The legal requirement for food safety (radiological, toxicological, microbiological, nutritional adequacy) and food labeling, irradiated food packaging
Food and Drug Administration: Irradiation in the Production, Processing, and Handling of Food, 2000	The U.S.	Guidelines for using safe ionizing radiation to reduce microbes in the sample and dose for sample irradiation resulting in slight adjustments in macronutrients
Food and Drug Act, 2008	Canada	Food labeling guidelines for irradiation treatment
Food Irradiation, 2003	Australia and New Zealand	Food irradiation and dose guidelines
Food Additives Guide, 2005	Australia	Guidelines for food additives use

VII. CONCLUSION

Each food ingredient irradiated with a different purpose has an extra dose depending on the food itself's characteristics. The rays commonly used to preserve food products with irradiation are gamma rays, X-rays, and electron beams, each of which has its advantages and disadvantages. Chemical, nutritional, microbiological, and toxicological aspects are used for food irradiation safety parameters. The principle of radiation is excitation, ionization, and changes in components contained in foods when the radiation source touches the material. The irradiation process has advantages and disadvantages, one of which is that the radiation process does not use heat so that food does not change its characteristics. However, the irradiation process is still a public fear of radioactive influence on foodstuffs. Irradiation can be applied to foods by paying attention to the dose according to the foodstuff.

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