FSAR 1978 **Food Science of Animal Resources**
Food Sci. Anim. Resour. 2024 July 44(4):779~789
DOI https://doi.org/10.5851/kosfa.2024.e35
pISSN : 2636-0772 eISSN : 2636-0780
http://www.kosfaj.org

REVIEW

The Effect of Irradiation on Meat Products

Yea-Ji Kim[1,2], Ji Yoon Cha[1], Tae-Kyung Kim[1], Jae Hoon Lee[1], Samooel Jung[3], and Yun-Sang Choi[1,*]

[1]Research Group of Food Processing, Korea Food Research Institute, Wanju 55365, Korea
[2]Department of Food Science and Biotechnology of Animal Resources, Konkuk University, Seoul 05029, Korea
[3]Division of Animal and Dairy Science, Chungnam National University, Daejeon 34134, Korea

Received March 14, 2024
Revised April 22, 2024
Accepted April 25, 2024

***Corresponding author** : Yun-Sang Choi
Research Group of Food Processing, Korea Food Research Institute, Wanju 55365, Korea
Tel: +82-63-219-9387
Fax: +82-63-219-9076
E-mail: kcys0517@kfri.re.kr

***ORCID**
Yea-Ji Kim
https://orcid.org/0000-0003-0937-5100
Ji Yoon Cha
https://orcid.org/0000-0002-1694-4343
Tae-Kyung Kim
https://orcid.org/0000-0002-6349-4314
Jae Hoon Lee
https://orcid.org/0000-0002-7440-6842
Samooel Jung
https://orcid.org/0000-0002-8116-188X
Yun-Sang Choi
https://orcid.org/0000-0001-8060-6237

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

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.

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 and the effects on meat constituents when used for processing meat.

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). The 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 (USFA) 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. (2018b) demonstrated using nuclear magnetic resonance 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. (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 liquid chromatography with tandem mass spectrometry 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 sodium dodecyl sulfate–polyacrylamide gel electrophoresis (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 result 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 CIE a* 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 CIE a* 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 thiobarbituric acid reactive substances (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 1,000 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 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

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 myofibrillar protein decreased and β-sheet content of myofibrillar protein increased by irradiation. - Irradiation of 5 kGy or above induced significant decrease in total sulfhydryl 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. - MHC was degraded by irradiation.	Shi et al. (2015)
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. - CIE a* 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	- CIE a* 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	- CIE a* 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 CIE a* 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	- CIE a* 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)

SDS-PAGE, sodium dodecyl sulfate–polyacrylamide gel electrophoresis.

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. (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 USFA, 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 TBARS 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 (European Committee of Standardization, 2003a; European Committee of Standardization, 2003b; Panseri et al., 2015). 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). 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 USFA 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.

Conflicts of Interest

The authors declare no potential conflicts of interest.

Acknowledgements

This research was supported by Main Research Program (E0211200-04) of the Korea Food Research Institute (KFRI) funded by the Ministry of Science and ICT (Korea).

Author Contributions

Conceptualization: Kim YJ, Choi YS. Data curation: Cha JY. Formal analysis: Kim YJ, Choi YS. Methodology: Kim YJ, Choi YS. Validation: Jung S, Choi YS. Investigation: Choi YS. Writing - original draft: Kim YJ, Cha JY, Kim TK, Lee JH, Choi YS. Writing - review & editing: Kim YJ, Cha JY, Kim TK, Lee JH, Jung S, Choi YS.

Ethics Approval

This article does not require IRB/IACUC approval because there are no human and animal participants.

References

Ahn DU, Mendonca A, Feng X. 2023. The storage and preservation of meat: II—Nonthermal technologies. In Lawrie's meat science. 9th ed. Toldrá F (ed). Woodhead, Sawston, UK. pp 245-280.

Amit SK, Uddin MM, Rahman R, Rezwanul Islam SM, Khan MS. 2017. A review on mechanisms and commercial aspects of food preservation and processing. Agric Food Secur 6:1-22.

Arshad MS, Kwon JH, Ahmad RS, Ameer K, Ahmad S, Jo Y. 2020. Influence of E-beam irradiation on microbiological and physicochemical properties and fatty acid profile of frozen duck meat. Food Sci Nutr 8:1020-1029.

Bailey AJ, Rhodes DN. 1964. Treatment of meats with ionising radiations. XI.: Changes in the texture of meat. J Sci Food Agric 15:504-508.

Bisht B, Bhatnagar P, Gururani P, Kumar V, Tomar MS, Sinhmar R, Rathi N, Kumar S. 2021. Food irradiation: Effect of ionizing and non-ionizing radiations on preservation of fruits and vegetables: A review. Trends Food Sci Technol 114:372-385.

Bliznyuk U, Avdyukhina V, Borshchegovskaya P, Bolotnik T, Ipatova V, Nikitina Z, Nikitchenko A, Rodin I, Studenikin F, Chernyaev A, Yurov D. 2022. Effect of electron and X-ray irradiation on microbiological and chemical parameters of chilled turkey. Sci Rep 12:750.

Brito MS, Villavicencio ALCH, Mancini-filho J. 2002. Effects of irradiation on trans fatty acids formation in ground beef. Radiat Phys Chem 63:337-340.

Chen YJ, Zhou GH, Zhu XD, Xu XL, Tang XY, Gao F. 2007. Effect of low dose gamma irradiation on beef quality and fatty acid composition of beef intramuscular lipid. Meat Sci 75:423-431.

Chlup H, Suchý T, Šupová M. 2023. The electron beam induced cross-linking of bovine collagen gels with various concentrations: The mechanical properties and secondary structure. Polymer 287:126423.

Cho YJ, Seo JE, Kim YJ, Lee NH, Hong SP, Kim YH. 2006. Study on the degradation of pigskin collagen using irradiation technique. J Korean Soc Food Sci Nutr 35:588-593.

Choi YS, Kim HW, Hwang KE, Song DH, Jeong TJ, Seo KW, Kim YB, Kim CJ. 2015. Effects of gamma irradiation on physicochemical properties of heat-induced gel prepared with chicken salt-soluble proteins. Radiat Phys Chem 106:16-20.

Choi YS, Sung JM, Jeong TJ, Hwang KE, Song DH, Ham YK, Kim HW, Kim YB, Kim CJ. 2016. Effect of irradiated pork on physicochemical properties of meat emulsions. Radiat Phys Chem 119:279-281.

European Committee of Standardization. 2003a. EN 1784: Foodstuffs – Detection of irradiated food containing fat – gas chromatographic analysis of hydrocarbons. European Committee for Standardization, Brussels, Belgium.

European Committee of Standardization. 2003b. EN 1785: Foodstuffs – Detection of irradiated food containing fat – gas chromatographic/mass spectrometric analysis of 2-alkylcyclobutanones. European Committee for Standardization, Brussels, Belgium.

Faustman C, Suman SP, Ramanathan R. 2023. The eating quality of meat: I Color. In Lawrie's meat science. 9th ed. Toldrá F (ed). Woodhead, Sawston, UK. pp 363-392.

Feng X, Moon SH, Lee HY, Ahn DU. 2017. Effect of irradiation on the parameters that influence quality characteristics of raw turkey breast meat. Radiat Phys Chem 130:40-46.

Fujimaki M, Arakawa N, Ogawa G. 1961. Effects of gamma irradiation on the chemical properties of actin and actomyosin of meats. J Food Sci 26:178-185.

Gauza-Włodarczyk M, Kubisz L, Włodarczyk D. 2017. Amino acid composition in determination of collagen origin and assessment of physical factors effects. Int J Biol Macromol 104:987-991.

Giroux M, Lacroix M. 1998. Nutritional adequacy of irradiated meat: A review. Food Res Int 31:257-264.

Ham YK, Kim HW, Hwang KE, Song DH, Kim YJ, Choi YS, Song BS, Park JH, Kim CJ. 2017. Effects of irradiation source and dose level on quality characteristics of processed meat products. Radiat Phys Chem 130:259-264.

Hopkins DL, Ertbjerg P. 2023. The eating quality of meat: II—Tenderness. In Lawrie's meat science. 9th ed. Toldrá F (ed). Woodhead, Sawston, UK. pp 393-420.

Horowits R, Kempner ES, Bisher ME, Podolsky RJ. 1986. A physiological role for titin and nebulin in skeletal muscle. Nature 323:160-164.

Hwang KE, Ham YK, Song DH, Kim HW, Lee MA, Jeong JY, Choi YS. 2021. Effect of gamma-ray, electron-beam, and X-ray irradiation on antioxidant activity of mugwort extracts. Radiat Phys Chem 186:109476.

Hwang KE, Kim HW, Song DH, Kim YJ, Ham YK, Lee JW, Choi YS, Kim CJ. 2015. Effects of antioxidant combinations on shelf stability of irradiated chicken sausage during storage. Radiat Phys Chem 106:315-319.

Jia W, Shi Q, Shi L. 2021. Effect of irradiation treatment on the lipid composition and nutritional quality of goat meat. Food Chem 351:129295.

Jia W, Wang X, Zhang R, Shi Q, Shi L. 2022. Irradiation role on meat quality induced dynamic molecular transformation: From nutrition to texture. Food Rev Int 39:4442-4464.

Jo Y, An KA, Arshad MS, Kwon JH. 2018. Effects of e-beam irradiation on amino acids, fatty acids, and volatiles of smoked duck meat during storage. Innov Food Sci Emerg Technol 47:101-109.

Jouki M. 2013. Evaluation of gamma irradiation and frozen storage on microbial load and physico-chemical quality of turkey breast meat. Radiat Phys Chem 85:243-245.

Kanatt SR, Chander R, Sharma A. 2005. Effect of radiation processing on the quality of chilled meat products. Meat Sci 69:269-275.

Kanatt SR, Chawla SP, Sharma A. 2015. Effect of radiation processing on meat tenderisation. Radiat Phys Chem 111:1-8.

Kim BH, Kim HJ, Yoon YH, Shin MG, Lee JW. 2010. Comparison of the effects of gamma ray and electron beam irradiation to improve safety of spices for meat processing. Korean J Food Sci Anim Resour 30:124-132.

Kim HW, Kim YHB, Hwang KE, Kim TK, Jeon KH, Kim YB, Choi YS. 2017. Effects of gamma-ray, electron-beam, and X-ray irradiation on physicochemical properties of heat-induced gel prepared with salt-soluble pork protein. Food Sci

Biotechnol 26:955-958.

Kim SY, Yong HI, Nam KC, Jung S, Yim DG, Jo C. 2018. Application of high temperature (14℃) aging of beef *M. semimembranosus* with low-dose electron beam and X-ray irradiation. Meat Sci 136:85-92.

Kim TK, Hwang KE, Ham YK, Kim HW, Paik HD, Kim YB, Choi YS. 2020. Interactions between raw meat irradiated by various kinds of ionizing radiation and transglutaminase treatment in meat emulsion systems. Radiat Phys Chem 166:108452.

Kim YH, Nam KC, Ahn DU. 2002. Volatile profiles, lipid oxidation and sensory characteristics of irradiated meat from different animal species. Meat Sci 61:257-265.

Lee JH, Kim YJ, Choi YJ, Kim TK, Cha JY, Park MK, Jung S, Choi YS. 2024. Effect of gamma-ray and electron-beam irradiation on the structural changes and functional properties of edible insect proteins from *Protaetia brevitarsis* larvae. Food Chem 434:137463.

Lee JW, Yook HS, Lee KH, Kim JH, Kim WJ, Byun MW. 2000. Conformational changes of myosin by gamma irradiation. Radiat Phys Chem 58:271-277.

Li C, He L, Ma S, Wu W, Yang H, Sun X, Peng A, Wang L, Jin G, Zhang J. 2018a. Effect of irradiation modification on conformation and gelation properties of pork myofibrillar and sarcoplasmic protein. Food Hydrocoll 84:181-192.

Li C, Jin G, He L, Xiao C. 2020. Effect of d-glucose on the chemical characteristics and irradiation off-odor performance in porcine meat emulsion system. LWT-Food Sci Technol 133:110138.

Li C, Peng A, He L, Ma S, Wu W, Yang H, Sun X, Zeng Q, Jin G, Zhang J. 2018b. Emulsifying properties development of pork myofibrillar and sacroplasmic protein irradiated at different dose: A combined FT-IR spectroscopy and low-field NMR study. Food Chem 252:108-114.

López-Bote C. 2017. Chemical and biochemical constitution of muscle. In Lawrie´s meat science. 8th ed. Toldrá F (ed). Woodhead, Sawston, UK. pp 99-158.

Lung HM, Cheng YC, Chang YH, Huang HW, Yang BB, Wang CY. 2015. Microbial decontamination of food by electron beam irradiation. Trends Food Sci Technol 44:66-78.

Lv M, Mei K, Zhang H, Xu D, Yang W. 2018. Effects of electron beam irradiation on the biochemical properties and structure of myofibrillar protein from *Tegillarca granosa* meat. Food Chem 254:64-69.

Macfarlane R. 2002. Integrating the consumer interest in food safety: The role of science and other factors. Food Policy 27:65-80.

Matharu AS, de Melo EM, Houghton JA. 2016. Opportunity for high value-added chemicals from food supply chain wastes. Bioresour Technol 215:123-130.

Nam KC, Ahn DU. 2002. Carbon monoxide-heme pigment is responsible for the pink color in irradiated raw turkey breast meat. Meat Sci 60:25-33.

Nam KC, Jo C, Ahn DU. 2017. Irradiation of meat and meat products. In Emerging technologies in meat processing: Production, processing and technology. Cummins EJ, Lyng JG (ed). John Wiley & Sons, Hoboken, NJ, USA. pp 7-36.

Panseri S, Chiesa LM, Biondi PA, Rusconi M, Giacobbo F, Padovani E, Mariani M. 2015. Irradiated ground beef patties: Dose and dose-age estimation by volatile compounds measurement. Food Control 50:521-529.

Pillai SD, Shayanfar S. 2017. Electron beam technology and other irradiation technology applications in the food industry. In Applications of radiation chemistry in the fields of industry, biotechnology and environment. Venturi M, D'Angelantonio M (ed). Springer, Berlin, Germany. pp 249-268.

Purslow PP. 2023. The structure and growth of muscle. In Lawrie's meat science. 9th ed. Toldrá F (ed). Woodhead, Sawston, UK. pp 51-103.

Rodrigues LM, Guimarães AS, de Lima Ramos J, de Almeida Torres Filho R, Fontes PR, de Lemos Souza Ramos A, Ramos EM. 2022. Application of gamma radiation in the beef texture development during accelerated aging. J Texture Stud 53:923-934.

Rodrigues LM, Sales LA, Fontes PR, de Almeida Torres Filho R, Andrade MPD, Ramos ALS, Ramos EM. 2020. Combined effects of gamma irradiation and aging on tenderness and quality of beef from nellore cattle. Food Chem 313:126137.

Sales LA, Rodrigues LM, Silva DRG, Fontes PR, de Almeida Torres Filho R, Ramos ALS, Ramos EM. 2020. Effect of freezing/irradiation/thawing processes and subsequent aging on tenderness, color, and oxidative properties of beef. Meat Sci 163:108078.

Shi Y, Li R, Tu Z, Ma D, Wang H, Huang X, He N. 2015. Effect of *γ*-irradiation on the physicochemical properties and structure of fish myofibrillar proteins. Radiat Phys Chem 109:70-72.

Song DH, Kim HW, Hwang KE, Kim YJ, Ham YK, Choi YS, Shin DJ, Kim TK, Lee JH, Kim CJ, Paik HD. 2017. Impacts of irradiation sources on quality attributes of low-salt sausage during refrigerated storage. Korean J Food Sci Anim Resour 37:698-707.

Yılmaz I, Geçgel U. 2007. Effects of gamma irradiation on *trans* fatty acid composition in ground beef. Food Control 18:635-638.

Yim DG, Kim HJ, Kim SS, Lee HJ, Kim JK, Jo C. 2023. Effects of different X-ray irradiation doses on quality traits and metabolites of marinated ground beef during storage. Radiat Phys Chem 202:110563.

Yook HS, Lee JW, Lee KH, Kim MK, Song C, Byun MW. 2001. Effect of gamma irradiation on the microstructure and post-mortem anaerobic metabolism of bovine muscle. Radiat Phys Chem 61:163-169.

Zabielski J, Kijowski J, Fiszer W, Niewiarowicz A. 1984. The effect of irradiation on technological properties and protein solubility of broiler chicken meat. J Sci Food Agric 35:662-670.

Zhang M, He L, Li C, Yang F, Zhao S, Liang Y, Jin G. 2020. Effects of gamma ray irradiation-induced protein hydrolysis and oxidation on tenderness change of fresh pork during storage. Meat Sci 163:108058.

Zu X, Li H, Xiong G, Liao T, Yu Y, Qiu J. 2022. Gamma irradiation on moisture migration and lipid degradation of micropterus salmoides meat. Radiat Phys Chem 192:109915.