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Abstract

The effects of irradiation on meat constituents including water, proteins, and lipids are multifaceted. Irradiation leads to the decomposition of water molecules, resulting in the formation of free radicals that can have both positive and negative effects on meat quality and storage. Although irradiation reduces the number of microorganisms and extends the shelf life of meat by damaging microbial DNA and cell membranes, it can also accelerate the oxidation of lipids and proteins, particularly sulfur-containing amino acids and unsaturated fatty acids. With regard to proteins, irradiation affects both myofibrillar and sarcoplasmic proteins. Myofibrillar proteins, such as actin and myosin, can undergo depolymerization and fragmentation, thereby altering protein solubility and structure. Sarcoplasmic proteins, including myoglobin, undergo structural changes that can alter meat color. Collagen, which is crucial for meat toughness, can undergo an increase in solubility owing to irradiation-induced degradation. The lipid content and composition are also influenced by irradiation, with unsaturated fatty acids being particularly vulnerable to oxidation. This process can lead to changes in the lipid quality and the production of off-odors. However, the effects of irradiation on lipid oxidation may vary depending on factors such as irradiation dose and packaging method. In summary, while irradiation can have beneficial effects, such as microbial reduction and shelf-life extension, it can also lead to changes in meat properties that need to be carefully managed to maintain quality and consumer acceptability.

Keywords: irradiation, meat, moisture, protein, lipid, meat product

Introduction

Advancements in the food industry, such as securing a stable supply of raw materials, hygienic production methods, efficient manufacturing processes, and safe storage and distribution technologies, have led to the production of high value–added products (Matharu et al., 2016). Processes such as heating, refrigeration, and freezing, as well as preservatives and fumigants used in food processing and storage are associated with many problems, such as effectiveness, cost, soundness, and environmental pollution (Amit et al., 2017). As public interest in food safety has increased, these problems have been solved or improved to establish a production base for hygienic foods (Macfarlane, 2002). Thus, irradiation technology was developed to meet the need of new food processing and storage technologies (Pillai and Shayanfar, 2017). In the food industry, irradiation technology is implemented using radioactive isotopes or mechanically generated ionization energy (Ham et al., 2017). It is a technology-intensive field that can be effectively utilized in the sanitization of processed products, safe storage and distribution, and for the improvement of manufacturing processes (Kim et al., 2020).

Irradiation technology is known to be the most efficient way to eliminate pathogenic and spoilage microorganisms without deteriorating the nutritional and organoleptic qualities of food during storage (Kim et al., 2010). Irradiation can be continuously applied without being affected by the temperature, humidity, or pressure of the food sterilization process (Hwang et al., 2021). It is also possible to increase the energy efficiency and sterilize contaminating microorganisms in packaged foods (Lee et al., 2024). Irradiation can prolong the shelf life of food when microbial spoilage is a limiting factor (Hwang et al., 2015). The 1980 FAO/IAEA/WHO joint expert committee on the wholesomeness of irradiated foods (JECFI) concluded that all foods irradiated at doses up to 10 kGy did not pose toxicological hazards or nutritional or microbiological problems (Autio et al., 1990).

The purpose of sanitizing meat using irradiation is to ensure microbiological safety, parasite control, and extension of refrigeration shelf-life (Song et al., 2017). In addition, the application of radiation technology in the manufacture of meat products ensures meat hygiene and safety (Choi et al., 2016). New technologies for maintaining the freshness and sanitization of meat and meat products are being developed using various irradiation technologies; however, these technologies are not widely used in the industry. This is because there is still apprehension among consumers regarding irradiated food products because of their lack of understanding of the mechanism and characteristics of irradiation (Choi et al., 2016). The use of irradiation technology in the food industry requires more scientific research, development, and industrialization foundations for sound development, and it is necessary to establish new technologies that can contribute to food safety and public health improvement.

Therefore, the purpose of this review is to elucidate the mechanism of irradiation technology when used for processing meat. Further, we review technologies that can be used to develop new processes for the irradiation of food products.

The types of radiation and mechanism of irradiation technology

Irradiation is transferring energy from an ionized radioactive material, such as cobalt 60 and cesium 137, to the surface or interior of an objective material in order to change its properties (Jia et al., 2022). There are three types of representative radioactive ray utilized in the foods irradiation: gamma ray, electron beam, and X-ray. Gamma ray is the electromagnetic wave emitted from the radioactive material. It has a high-energy and penetration ability, which can reach a depth of 80 cm (Ahn et al., 2023). The electron beam is the high energy accelerated electron, emitted from the ionized radioactive material. Due to the high energy efficiency of the electron beam, the irradiation speed for the identical dose is considerably fast compared to the other radiation. However, its penetration depth is limited within 10 cm, which is lower than that of gamma rays, due to the difference of nature between particle and wave. The X-ray is an energy spectrum of photons produced by accelerated electrons colliding with a metal target (Bisht et al., 2021). It presents a higher penetration capability than the electron beam, while its energy efficiency is relatively low among the mentioned three main types of radiation.

The electrons ejected from the electron beam can directly ionize the atoms in food. In contrast, the gamma ray and X-ray are electromagnetic waves, which transfer a portion of their energy to the electrons of the atoms in the food (Jia et al., 2022). This excitation of electrons results in their exit from the orbits (Ahn et al., 2023). These electrons continually excite and ionize atoms in food, until the energy remains sufficient to cause these reactions. The entire constituents of irradiated food undergo this process simultaneously and interactively, and it affects the quality properties of food products. Therefore, in this review, we delicately discussed the impact of irradiation on each constituent of meat in order to understand the effect of irradiation on meat products.

Effects of irradiation on the constituents of meat

Water

When food is irradiated, the water molecules in the food are decomposed into free radicals such as hydrogen radicals, aqueous electrons, hydroxyl radicals, and hydrogen peroxide (Jia et al., 2022). These free radicals have both positive and negative effects on meat storage and its physicochemical properties. First, they can affect the physiological functions of microorganisms, thus decreasing the risk of pathogens and thereby extending the shelf life of the meat. Irradiation can directly reduce the number of microorganisms by breaking down DNA structure and denaturing the cell membrane. In addition, highly reactive free radicals produced by the irradiation of water can impair cellular metabolic pathways of the microorganisms (Lung et al., 2015). This extent of this effect usually has a direct relationship with irradiation dose (Jouki, 2013; Kanatt et al., 2005). Free radicals produced via the decomposition of water induce and accelerate the oxidation of lipids and proteins. In particular, sulfur-containing amino acids and unsaturated fatty acids in meat are vulnerable to irradiation, and oxygen-containing conditions accelerate irradiation-induced oxidation (Nam et al., 2017), which is related with the irradiation dose. The type and state of water in meat are also factors in the irradiation effect; therefore, strategies for preventing the deterioration of meat quality due to free radicals should be considered.

Muscle tissue has abundant water, which is classified into three types according to its bonding with the protein structure: bound water, immobilized water, and free water. Water distribution in meat protein structures and its retention can be affected by irradiation. Li et al (Li et al., 2018b) demonstrated using nuclear magnetic resonance (NMR) that free water in the extra-myofibrillar space migrates to the myofibrillar network after 3 kGy gamma ray irradiation. However, irradiation at 5 and 7 kGy showed the opposite effect. Broiler chicken meat irradiated with 5 kGy gamma rays had a higher free water content than non-irradiated meat (Zabielski et al., 1984). The alteration in water content or state may be caused by irradiation-induced structural changes in meat proteins (Rodrigues et al., 2020). Irradiation can also affect water during the drying or freeze-thawing process. Zu et al (Zu et al., 2022) showed that 3.36 kGy gamma ray irradiation can accelerate the loss of bound water and free water during the drying of meat containing more than 40% moisture. However, the irradiated meat which had moisture content less than 40% showed rather higher binding force of those water than non-irradiated meat. Irradiation of frozen beef with 9 kGy gamma rays increased water loss during thawing; however, doses less than 9 kGy did not produce a similar effect (Sales et al., 2020).

Protein

Myofibrillar protein

Myofibrillar proteins are the most abundant fibril proteins in muscles and are composed of myosin, actin, titin, nebulin, tropomyosin, troponin, actinin, desmin, and vinculin. Myosin and actin are the main components that affect protein functionality and meat quality. Actomyosin is a bound form of actin and myosin that negatively affects protein solubility. Irradiation with gamma rays can depolymerize actomyosin molecules (Fujimaki et al., 1961). By determining the peptides below 5 kDa generated after irradiation using LC-MS/MS analysis, it was revealed actin shows higher resistance than myosin to fragmentation by gamma ray irradiation (Zhang et al., 2020). Electron beam irradiation decomposes actin, paramyosin, and myosin heavy chain, with the irradiation dose also being a factor (Lv et al., 2018). Gamma ray irradiation of 2–10 kGy degrades myosin heavy chain, actin, paramyosin, and tropomyosin (Shi et al., 2015). Moreover, the titin and nebulin, which are key proteins to identify the integrity of cytoskeleton proteins, are prone to be degraded by ionized radiation of 2-15 kGy (Horowits et al., 1986). The desmin, another structural protein, in bovine muscle was damaged by 3 and 5 kGy of gamma ray irradiation (Yook et al., 2001). Meanwhile, irradiation with 5 kGy gamma rays reduces the myosin band and generates new high–molecular weight bands on SDS-PAGE (Lee et al., 2000). The observed difference can be attributed to the effect of vacuum packaging of meat, because the aggregation of irradiated protein occurs in the absence of oxygen (Giroux and Lacroix, 1998). In contrast, the presence of oxygen seems to induce the fragmentation of proteins. Gamma-ray irradiation of myofibrillar proteins results in a decrease in total sulfhydryl and free thiol groups with increasing doses (Li et al., 2018b; Lv et al., 2018). This can be because of the formation of disulfide bonds; however, these were also decreased with irradiation (Li et al., 2018a). Thus, it might be resulted from the other oxidative reactions of sulfur-containing amino acids.

By degradation and aggregation, irradiation affects the solubility and tenderness of myofibrillar proteins. It has been reported in previous studies that gamma ray irradiation decreased myofibrillar protein solubility in chicken meat, which correlated with the radiation dose (Choi et al., 2015; Zabielski et al., 1984). However, in contrast, there are also studies reporting that the myofibrillar protein solubility of chicken, lamb, and buffalo increased with gamma ray irradiation, which was positively related to the dose (Kanatt et al., 2015). Moreover, it has been reported that the direct irradiation on myofibrillar proteins increases their solubility (Li et al., 2018a). Among the sources of irradiation, at an identical dose of 5 kGy, electron beams and X-rays resulted in higher protein solubility than gamma rays (Kim et al., 2017). However, when minced pork was irradiated with 10 kGy, gamma rays resulted in the highest myofibrillar protein solubility among those three types of radiation (Kim et al., 2020). Interestingly, although myofibrillar proteins can be fragmented by irradiation, it negatively affected to the myofibrillar protein fragmentation and tenderness during aging, since the irradiation inactivated proteases in meat (Rodrigues et al., 2022). Overall, changes to myofibrillar proteins during irradiation is undeniable; however, the irradiation type and dose, packaging method, species, and type of meat strongly affect the products and solubility of the proteins.

Sarcoplasmic protein

Sarcoplasmic proteins include myoglobin, which is responsible for meat color, and various enzymes, such as glyceraldehyde phosphate dehydrogenase, aldolase, creatine kinase, and phosphorylase (López-Bote, 2017). Among these, a major consideration is the state of myoglobin. Myoglobin is an iron-containing protein, in which the meat color is altered depending on the redox state and reacted compounds on the ligand. Irradiation-induced oxidation can increase metmyoglobin levels (Arshad et al., 2020). Metmyoglobin is a type of myoglobin with water bound at the sixth coordination site of the heme iron. This produces a brown color, which is inappropriate for raw meat. Meanwhile, the redness of raw turkey meat increased after 4.5 kGy electron beam irradiation because it can produce carbon monoxide in meat (Nam and Ahn, 2002). When CO binds to myoglobin, carboxymyoglobin (CO-Mb), which has a red color similar to oxymyoglobin, is produced. Meanwhile, according to the species, muscle type, the amino acids sequence or content of myoglobin can be differ, thus the irradiation on myoglobin can differently influence (Faustman et al., 2023). Truly, the effect of irradiation on color of white meat and red meat is divided, and also the oxygen presence in packaging highly affected (Ahn et al., 2023). The improvement of redness induced by formation of CO-Mb is more pronounced in white meat, and this effect was positively correlated with the radiation dose (Feng et al., 2017). Therefore, it is important to determine the appropriate radiation type and dose, considering its effect on the color of fresh meat color. Regarding internal bonding and structural changes, sarcoplasmic proteins undergo unfolding and nonpolar groups are exposed when meat is irradiated at 3 kGy of gamma-ray (Li et al., 2020). In addition, the emulsion prepared with porcine sarcoplasmic protein increased the carbonyl content and TBARS values compared to the emulsion prepared with myofibrillar protein, due to pro-oxidative effect of iron in myoglobin (Li et al., 2020). However, no changes in the sarcoplasmic proteins were observed on SDS-PAGE after 5 kGy irradiation with electron beam and X-rays (Kim et al., 2018). According to a previous study, ionic and hydrogen bonds are decreased and hydrophobic interactions are increased in sarcoplasmic proteins when meat is irradiated with 7 kGy gamma rays (Li et al., 2018a). Sarcoplasmic proteins irradiated with 7 kGy gamma rays showed increased carbonyl content and decreased total sulfhydryl and free thiol groups because these structural alterations of the protein can induce reactions with products of water radiolysis (Li et al., 2018b).

Collagen

Collagen primarily comprises proline, hydroxyproline, and glycine. It is composed of connective tissue in muscle, such as the epimysium, perimysium, and endomysium. Collagen molecules consist of three peptide chains that usually form a triple-helical structure, which can covalently crosslink. These interactions increase the mechanical strength of collagen (Purslow, 2023); therefore the collagen content in muscle and its solubility strongly affect meat toughness (Hopkins and Ertbjerg, 2023). When irradiation energy is absorbed by meat, collagen molecules are degraded, and collagen solubility increases. Irradiation of the porcine *biceps femoris* muscle with 7 kGy gamma rays completely decomposed the collagen type IV alpha 3 chain, which exists in non-irradiated muscle (Zhang et al., 2020). In addition, irradiation of bovine, chicken, lamb, and buffalo muscle with 9–10 kGy gamma ray significantly increased collagen solubility (Kanatt et al., 2015; Rodrigues et al., 2020). By gamma-ray irradiation of 20-300 kGy on pork rind, collagen solubility was increased according to the dose increase, and obvious degradation was observed by SDS-PAGE (Cho et al., 2006). High-dose gamma-ray irradiation (50 and 500 kGy) breaks the N–C bonds in collagen; thus, it can also result in an increase in solubility, despite the loss of amino acids at a 500 kGy dose (Giroux and Lacroix, 1998). Extremely high-dose gamma ray irradiation (50, 500, and 1000 kGy) reduced collagen content and increased ammonia content (Gauza-Włodarczyk et al., 2017). Unlike gamma irradiation, there is a lack of research on the effects of electron beam or X-ray irradiation on collagen in meat. Electron beam irradiation of beef muscle at doses of 20 and 40 kGy increases collagen solubility (Bailey and Rhodes, 1964). On the contrary, the cross-linking between collagens was enhanced, and collagen gels became stiff by electron beam irradiation of 2 and 100 kGy, rather than inducing the collagen degradation (Chlup et al., 2023). Put together, recent studies demonstrating the effects of irradiation on meat proteins are summarized in Table 1.

Lipid

Meat is a good source of both unsaturated and saturated fatty acids, which are present in neutral lipids and phospholipids (López-Bote, 2017). Phospholipids comprise a relatively small portion of the total lipid in meat (0.5–1%); however, they have a high content of unsaturated fatty acids (USFA) (Giroux and Lacroix, 1998). Polyunsaturated fatty acids in meat, such as linoleic and arachidonic acids, are valuable nutrients in the human diet. Irradiation can induce differences in the qualitative and quantitative characteristics of lipids (Jia et al., 2021). The most vulnerable site for the oxidation of lipids is the USFA double bond. According to Arshad et al. (Arshad et al., 2020), 7 kGy gamma ray irradiation of duck meat decreased USFA content because of the oxidative processes on double bonds initiated by highly reactive radicals. In another study, gamma ray irradiation (1.13–3.17 kGy) decreased polyunsaturated fatty acids in both neutral lipids and phospholipids of beef, regardless of dose (Chen et al., 2007). Moreover, trans-fatty acids, which are isomers of unsaturated fatty acids, can be manufactured by irradiation. Gamma-ray irradiation of ground beef increases the trans-fatty acid content, even at a dose of 1 kGy (Brito et al., 2002; Yılmaz and Geçgel, 2007). However, electron beam irradiation of smoked duck meat up to 4.5 kGy did not affect the trans-fatty acid content (Jo et al., 2018).

Lipids degraded by irradiation produce various volatile compounds that cause characteristic irradiation off-odors. Electron beam irradiation of pork, beef, and turkey at a dose of 3 kGy generate volatile hydrocarbons, such as 1-butane, 1-pentene, 1-hexene, and 1-heptene, and increased thiobarbituric acid reactive substance values (Kim et al., 2002). The irradiation dose mainly affects the amount of lipid radiolysis products, but does not completely alter the radiolysis products (Giroux and Lacroix, 1998). Following the recommendations of the European Committee for Standardization, 2-alkylcylcyclobutanone (2-ACB) chiefly from palmitic acid and hydrocarbons from C_n fatty acids have been used as irradiation markers (EN, 2003; Panseri et al., 2015; Standardization, 2003). Heterocyclic compounds with oxygen can act as odor inducers (Yim et al., 2023). A recent study demonstrated that aldehydes can be used as irradiation markers instead of 2-ACB when both the irradiation dose and fat content in meat are low (Bliznyuk et al., 2022). Similarly, free radicals generated by water irradiation can initiate lipid oxidation (Jia et al., 2022). However, X-ray irradiation (2.5–10 kGy) did not significantly influence lipid oxidation in ground beef (Yim et al., 2023). Furthermore, irradiation in vacuum packaging did not induce lipid oxidation in meat (Nam et al., 2017).

Conclusion

Irradiation effectively reduces microbial contamination and extends the shelf-life of meat by damaging DNA and cell membranes. However, it also triggers various biochemical reactions that affect meat quality. Structural modifications of protein components, including myofibrillar and sarcoplasmic proteins, lead to changes in solubility, fragmentation, and alterations in meat color and texture. Collagen, which is essential for meat toughness, undergoes increased solubility owing to irradiation-induced degradation, further affecting meat quality. The lipid composition is significantly influenced by unsaturated fatty acid oxidation and the production of off-odors. Although irradiation offers benefits for food safety and shelf-life extension, careful consideration of its effects on meat quality is essential. Strategies to mitigate adverse effects, such as optimizing irradiation doses, implementing suitable packaging methods, and monitoring lipid oxidation, are crucial for maintaining the overall quality and consumer acceptance of irradiated meat products.

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Tables

Table 1. Recent studies evaluating effects of irradiation on meat proteins

Sample type	Source of radiation	Radiation dose	Effects	Reference
Myofibrillar protein and sarcoplasmic protein	Gamma ray	3, 5, and 7 kGy	Total sulfhydryl group and free thiol groups decreased with increasing dose in both proteins. Surface charge of myofibrillar protein increased when irradiated with 3 and 5 kGy. Surface charge of sarcoplasmic protein decreased with increasing dose.	(Li et al., 2018a)
Myofibrillar protein and sarcoplasmic protein	Gamma ray	3, 5, and 7 kGy	Disulfide bonds in both proteins were decreased with increasing dose in both proteins. Myofibrillar protein solubility increased with increasing dose. Sarcoplasmic protein solubility decreased after irradiation.	(Li et al., 2018b)
M. biceps femoris muscles from porcine	Gamma ray	3, 5, and 7 kGy	Myosin and collagen were degraded by irradiation, which increase tenderness in a dose-dependent manner.	(Zhang et al., 2020)
Tegillarca granosa meat	Electron beam	1, 3, 5, 7, and 9 kGy	Actin, paramyosin, and myosin heavy chain (MHC) were degraded by irradiation. α-helix content of myofbrillar protein decreased and β-sheet content of myofbrillar protein increased by irradiation. Irradiation of 5 kGy or above induced significant decrease in total SH content and Ca^{2+}-ATPase activity of myofibrillar protein.	(Lv et al., 2018)
Myofibrillar protein from grass carps	Gamma ray	2, 4, 6, 8, and 10 kGy	Emulsifying activity and stability decreased with increasing dose. Surface hydrophobicity increased by irradiation. Total sulfhydryl group and free thiol group decreased with increasing dose.	(Shi et al., 2015)

			MHC was degraded by irradiation.	
Myofibrillar protein from chicken	Gamma ray	3, 7, and 10 kGy	Myofibrillar protein solubility decreased by irradiation to the significantly identical level, regardless of radiation dose.	(Choi et al., 2015)
M. biceps femoris of lamb and buffalo and *M. pectoralis major* of chicken	Gamma ray	2.5, 5, and 10 kGy	Myofibrillar protein solubility, sarcoplasmic protein solubility, and collagen solubility of muscles increased with increasing dose. Redness of muscles increased by irradiation.	(Kanatt et al., 2015)
M. biceps femoris, M. semitendinosus, and *M. semimembranosus* from porcine	Gamma ray, electron beam, X-ray	5 kGy	Redness was decreased by all radiation. Myofibrillar protein solubility and sarcoplasmic protein solubility were decreased by irradiation.	(Kim et al., 2017)
Pork ham	Gamma ray, electron beam, X-ray	10 kGy	Redness of raw meat emulsion irradiated X-ray was increased. Myofibrillar protein solubility was increased and sarcoplasmic protein solubility was decreased by irradiation.	(Kim et al., 2020)
Duck breast	Electron beam	3 and 7 kGy	Metmyoglobin content was increased, and oxymyoglobin content and redness of duck breast meat were decreased by irradiation of 7 kGy electron beam.	(Arshad et al., 2020)
M. semimembranosus from bovine	Electron beam and X-ray	5 kGy	Redness was decreased by irradiation. Sarcoplasmic protein pattern did not change in SDS-PAGE.	(Kim et al., 2018)
M. longissimus lumborum from Nellore bovine	Gamma ray	3, 6, and 9 kGy	Soluble collagen content was increased by irradiation. Metmylglobin content was increased by irradiation with increasing dose.	(Rodrigues et al., 2020)