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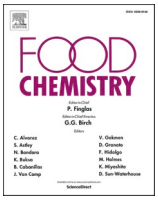

Review

Combination of ionizing radiation and bio-based active packaging for muscle foods: A global systematic review and *meta*-analysis

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ABSTRACT

A systematic review and *meta*-analysis assessed the combined effects of biopolymer-based active packaging and ionizing radiation on muscle foods' quality. Radiation processing of muscle foods reduced the initial counts and growth rates of microbial flora. Irradiation did not affect the initial level of total volatile nitrogen while decreasing its increasing rate during storage. The initial levels and increasing lipid and protein oxidation rates increased after irradiation. Packaging of muscle foods with biopolymer + active compounds before irradiation was the most effective way to decrease microbial flora's initial counts and growth rates. During storage, lower lipid and protein oxidation was found in irradiated muscle foods packed with biopolymer + active compounds. From an industrial standpoint, the packaging of muscle foods with biopolymer + active compounds, particularly plant-based ones, synergistically acts with ionizing radiation to decrease microbial flora counts; therefore, lowering radiation doses can be applied, which minimizes the adverse effects of irradiation on muscle foods.

1. Introduction

Muscle foods are one of the most stapled food sources for many consumers worldwide, rich in high-quality proteins, B-complex vitamins, essential amino acids, minerals, and polyunsaturated fatty acids (Rokni, 2019). Due to the world's ever-growing population and increasing demand for muscle-based foods, more attention has been devoted to producing safe and healthier products in the food supply chain. Muscle foods, however, are highly perishable commodities susceptible to microbial spoilage and oxidative reactions, necessitating effective preservation methods to extend the shelf-life and storage and efficient packaging technologies to postpone quality loss (Belmonte et al., 2021; Umaraw et al., 2020).

In recent decades, food irradiation, as an emerging green technology, has been at the core of several research activities related to food preservation. Food irradiation is a non-thermal food preservation process that includes subjecting a particular product that has already been packed or in bulk to controlled doses of ionizing radiation to eliminate pathogenic microorganisms and shelf-life extension, ultimately contributing to a safer and longer-lasting food supply for human consumption (Indiarto & Qonit, 2020; Jia, Wang, Zhang, Shi, & Shi, 2022; Nematollahi, Alinasab, Nassiri, & Khaneghah, 2020). The common sources of ionizing radiation utilized in food preservation chiefly originate from accelerated electrons (also known as electron beams), X-rays, and Gamma rays, each with its characteristics and set of applications (Indiarto & Qonit, 2020).

The efficiency of food irradiation varies depending on the characteristics of the target food, the type, and condition of the radiation source, the characteristics of the microorganisms, and the radiation intensity. The joint FAO/WHO Codex Alimentarius Commission (1983) has certified applying irradiation dosages of < 10 kGy in foodstuffs; Moreover, the doses < 45 kGy introduces no specific toxicological

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hazard in foods (Roberts, 2016). In this regard, previous studies have demonstrated that low doses of ionizing radiation are hand in hand with a lack of microbial safety and failure in considerable product shelf-life extension (Dini, Fallah, Bonyadian, Abbasvali, & Soleimani, 2020; Fallah et al., 2022; Fallah, Saei-Dehkordi, & Rahnama, 2010). On the other hand, the application of irradiation in higher approved doses is associated with the formation of free radicals that can be oxidized into peroxides, acceleration of lipid oxidation, protein components breakdown, vitamin loss, and the induction of unappealing color, taste, and odor changes (Brewer, 2009). As a result, the simultaneous application of other preservation technologies with radiation is necessary to achieve microbiological safety, extend storage life, and limit the aforementioned adverse effects.

Packaging is of particular importance among the various phases of food processing. Food packaging is generally designed to protect foodstuffs from physical, chemical, and biological threats while extending their shelf life (Moeini, Germann, Malinconico, & Santagata, 2021). Petroleum-based plastics are the most commonly used materials for food packaging owing to their considerable resilience against mechanical pressures, excellent barrier characteristics, cost efficiency, and high mold flexibility. However, plastics are neither biodegradable nor compostable, which results in the pollution of land and water that ultimately endanger human health (Bhargava, Sharanagat, Mor, & Kumar, 2020; Madanayake, Hossain, & Adassooriya, 2021). Over the past decades, these issues have concentrated the food industry's attention on developing sustainable and environmentally friendly packaging materials. A new progressive packaging system known as biopolymer-based active packaging has recently been regarded as a potential replacement for non-biodegradable petroleum-based plastic packaging materials (Moeini et al., 2021).

Active packaging refers to an innovative packaging system in which the food product, incorporated additives, and packaging environment interact positively to enhance the quality, safety, or shelf-life of the foodstuffs (Bashiry et al., 2021; Bhargava et al., 2020; Liu et al., 2021). The critical component of an efficient biopolymer-based active packaging system is its biopolymer type. The common bio-based polymers employed in active packaging systems fall into one of the following principal categories: (*i*) carbohydrate-based, such as chitosan, alginate, starch, pectin, cellulose, and carrageenan; (*ii*) protein-based, such as gelatin, collagen, whey proteins, soy proteins, gluten, and caseinate (Dutta & Sit, 2022; Noonim & Venkatachalam, 2021; Rathod, Bangar, Šimat, & Ozogul, 2022; Yadav et al., 2022). While using proteins to make films has advantages; studies have revealed that the films may be degraded by the enzymes found in muscle-building foods. Additionally, applying protein-based films to foods containing muscle may pose health risks, particularly for those who are allergic to egg, milk, peanut, rice, or soybean proteins (Ballini et al., 2021; Cavazza et al., 2022; Rodríguez-Catalán, González-Arias, Casas, & Camacho, 2021). Aside from the kind of biopolymer employed, the inclusion of appropriate additives (that are released in a controlled manner during food storage) contributes to the higher performance of the desired active packaging systems by boosting food product quality while retaining its nutritional value and organoleptic properties (Bhargava et al., 2020).

The concurrent application of ionizing radiation with active packaging (shown briefly in Fig. 1) can be considered a hurdle technology for food preservation. This combination reduces the irradiation doses to eliminate pathogens and assure food safety (Dini et al., 2020; Jamshidi & Lacroix, 2018). Although earlier research has employed this new trending concept to preserve muscle foods, to the best of our knowledge, no integrative conclusions have been achieved as to whether this technology is beneficial. To address this issue, the current systematic review and *meta*-analysis were conducted to provide insights regarding the combined use of ionizing radiation and biopolymer-based active packaging to preserve muscle foods.

2. Methodology

2.1. The protocol and search strategy

A literature search was conducted on PubMed, Scopus, ISI Web of Science, and Scientific Information Database (SID) from inception to 28 April 2022. The following combination of keywords was applied for searching: ("ionizing radiation" OR "radiation" OR "irradiation" OR "gamma-ray" OR "γ-irradiation" OR "electron beam" OR "X-ray") AND

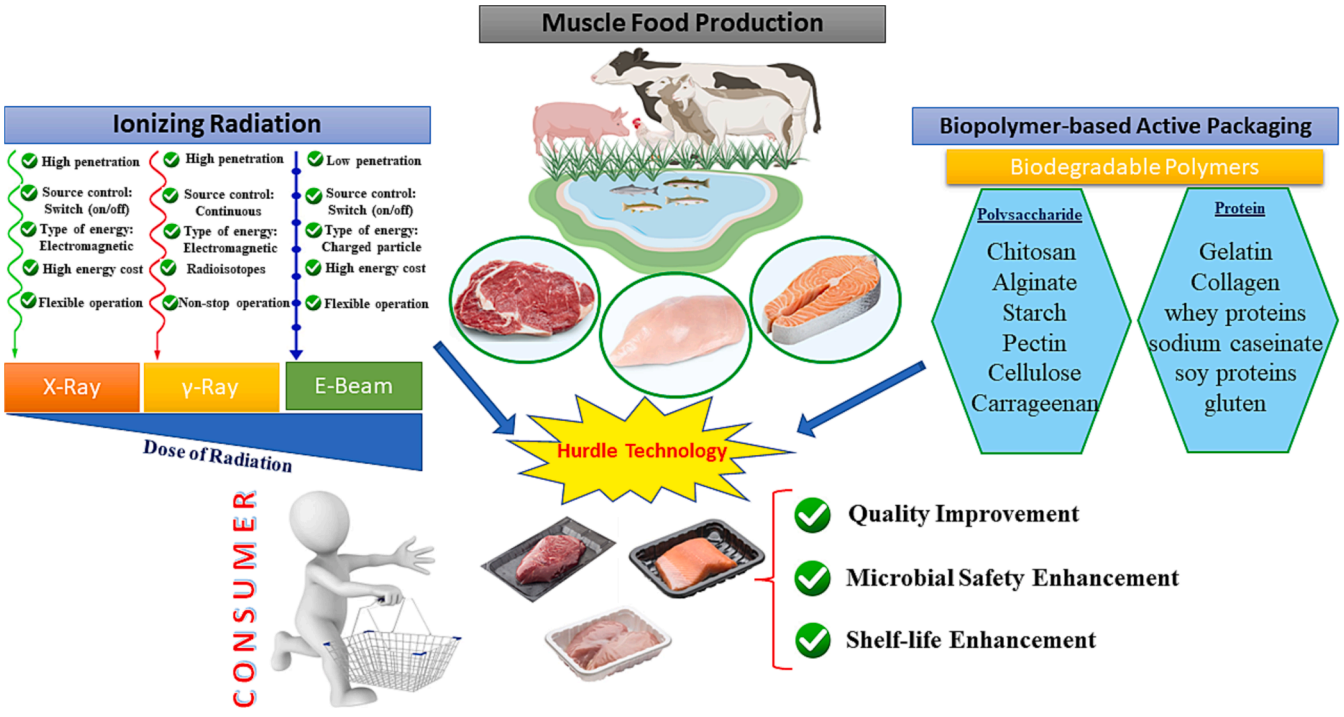

Fig. 1. The concurrent application of ionizing radiation with biopolymer-based active packaging for the preservation of muscle foods.

("active packaging" OR "coating" OR "film" OR "composite film" OR "biodegradable" OR "edible packaging" OR "biopolymer") AND ("muscle food" OR "muscle foods" OR "meat" OR "lamb" OR "beef" OR "goat" OR "pork" OR "broiler" OR "chicken" OR "poultry" OR "turkey" OR "duck" OR "quail" OR "sausage" OR "seafood" OR "seafoods" OR "fish" OR "shrimp" OR "prawn"). A manual search of the references of relevant review articles and eligible research articles was carried out to retrieve the missing articles.

2.2. Study qualification

Studies were selected based on eligibility criteria as follows: (*a*) Studies that investigate the combined effect of biopolymer-based active packaging and ionizing radiation for preserving muscle foods; (*b*) The experimental design of the studies included control (untreated) and irradiated muscle foods alone and combined with biopolymer-based active packaging; (*c*) Studies reported the mean and variance at the initial stage and after storage time for total mesophilic bacteria (TMB), total psychrophilic bacteria (TSB), *Enterobacteriaceae* (ENB), lactic acid bacteria (LAB), total volatile nitrogen (TVN), thiobarbituric acid reactive substances (TBARS), or protein carbonyls.

2.3. Data collection

The extracted data from selected studies included the first author's surname, year of publication, kind of ionizing radiation and its dose, type of biopolymer used as active packaging, type of bioactive compound and its concentration, type of muscle food, storage duration, and temperature, mean and variance of microbial and chemical indices at the initial stage and end of the storage time, and the number of replicates. The GetData Graph Digitizer software version 2.26.0.20 was used to extract the numeric data from studies with the graphical format of data. Three authors (ES, TJ, and AAF) separately screened the studies based on the inclusion criteria to select the eligible studies and also extracted the data from the selected studies. The conflicts were discussed within the study team to reach a consensus.

2.4. Statistical analysis

In this study, we designed two *meta*-analysis approaches. The first approach was developed to assess the immediate impact of irradiation alone and in combination with active packaging on the microbial and chemical quality of muscle foods; and the second approach was developed to evaluate the effect of ionizing radiation alone and combined with active packaging on the microbial and chemical quality of muscle foods during the storage period. A response ratio (R) was computed for both approaches (Borenstein, Hedges, Higgins, & Rothstein, 2021; Fallah, Sarmast, Jafari, & Mousavi Khaneghah, 2022; Sarmast, Fallah, Jafari, & Mousavi Khaneghah, 2021).

Considering the immediate effects of the treatments, R and its variance were estimated from the initial values of control and treatment groups (irradiation and irradiation + active packaging) for each of the microbial and chemical parameters by the following equation:

$$R = \frac{X_{initial(treatment)}}{X_{initial(control)}} \quad (1)$$

$X_{initial\ (control)}$ and $X_{initial\ (treatment)}$ are the initial values of the control and treatment groups, respectively. Afterward, the R was converted to a natural logarithm (L) in order to normalize its distribution:

$$L = \ln(R) \quad (2)$$

The variance for L (V_{lnR}) was estimated by the following equation:

$$V_{lnR} = \left(SD_{pooled}\right)^2 \times \left(\frac{1}{(n_{control} \times X^2_{initial(control)})} + \frac{1}{(n_{treatment} \times X^2_{initial(treatment)})}\right) \quad (3)$$

The approximate standard error was calculated as

$$SE_{lnR} = \sqrt{V_{lnR}} \quad (4)$$

The overall L was calculated using the random-effects model because of the variation in the design of the included studies. The L value of each study gained weight based on the random-effects model and the individual experiment variance. In the last step, the weighted overall L (L^*) was transformed to weighted overall R (R^*) as

$$R^* = \exp(L^*) \quad (5)$$

Considering the impacts of the treatments during the storage period, the mean change (X_{change}) for each microbial and chemical parameter was estimated as follows:

$$X_{change} = X_{end} - X_{initial} \quad (6)$$

X_{end} is the mean value at the end of the storage period, and $X_{initial}$ is the mean value at the initial time of the experiments for the control or treatment groups. The standard deviation of the mean change (SD_{change}) in the control or treatment group was estimated by the following equation:

$$SD_{change} = \sqrt{[(SD_{initial})^2 + (SD_{end})^2] - [(2r \times SD_{initial} \times SD_{end})]} \quad (7)$$

Herein, $SD_{initial}$ signifies the standard deviations of the mean at the initial time of the experiment, SD_{end} represents the standard deviations of the mean at the end of the storage time, and r is the correlation coefficient, assumed as $r = 0.5$ (Fallah, Sarmast, Fatehi, & Jafari, 2020; Fallah, Sarmast, & Jafari, 2020; Sarmast et al., 2021).

For each microbial or chemical parameter, R was calculated from the mean changes (X_{change}) by the following equation:

$$R = \frac{X_{change(treatment)}}{X_{change(control)}} \quad (8)$$

$X_{change(control)}$ and $X_{change(treatment)}$ are the mean changes in the control and treatment groups, respectively. In order to estimate the L, V_{lnR}, SE_{lnR}, and R^*, the equations mentioned above of 2, 3, 4, and 5 were employed, respectively.

The evidence of heterogeneity among the included studies was evaluated by Cochran's Q test, while the amount of heterogeneity was assessed by I-squared (I^2) index. The $P \leq 0.05$ for Cochran's Q test indicates the presence of heterogeneity, and $I^2 > 50\%$ demonstrates high heterogeneity among the studies (Higgins et al., 2019).

The subgroup analyses were conducted based on the kind of muscle food (red meat, chicken, and seafood), irradiation dose ($\leq$ 2.5 kGy and $>$ 2.5 kGy), and type of active packaging (without active packaging, biopolymer packaging, and biopolymer + active compound packaging). Begg and Mazumdar adjusted the rank correlation test (Begg & Mazumdar, 1994; Jafari, Rostampour, Fallah, & Hesami, 2017) and Egger's regression asymmetry test (Egger, Smith, Schneider, & Minder, 1997; Jafari, Feizi, Askari, & Fallah, 2015) were employed to assess the potential publication bias. meta-analysis was carried out using Stata software ver. 11.2 (Stata Corp., College Station, TX) and $P \leq 0.050$ were considered significant values.

3. Results and discussion

3.1. Selection of process of studies

The study selection process to identify relevant articles is depicted in Fig. 2. Among the total of 5815 records, 955 were duplicates and

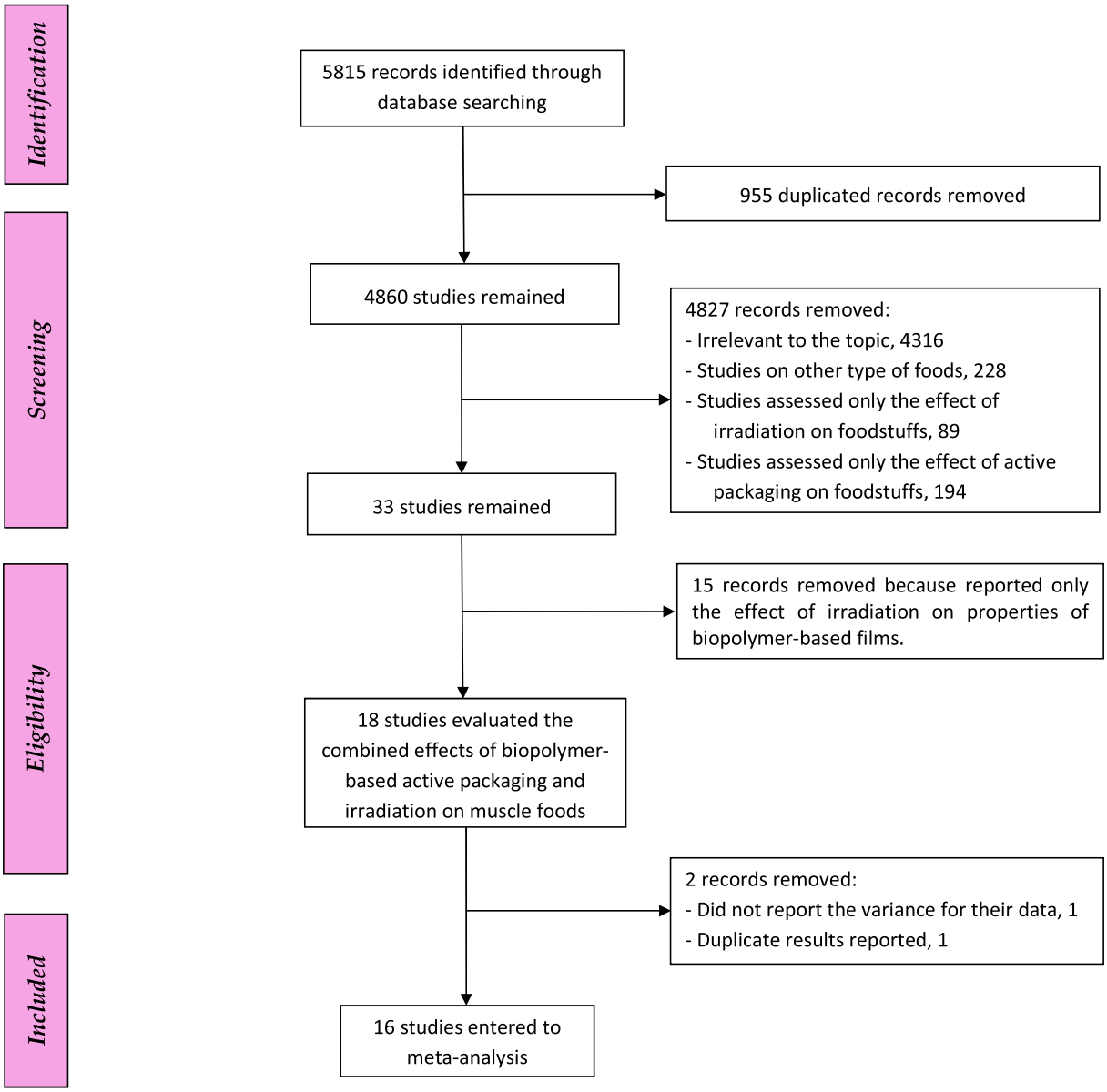

Fig. 2. Flow diagram of study selection.

removed. After further assessment, 4827 records were omitted due to being irrelevant to the topic (4316 records), examining other sorts of foodstuffs rather than muscle foods (228 records), assessing the effect of irradiation (89 records) or active packaging (194 records) separately. From the 33 remaining studies, 15 were excluded because of reporting the effect of irradiation on the characteristics of biopolymer-based films. Following a thorough investigation of 18 remaining studies that evaluated the combined effects of biopolymer-based active packaging and ionizing radiation on muscle foods, 2 studies were removed because one did not disclose the variance for their data, and the other reported identical results. Finally, 16 articles (Abdeldaiem, Mohammad, & Ramadan, 2018; Dini et al., 2020; Fallah et al., 2022; Hassanzadeh et al., 2011, 2017; Kakatkar, Gautam, & Shashidhar, 2017; Kanatt, Chander, & Sharma, 2004; Kang et al., 2007; Lacroix, Ouattara, Saucier, Giroux, & Smoragiewicz, 2004; Nortjé, Buys, & Minnaar, 2006; Ouattara, Giroux, Smoragiewicz, Saucier, & Lacroix, 2002; Ouattara, Sabato, & Lacroix, 2001; Rao, Chander, & Sharma, 2005; Shahhosseini, Hosseini, & Ziyaei, 2019; Shankar, Danneels, & Lacroix, 2019; Zhang et al., 2017) that followed the inclusion criteria were selected for systematic review and *meta*-analyses.

The characteristics of the selected studies are demonstrated in Table 1. The muscle foods applied in the eligible studies included beef (4 studies), lamb (3 studies), pork (2 studies), chicken (2 studies), fish fillets or steaks (5 studies), and shrimp (1 study). The biopolymers used as active packaging in the eligible studies were varied: chitosan (6 studies), calcium caseinate + whey protein isolate (3 studies), sodium alginate (1 study), pectin (2 studies), soy protein isolate + whey protein isolate (1 study), fish proteins (1 study), calcium caseinate (1 study), and basil seed gum (1 study). Most of the studies (11 studies) combined plant-based bioactive compounds such as thyme essential oil, *trans* cinnamaldehyde, mixed spices (thyme, rosemary, and sage), grape seed extract, green tea leaf extract, nanoemulsions of cumin and ajowan essential oils, citrus extract, rose polyphenols, rosemary essential oil, curcumin nanoparticles, and marjoram extract in their active packaging; and 1 study used nisin. The active packaging methods immersed muscle food models in coating solutions (12 studies) or wrapped the samples in the prepared films (4 studies). All the eligible studies used Gamma rays for radiation processing of muscle foods at doses between 1 and 5 kGy.

Table 1
Characteristics of studies used in *meta*-analyses.

Study	Muscle food	Packaging biopolymer	Bioactive compound	Active packaging method	Type of ionizing radiation	Irradiation dose (kGy)	Storage time (days)	Storage temperature (°C)	Studied parameters
Ouattara et al. (2001)	Pre-cooked shrimp	Soy protein isolate + whey protein isolate	Thyme essential oil and *trans* cinnamaldehyde	Film	Gamma	3	21	4 ± 1	TMB
Ouattara et al. (2002)	Ground beef	Calcium caseinate + whey protein isolate	Mixed spice powder (thyme, rosemary, and sage)	Film	Gamma	1, 2, 3	10	4 ± 2	TMB, ENB, LAB, TBARS, PCs
Kanatt et al. (2004)	Lamb (leg and rib)	Chitosan	–	Coating	Gamma	2.5, 5	7	0–3	TBARS
Lacroix et al. (2004)	Ground beef	Calcium caseinate + whey protein isolate	Mixed spice powder (thyme, rosemary, and sage)	Film	Gamma	1, 2, 3	10	4 ± 2	TMB, TBARS, PCs
Rao et al. (2005)	Mutton kebab, Bacon	Chitosan	–	Coating	Gamma	4	28	Ambient temperature	TBARS
Nortje et al. (2006)	Beef	Casein + whey protein isolate	–	Coating	Gamma	4	3	4	TMB
Kang et al. (2007)	Pork patty	Pectin	Green tea leaf extract	Coating	Gamma	3	14	10	TMB, TBARS
Hassanzadeh et al. (2011)	Chicken	Chitosan	–	Coating	Gamma	2.5	21	4	TMB, TSB, TBARS
Hassanzadeh et al. (2017)	Chicken	Chitosan	Grape seed extract	Coating	Gamma	2.5	21	4	TMB, TSB, TBARS
Kakatkar et al. (2017)	Seer fish steak	Fish proteins	Nisin	Coating	Gamma	2, 5	42	4	TMB, TVN, TBARS
Zhang et al. (2017)	Carp fillet	Chitosan	Rose polyphenols	Coating	Gamma	3	2.5	4	TMB, TSB, TBARS
Abdeldaiem et al. (2018)	Silver carp fillet	Calcium caseinate	Rosemary essential oil	Coating	Gamma	1, 3, 5	27	4 ± 1	TMB, TSB, ENB, LAB, TVN, TBARS
Shahhosseini et al. (2019)	Ship sturgeon fillet	Basil seed gum	Marjoram extract	Coating	Gamma	3, 4	25	4	TMB, TSB, ENB
Shankar et al. (2019)	*Merluccius* sp. fillet	Sodium alginate	Mixture of essential oils and citrus extract	Coating	Gamma	1	28	4	TMB
Dini et al. (2020)	Beef loin	Chitosan	Cumin essential oil nanoemulsion	Film	Gamma	2.5	21	4 ± 0.2	TMB, TSB, ENB, LAB, TVN, TBARS, PCs
Fallah et al. (2022)	Lamb loin	Pectin	Curcumin nanoparticles, ajowan essential oil nanoemulsion	Coating	Gamma	2	25	3 ± 1	TMB, TSB, ENB, LAB, TVN, TBARS, PCs

Abbreviations: TMB, total mesophilic bacteria; TSB, total psychrophilic bacteria; ENB, *Enterobacteriaceae*; LAB, lactic acid bacteria; TVN, total volatile nitrogen; TBARS, thiobarbituric acid reactive substances; PCs, protein carbonyls.

3.2. Microbial flora

Microbial spoilage is considered the leading cause of quality deterioration in various muscle food products. Microbial growth causes alterations in the physicochemical properties of muscle foods and makes them undesirable and unacceptable for consumers. Since the shelf-life enhancement of muscle food products is essential for the sustainable development of society, the retarding or preventing of microbial growth to enhance the products' shelf-life is critical (Rokni, 2019; Ullah et al., 2022).

The overall results of this *meta*-analysis showed that radiation processing of muscle foods significantly decreased the initial counts of microbial flora including TMB, TSB, ENB, and LAB by 57.8% ($R^* = 0.422$), 49.3% ($R^* = 0.507$), 60.2% ($R^* = 0.398$), and 16.7% ($R^* = 0.833$), respectively (Table 2a). Moreover, irradiation caused significant reductions of 53.7% ($R^* = 0.463$), 36.6% ($R^* = 0.634$), 77.9% ($R^* = 0.221$), and 30.9% ($R^* = 0.691$) in the TMB, TSB, ENB, and LAB counts of muscle foods during storage period (Table 2b). The detrimental effect of ionizing radiation on microorganisms can be related to the function of multiple electrons and ions, known as ionizing energy's direct and indirect impact on modifying or damaging the essential components of microbial cells. Chromosomal DNA can be a direct target for ionizing radiation, which loses its functionality due to exposure to irradiation. In another mechanism, the ionizing of water molecules results in the formation of reactive hydroxyl radicals, which can damage the DNA of microorganisms, cause base modification, break the DNA strand, and eventually lead to microbial cell death (Ji, Allahdad, Sarmast, Salmieri, & Lacroix, 2022; Odueke, Farag, Baines, & Chadd, 2016). It was found that ENB was the most sensitive, while LAB was the most resistant bacteria to ionizing radiation. Our result is consistent with the previous studies performed on muscle food products (Chouliara, Badeka, Savvaidis, & Kontominas, 2008; Dini et al., 2020; Fallah, Saei-Dehkordi, & Rahnama, 2010; Fallah, Tajik, Razavi Rohani, & Rahnama, 2008). It has been reported that LAB could preserve their structure and cell membrane integrity even after gamma irradiation (Porfiri et al., 2022). A study by Beauchamp and Lacroix (2012) revealed that the genome of *Listeria monocytogenes* is more resistant to Gamma irradiation than that of *Escherichia coli*.

Variation in radiosensitivity among the different microorganisms has been explained in the literature. Several intrinsic and extrinsic factors influence the intensity of radiation-induced damage, the amount and kind of damage, and the radiosensitivity of microorganisms. These

Table 2a
Effect of irradiation on the initial microbial flora of active packaged muscle foods.

Subgroup	Total mesophilic bacteria			Total psychrophilic bacteria			*Enterobacteriaceae*			Lactic acid bacteria		
	No[a]	*R** (95% CI)	*P* value	No[a]	*R** (95% CI)	*P* value	No[a]	*R** (95% CI)	*P* value	No[a]	*R** (95% CI)	*P* value
Product type												
Red meat	22	0.400 (0.334, 0.478)	<0.001	8	0.556 (0.532, 0.581)	<0.001	14	0.367 (0.343, 0.391)	<0.001	14	0.880 (0.865, 0.924)	<0.001
Seafood	21	0.414 (0.346, 0.479)	<0.001	11	0.494 (0.301, 0.718)	<0.001	7	0.419 (0.352, 0.498)	<0.001	3	0.814 (0.610, 0.903)	0.003
Chicken	5	0.471 (0.445, 0.499)	<0.001	5	0.552 (0.500, 0.610)	<0.001	0	–	–	0	–	–
Radiation dose												
≤ 2.5 kGy	22	0.512 (0.453, 0.580)	<0.001	14	0.667 (0.653, 0.700)	<0.001	13	0.548 (0.440, 0.682)	<0.001	13	0.882 (0.844, 1.018)	0.069
> 2.5 kGy	26	0.354 (0.292, 0.430)	<0.001	10	0.313 (0.202, 0.485)	<0.001	8	0.335 (0.316, 0.355)	<0.001	4	0.624 (0.464, 0.889)	<0.001
AP type												
Without AP	14	0.483 (0.347, 0.597)	<0.001	5	0.651 (0.575, 0.736)	<0.001	5	0.425 (0.349, 0.516)	<0.001	5	0.895 (0.861, 1.014)	0.058
Biopolymer	10	0.435 (0.368, 0.514)	<0.001	5	0.686 (0.641, 0.733)	<0.001	3	0.406 (0.314, 0.484)	<0.001	2	0.862 (0.741, 1.009)	0.055
Biopolymer + AC	24	0.335 (0.268, 0.522)	<0.001	14	0.390 (0.302, 0.503)	<0.001	13	0.273 (0.245, 0.366)	<0.001	10	0.743 (0.682, 0.860)	<0.001
Overall estimate	48	0.422 (0.371, 0.478)	<0.001	24	0.507 (0.438, 0.586)	<0.001	21	0.398 (0.347, 0.470)	<0.001	17	0.833 (0.781, 0.887)	<0.001

*Abbreviations: R**, weighted overall response ratio; CI, confidence interval; AP, active packaging; AC, active compounds.
[a] Number of trials.

Table 2b
Effect of irradiation on the microbial flora growth rate of active packaged muscle foods during storage period.

Subgroup	Total mesophilic bacteria			Total psychrophilic bacteria			*Enterobacteriaceae*			Lactic acid bacteria		
	No[a]	*R** (95% CI)	*P* value	No[a]	*R** (95% CI)	*P* value	No[a]	*R** (95% CI)	*P* value	No[a]	*R** (95% CI)	*P* value
Product type												
Red meat	26	0.513 (0.449, 0.586)	<0.001	8	0.643 (0.531, 0.778)	<0.001	8	0.215 (0.132, 0.353)	<0.001	8	0.691 (0.577, 0.826)	<0.001
Seafood	20	0.415 (0.360, 0.478)	<0.001	11	0.662 (0.509, 0.860)	0.002	7	0.233 (0.156, 0.349)	<0.001	3	0.692 (0.452, 0.976)	0.044
Chicken	5	0.512 (0.486, 0.584)	<0.001	5	0.583 (0.542, 0.626)	<0.001	0	–	–	0	–	–
Radiation dose												
≤ 2.5 kGy	26	0.540 (0.474, 0.616)	<0.001	14	0.691 (0.604, 0.790)	<0.001	9	0.273 (0.172, 0.432)	<0.001	9	0.778 (0.592, 1.040)	0.088
> 2.5 kGy	25	0.414 (0.359, 0.478)	<0.001	10	0.585 (0.447, 0.766)	0.002	6	0.166 (0.131, 0.283)	<0.001	2	0.569 (0.318, 0.983)	0.037
AP type												
Without AP	15	0.509 (0.406, 0.613)	<0.001	5	0.725 (0.541, 0.881)	0.005	2	0.255 (0.176, 0.369)	<0.001	2	0.836 (0.623, 1.122)	0.233
Biopolymer	9	0.506 (0.382, 0.670)	<0.001	5	0.697 (0.584, 0.831)	<0.001	2	0.278 (0.191, 0.430)	<0.001	2	0.826 (0.561, 1.214)	0.330
Biopolymer + AC	27	0.399 (0.347, 0.509)	<0.001	14	0.543 (0.394, 0.742)	0.001	11	0.135 (0.098, 0.184)	<0.001	7	0.600 (0.506, 0.711)	<0.001
Overall estimate	51	0.463 (0.409, 0.524)	<0.001	24	0.634 (0.550, 0.711)	<0.001	15	0.221 (0.157, 0.312)	<0.001	11	0.691 (0.581, 0.815)	<0.001

*Abbreviations: R**, weighted overall response ratio; CI, confidence interval; AP, active packaging; AC, active compounds.
[a] Number of trials.

factors are species and strains of the organisms, genome size, growth stage, oxygen and antioxidant concentrations, temperature, water availability, and post-irradiation storage conditions. In addition, some inherent characteristics, such as chemical and physical structure, as well as the repair process of damaged DNA, determines the differences in the handling of radiation in sensitive and resistant microorganisms (Hussain, Weng, & Munawar, 2022; Shuryak, 2019). The enhanced antibacterial impact of irradiation could be achieved in the presence of O_2, which can synthesize other radicals like proxies and superoxide. As mentioned earlier, radicals formed through ionizing radiation indirectly affect microorganisms. One of the critical factors in determining the effective dose of irradiation for eliminating the microorganisms in food is the nature of the food system. Hence, different components in the food matrix, such as alcohols, proteins, carbohydrates, and sulfhydryl-rich compounds, can interact with the free radicals, act as a protective substance for microorganisms from the damaging impact, and increase their radioresistance. In addition, some radical scavenger compounds in the food matrix can remove or deactivate the produced radicals and protect

against possible damage to bacterial cells. It has been claimed that meat with a high content of antioxidants may have a detrimental effect on the antibacterial action of ionizing radiation due to the radicals being neutralized (Shuryak, 2019; Verde, 2018).

The results of subgroup analysis based on muscle food type showed that ionizing radiation significantly decreased the initial counts of microbial flora in all kinds of muscle food products. The decreasing rates of TMB, TSB, ENB, and LAB were 60% ($R^* = 0.400$), 44.4% ($R^* = 0.556$), 63.3% ($R^* = 0.367$), and 12% ($R^* = 0.880$) in red meat, 58.6% ($R^* = 0.414$), 50.6% ($R^* = 0.494$), 58.1% ($R^* = 0.419$), and 18.6% ($R^* = 0.814$) in seafood, and 52.9% ($R^* = 0.471$) and 44.8% ($R^* = 0.552$) in chicken, respectively (Table 2a). Moreover, irradiation significantly decreased the growth rates of TMB, TSB, ENB, and LAB by 48.7% ($R^* = 0.513$), 35.7% ($R^* = 0.643$), 78.5% ($R^* = 0.215$), and 30.9% ($R^* = 0.691$) in red meat, 58.5% ($R^* = 0.415$), 33.8% ($R^* = 0.662$), 76.7% ($R^* = 0.233$), and 30.8% ($R^* = 0.692$) in seafood, and 48.8% ($R^* = 0.512$) and 41.7% ($R^* = 0.583$) in chicken during storage period, respectively (Table 2b). Our results indicated no considerable difference in the initial counts and growth rates of a specific microbial flora among the various muscle foods. It has been determined that intrinsic factors such as count and type of spoilage microflora, pH, and proximate composition, which differ depending on the muscle food type, may affect the impact of an antimicrobial process on the initial count and growth rate of microbial flora in muscle foods during storage (Fallah et al., 2022; Lee, Park, & Kang, 2021; Rokni, 2019). Future surveys may illuminate the impact of different intrinsic factors on microbial flora's initial count and growth rate in various irradiated muscle food products during storage.

Our subgroup analysis revealed that both low-dose ($\leq$ 2.5 kGy) and high-dose ($>$ 2.5 kGy) radiation processing of muscle foods significantly decreased the initial counts of TMB, TSB, and ENB by 48.8% ($R^* = 0.512$), 33.3% ($R^* = 0.667$), and 45.2% ($R^* = 0.548$) for low-dose and 64.6% ($R^* = 0.354$), 68.7% ($R^* = 0.313$), and 66.5% ($R^* = 0.335$) for high-dose irradiation, respectively. The reduction (11.8%, $R^* = 0.882$) of initial LAB count in low-dose irradiated muscle foods was not significant, while this reduction (35.8%, $R^* = 0.642$) was significant in high-dose irradiated ones (Table 2a). However, the initial counts of TMB, TSB, ENB, and LAB were 1.32, 2.06, 1.47, and 3.03 times higher in muscle foods treated with low-dose compared to those treated with high-dose irradiation. It was found that the growth rates of TMB, TSB, and ENB significantly decreased by 46% ($R^* = 0.540$), 30.9% ($R^* = 0.691$), and 72.7% ($R^* = 0.273$) in low-dose ($\leq$ 2.5 kGy) and 58.6% ($R^* = 0.414$), 41.5% ($R^* = 0.585$), and 83.4% ($R^* = 0.166$) in high-dose ($>$ 2.5 kGy) irradiated muscle foods during storage period, respectively. A non-significant decrease of 22.2% ($R^* = 0.778$) was found in the LAB growth rate of the low-dose irradiated muscle foods. In comparison, a significant reduction of 43.1% ($R^* = 0.569$) was detected for high-dose irradiated ones (Table 2b). The results demonstrated 1.27, 1.34, 1.15, and 1.94 times higher growth rates in TMB, TSB, ENB, and LAB during storage of muscle foods treated with low-dose compared to those treated with high-dose irradiation. The irradiation dose is another influential parameter in eliminating microorganisms. In general, at high dose rates, microorganisms are more likely to be inactivated, which might be related to bacteria's inability to repair damage caused by ionizing radiation. On the contrary, bacteria exposed to low-dose irradiation are more successful in repairing themselves (Verde, 2018).

The subgroup analysis based on active packaging type demonstrated that irradiation significantly decreased the initial counts of TMB, TSB, and ENB by 51.7% ($R^* = 0.483$), 34.9% ($R^* = 0.651$), and 57.5% ($R^* = 0.425$) for without active packaging, 56.5% ($R^* = 0.435$), 31.4% ($R^* = 0.686$), and 59.4% ($R^* = 0.406$) for biopolymer packaging, and 66.5% ($R^* = 0.335$), 61% ($R^* = 0.390$), and 72.7% ($R^* = 0.273$) for biopolymer + active compounds packaging, respectively. The non-significant reductions were found in the initial LAB count after radiation processing of muscle foods without active packaging (10.5%, $R^* = 0.895$) and with biopolymer packaging (13.8%, $R^* = 0.862$). In comparison, the initial LAB count reduction (25.7%, $R^* = 0.743$) after radiation processing of muscle foods packed with biopolymer + active compounds was significant (Table 2a). Moreover, the significant reductions in the growth rates of TMB, TSB, and ENB of muscle foods during storage time were 49.1% ($R^* = 0.509$), 27.5% ($R^* = 0.725$), and 74.5% ($R^* = 0.255$) for without active packaging, 49.4% ($R^* = 0.506$), 30.3% ($R^* = 0.697$), and 72.2% ($R^* = 0.278$) for biopolymer packaging, and 60.1% ($R^* = 0.399$), 45.7% ($R^* = 0.543$), and 86.5% ($R^* = 0.135$) for biopolymer + active compounds packaging, respectively. The non-significant reductions were found in the growth rate of LAB during storage time in irradiated muscle foods without active packaging (16.4%, $R^* = 0.836$) and with biopolymer packaging (17.4%, $R^* = 0.826$), while a significant reduction (40%, $R^* = 0.600$) was detected in irradiated ones packed with biopolymer + active compounds (Table 2b). The studies eligible for this *meta*-analysis used the biopolymers such as whey protein isolate, calcium caseinate, soy protein isolate, chitosan, pectin, alginate, and basil seed gum for packaging of muscle foods; among them, chitosan that used by six eligible studies (Dini et al., 2020; Hassanzadeh et al., 2011, 2017; Kanatt et al., 2004; Rao et al., 2005; Zhang et al., 2017) had antimicrobial activity, and the others had no considerable antimicrobial effects. The antimicrobial activity of chitosan is mostly due to the positive charge, which can interact with the negative charge of the microbial cell membrane. This electronegative interaction alters membrane permeability, stimulates the imbalance of internal osmosis, and eventually inhibits microbial growth. Besides, chitosan can hydrolyze the peptidoglycan parts of the bacterial membrane, which leads to the leakage of cell contents such as proteins, electrolytes, and nucleic acids (Ke, Deng, Chuang, & Lin, 2021). However, no substantial difference was found in the initial counts and growth rates of a specific type of microflora between the irradiated muscle foods without active packaging and those packed with biopolymers. It was found that the packaging containing biopolymer + active compounds was more efficient than without active packaging and with biopolymer packaging in decreasing the initial counts and growth rates of microbial flora. Our result demonstrated approximately 1.2, 1.9, 1.3, and 2 times lower initial counts and 1.2, 1.6, 1.2, and 2.3 times lower growth rates in TMB, TSB, ENB, and LAB of irradiated muscle food samples packed with biopolymer + active compounds than those without active packaging and with biopolymer packaging, respectively. Most studies eligible for this *meta*-analysis added plant-based products, such as essential oils or extracts, as active compounds, to the biopolymers before packaging muscle foods. The phenolic and flavonoid compounds in plant extracts and essential oils interact with lipid bilayers and cause segregation of the bacterial cell wall, formation of pores in the membrane, leaking of essential electrolytes, and eventually cell lysis. Also, other alterations in the integrity of cell membranes may cause by essential oils are changes in electrical charge and polarity, permeability, and delocalizing of the membrane proteins (Álvarez-Martínez, Barrajón-Catalán, Herranz-López, & Micol, 2021). The combined application of ionizing radiation and active packaging can have a synergistic or additive antimicrobial effect that could not be achieved by one of these alone. In this regard, researchers demonstrated that the free radical-mediated mechanism of ionizing radiation could favor the interaction of active agents and biopolymers. Hence, the cross-linking between biopolymer and active compounds/biopolymers increases the entrapment of active agents in biopolymer structure; consequently, controlled and gradual release of active compounds from active packaging into the food matrix happens. Also, irradiated microorganisms were more susceptible to the antimicrobial effect of plant-based compounds (Jamshidi & Lacroix, 2018; Ouattara et al., 2002).

3.3. Total volatile nitrogen

In muscle foods, the decomposition of proteins and other nitrogenous compounds due to the activity of microbial and/or endogenous proteolytic enzymes leads to the production of ammonia and organic amines, which are known as TVN. The accumulation of such compounds

causes substantial color and flavor alterations, which influence the sensory acceptability of muscle foods (Al-Obaidi et al., 2021; Bekhit, Giteru, Holman, & Hopkins, 2021; Wang et al., 2021). The TVN index is commonly used for assessing the freshness of various muscle food products (Bekhit, Holman, Giteru, & Hopkins, 2021). The overall estimate of the current *meta*-analysis showed that radiation processing of muscle foods had no significant effect on the initial TVN level ($R^* = 0.997$, $P = 0.788$). In addition, the subgroup analysis based on the type of muscle food, irradiation dose, and active packaging type revealed no significant change in the initial TVN level of irradiated muscle foods (Table 3a). Our result is consistent with the previous studies that reported no significant change in the initial TVN levels of irradiated muscle foods with or without active packaging compared to the control group (Dini et al., 2020; Fallah et al., 2022; Li et al., 2022; Shahhosseini et al., 2019). The production of volatile bases and the increase in TVN level mainly depend on microbial growth and the production of proteolytic enzymes, which is not instantaneous and usually occurs during the storage period (Jafarinia, Fallah, & Habibian Dehkordi, 2022; Sarmast, Fallah, Habibian Dehkordi, & Rafieian-Kopaei, 2019).

The overall estimate of this *meta*-analysis showed that irradiation caused a significant reduction of 63.4% ($R^* = 0.366$) in the TVN level of muscle foods during the storage period (Table 3b). Because irradiation decreased the population of microbial flora, the production of volatile bases was reduced in radiation-processed muscle foodstuffs (Abdeldaiem et al., 2018; Kakatkar et al., 2017). The subgroup analysis based on the type of muscle food revealed that ionizing radiation significantly decreased the TVN levels in red meat and seafood by 63% ($R^* = 0.370$) and 66.6% ($R^* = 0.334$) during the storage period, respectively (Table 3b). The intrinsic factors such as count and type of spoilage microflora and pH, which differ based on the muscle food type, may affect the TVN level of muscle foods during storage. In this regard, irradiation dose, temperature, and levels of antimicrobial compounds are the main extrinsic factors (Fallah et al., 2022; Rokni, 2019). Future surveys may illuminate the impact of different intrinsic and extrinsic factors on the TVN levels of various muscle food products during storage.

The result of the subgroup analysis demonstrated that the TVN levels significantly decreased in both low-dose ($\leq$ 2.5 kGy) and high-dose ($>$ 2.5 kGy) irradiated muscle foods by 57.2% ($R^* = 0.428$) and 77.3% ($R^* = 0.227$) during the storage period, respectively (Table 3b). The result indicated a 1.35 times higher TVN level during storage in muscle foods treated with low-dose compared to those treated with high-dose irradiation. The higher doses of irradiation caused more reduction of spoilage microflora. Hence the production of volatile bases was reduced over the storage period (Abdeldaiem et al., 2018; Dini et al., 2020).

Our subgroup analysis showed that TVN levels significantly decreased in muscle foods without active packaging, with biopolymer packaging, and biopolymer + active compounds packaging during

Table 3a
Effect of irradiation on the initial chemical parameters of active packaged muscle foods.

Subgroup	Total volatile nitrogen			Thiobarbituric acid reactive substances			Protein carbonyls		
	No[a]	R^* (95% CI)	*P* value	No[a]	R^* (95% CI)	*P* value	No[a]	R^* (95% CI)	*P* value
Product type									
Red meat	8	0.998 (0.974, 1.022)	0.849	32	1.767 (1.350, 2.309)	<0.001	11	1.557 (1.323, 1.818)	<0.001
Seafood	7	0.994 (0.975, 1.019)	0.817	11	1.707 (1.327, 2.197)	<0.001	0	–	–
Chicken	0	–	–	5	1.784 (1.236, 2.573)	0.002	0	–	–
Radiation dose									
$\leq$ 2.5 kGy	11	0.998 (0.975, 1.021)	0.868	24	1.619 (1.425, 2.160)	0.005	11	1.557 (1.323, 1.818)	<0.001
$>$ 2.5 kGy	4	0.987 (0.921, 1.059)	0.723	24	1.910 (1.470, 2.482)	<0.001	0	–	–
AP type									
Without AP	4	1.002 (0.955, 1.051)	0.930	16	1.804 (1.225, 2.656)	0.003	3	1.610 (1.318, 1.966)	<0.001
Biopolymer	2	0.970 (0.933, 1.008)	0.125	17	1.866 (1.160, 2.557)	0.007	2	1.647 (1.218, 3.304)	<0.001
Biopolymer + AC	9	1.014 (0.981, 1.047)	0.410	15	1.593 (1.333, 2.323)	<0.001	6	1.202 (0.904, 1.358)	0.180
Overall estimate	15	0.997 (0.975, 1.019)	0.788	48	1.754 (1.425, 2.160)	<0.001	11	1.557 (1.332, 1.818)	<0.001

Abbreviations: R^*, weighted overall response ratio; CI, confidence interval; AP, active packaging; AC, active compounds.
[a] Number of trials.

Table 3b
Effect of irradiation on the chemical parameters of active packaged muscle foods during storage period.

Subgroup	Total volatile nitrogen			Thiobarbituric acid reactive substances			Protein carbonyls		
	No[a]	R^* (95% CI)	*P* value	No[a]	R^* (95% CI)	*P* value	No[a]	R^* (95% CI)	*P* value
Product type									
Red meat	8	0.370 (0.318, 0.526)	<0.001	34	1.372 (1.069, 1.759)	0.013	11	1.171 (1.040, 1.461)	0.012
Seafood	7	0.334 (0.197, 0.463)	<0.001	11	1.203 (1.036, 1.425)	0.032	0	–	–
Chicken	0	–	–	5	1.173 (1.033, 1.265)	0.029	0	–	–
Radiation dose									
$\leq$ 2.5 kGy	11	0.428 (0.331, 0.530)	<0.001	26	1.272 (1.022, 1.584)	0.031	11	1.171 (1.040, 1.461)	0.012
$>$ 2.5 kGy	4	0.227 (0.132, 0.390)	<0.001	24	1.369 (1.041, 1.950)	0.028	0	–	–
AP type									
Without AP	4	0.423 (0.282, 0.632)	<0.001	17	1.781 (1.222, 2.593)	0.003	3	1.327 (1.115, 1.611)	<0.001
Biopolymer	2	0.436 (0.365, 0.407)	<0.001	17	1.401 (1.001, 1.962)	0.049	2	1.216 (1.093, 1.455)	0.018
Biopolymer + AC	9	0.302 (0.244, 0.414)	<0.001	16	0.818 (0.680, 0.984)	0.033	6	0.899 (0.741, 0.945)	0.009
Overall estimate	15	0.366 (0.301, 0.445)	<0.001	50	1.324 (1.074, 1.636)	0.009	11	1.171 (1.040, 1.461)	0.012

Abbreviations: R^*, weighted overall response ratio; CI, confidence interval; AP, active packaging; AC, active compounds.
[a] Number of trials.

storage time by 57.7% ($R^* = 0.423$), 56.4% ($R^* = 0.436$), and 69.8% ($R^* = 0.302$), respectively (Table 3b). It was found that biopolymer + active compounds packaging was more effective compared to without active packaging and biopolymer packaging in slowing down the formation of volatile bases in irradiated muscle foods during storage because the TVN level was approximately 1.2 times lower in the irradiated samples packed with biopolymer + active compounds than those without active packaging and with biopolymer packaging. Most studies eligible for this *meta*-analysis added plant-based products, such as essential oils or extracts, as active compounds, to the biopolymers before packaging muscle foods. The antimicrobial activity of such compounds caused a reduction in the count of spoilage microbial flora; therefore, the production of volatile bases decreased during storage time (Dini et al., 2020; Fallah et al., 2022).

3.4. Lipid oxidation

Lipid oxidation is the major non-microbial cause of quality deterioration in muscle foods. The oxidation processes occur from animal slaughtering and continue during the product preparation and storage until consumption. Lipid oxidation not only reduces the nutritive value of muscle foods because of the degradation of essential fatty acids and vitamins but also influences the sensory quality of the products due to the formation of compounds that cause rancid odor and flavor. The changes in color and texture of the muscle food products are the other negative effects of lipid oxidation (Domínguez et al., 2019; Wu, Richards, & Undeland, 2022; Zhang, Li, Yang, Yang, & Zhao, 2020). Moreover, several toxic compounds like hydroperoxides and oxysterols formed during lipid oxidation may adversely affect human health (Huang & Ahn, 2019).

The TBARS assay is a standard method to determine lipid oxidation in various muscle food products. This assay measures malondialdehyde (MDA), the secondary end product formed during the oxidation of lipid substrates (Abeyrathne, Nam, & Ahn, 2021). The overall estimate of the current *meta*-analysis showed that radiation processing of muscle foods resulted in a significant increase of 75.4% ($R^* = 1.754$) in the initial TBARS level (Table 3a). Moreover, irradiation caused a significant increase of 32.4% ($R^* = 1.324$) in the TBARS level of muscle foods during the storage period (Table 3b). Ionizing radiation accelerates lipid oxidation in muscle foods, which is the primary cause of product quality deterioration. During radiation processing, water radiolysis, especially in foods with high water content, such as muscle foods, produces free radicals that react with macromolecules such as lipids and initiate lipid oxidation that progressively increases during storage (Fernandes, Pereira, Antonio, & Ferreira, 2018).

The result of subgroup analysis based on muscle food type showed that ionizing radiation significantly increased the initial TBARS levels in all types of muscle foods, including red meat, seafood, and chicken, by 76.7% ($R^* = 1.767$), 70.7% ($R^* = 1.707$), and 78.4% ($R^* = 1.784$), respectively (Table 3a), which indicated no considerable difference on the levels of lipid oxidation among the various types of muscle foods. Fat content and fatty acid composition of muscle foods are considered the main intrinsic factors that may affect the initial levels of lipid oxidation. In this regard, irradiation dose, temperature, presence of oxygen, and levels of antioxidants are the main extrinsic factors (Ahn et al., 1998; Ahn & Nam, 2004; Rokni, 2019). Future studies may clarify the effect of various intrinsic and extrinsic factors on the initial levels of lipid oxidation during the radiation processing of muscle foods.

Our subgroup analysis revealed that both low-dose ($\leq$ 2.5 kGy) and high-dose ($>$ 2.5 kGy) irradiation significantly increased the initial TBARS levels of muscle foods by 61.9% ($R^* = 1.619$) and 91% ($R^* = 1.910$), respectively (Table 3a). However, the initial TBARS level was approximately 1.5 times higher in muscle foods treated with high-dose than those treated with low-dose irradiation. It was found that the TBARS levels significantly increased in low-dose ($\leq$ 2.5 kGy) and high-dose ($>$ 2.5 kGy) irradiated muscle foods by 27.2% ($R^* = 1.272$) and 36.9% ($R^* = 1.369$) during storage period, respectively (Table 3b). The result indicated a 1.36 times higher rate of lipid oxidation during storage in muscle foods treated with high-dose compared to those treated with low-dose irradiation. In agreement with our result, previous studies on muscle foods reported lipid oxidation induction in a dose-dependent manner (Al-Bachir & Zeinou, 2014; Fallah, Tajik, & Farshid, 2010; Li, Yu, Xiong, Liao, & Zu, 2020). More free radicals are generated during high-dose irradiation, leading to higher lipid oxidation levels.

The subgroup analysis based on active packaging type revealed that irradiation significantly increased the initial TBARS levels in muscle foods without active packaging, with biopolymer packaging, and biopolymer + active compounds packaging by 80.4% ($R^* = 1.804$), 86.6% ($R^* = 1.866$), and 59.3% ($R^* = 1.593$), respectively (Table 3a). There was no substantial difference in the initial levels of lipid oxidation between the irradiated muscle foods without active packaging and those packed with biopolymers (80.4% vs 86.6%). The studies eligible for this *meta*-analysis used the biopolymers such as whey protein isolate, calcium caseinate, soy protein isolate, chitosan, pectin, alginate, and basil seed gum for packaging muscle foods. The mentioned biopolymers had no considerable antioxidative effects. However, the packaging containing biopolymer + active compounds was more efficient compared to without active packaging and with biopolymer packaging to prevent the initial lipid oxidation because the TBARS levels were 1.36 and 1.46 folds lower in the irradiated muscle food samples packed with biopolymer + active compounds than those without active packaging and with biopolymer packaging, respectively. Most studies eligible for this *meta*-analysis added plant-based products, such as essential oils or extracts, as active compounds, to the biopolymers before packaging muscle foods. Plant essential oils and extracts are good sources of bioactive components such as terpenes, flavonoids, or tannins responsible for the plant-based products' antioxidative effects (Aziz & Karboune, 2018). The mentioned components can scavenge the free radicals generated during ionizing radiation by donating hydrogen atoms or electrons, hence reducing the initial level of lipid oxidation in the muscle foods packed with biopolymer + active compounds (D'Amelia, Aversano, Chiaiese, & Carputo, 2018; Domínguez et al., 2018; Krishnaiah, Sarbatly, & Nithyanandam, 2011; Shen et al., 2022).

The result of the subgroup analysis revealed that TBARS levels significantly increased in muscle foods without active packaging and with biopolymer packaging by 78.1% ($R^* = 1.781$) and 40.1% ($R^* = 1.401$) during the storage period, respectively. In contrast, a significant reduction of 18.2% ($R^* = 0.818$) was found in the TBARS level of the samples packed with biopolymer + active compounds during storage time (Table 3b). It was found that biopolymer packaging was more effective than without active packaging to retard lipid oxidation of irradiated muscle foods during storage because the TBARS level was 1.95 times lower in irradiated samples packed with biopolymers than in the irradiated samples those without active packaging. The barrier properties of the biopolymers retard the progress of lipid oxidation in the products. In addition, irradiation, even at low doses, caused molecular crosslinking of the biopolymers and increased their barrier properties (Jamshidi & Lacroix, 2018). As mentioned earlier, most studies eligible for this *meta*-analysis added plant-based products, such as essential oils or extracts, as active compounds, to the biopolymers before packaging muscle foods. Because oxidation processes are one of the main adverse effects of ionizing radiation, this packaging is the best approach to control lipid oxidation in irradiated muscle foods during storage. The molecular crosslinking of the irradiated biopolymers increases their capacity to retain bioactive compounds and allows the gradual and continuous release of such compounds into the foods (Hossain et al., 2019; Jamshidi & Lacroix, 2018).

3.5. Protein oxidation

Protein oxidation is determined as the changes in the covalent bonds of proteins, which lead to unfavorable alterations in the sensory,

nutritional, and processing characteristics of meat, poultry, and seafood products. The changes caused by protein oxidation are irreversible and lead to adverse side effects such as amino acid side chain modifications, protein fragmentation, and protein cross-linking (Domínguez et al., 2022; Estévez & Xiong, 2021; Islam et al., 2022). Oxidation of proteins has detrimental effects on the color and texture of muscle foods during storage. Also, it reduces the water-holding capacity (WHC) of processed muscle food products (Bao & Ertbjerg, 2019). The oxidized proteins are less susceptible to proteolytic enzymes, hence causing the lower digestibility and bio-accessibility of the oxidized products (Lund, Heinonen, Baron, & Estévez, 2011; Xiong & Guo, 2021).

The protein carbonyls assay is the most common method for assessing protein oxidation in muscle food products because the carbonylation happens in most amino acid side chains. The protein carbonyls are derivatized by 2,4-dinitrophenylhydrazine to form hydrazones that can be determined by spectrophotometry (Hellwig, 2020). The current *meta*-analysis's overall estimate showed that the radiation processing of muscle foods resulted in a significant increase of 55.7% ($R^* = 1.557$) in the initial protein carbonyl level (Table 3a). Moreover, irradiation caused a significant increase of 17.1% ($R^* = 1.171$) in the protein carbonyl level of muscle foods during the storage period (Table 3b). Ionizing radiation speeds up oxidative processes in muscle foods by generating free radicals that react with macromolecules such as proteins and initiate protein oxidation that progressively increases during the storage period. The generated free radicals attack protein molecules and start protein oxidation via the abstraction of hydrogen atoms. On the other hand, irradiation accelerates lipid oxidation in muscle foods. The oxidized lipids can react with proteins and initiate protein oxidation (Domínguez et al., 2022; Wazir et al., 2021).

The result of subgroup analysis based on active packaging type revealed that irradiation significantly increased the initial protein carbonyls levels in muscle foods without active packaging and with biopolymer packaging by 61% ($R^* = 1.610$) and 64.7% ($R^* = 1.647$), respectively. A non-significant increase of 20.2% ($R^* = 1.202$) was detected in the initial protein carbonyl level of the irradiated samples packed with biopolymer + active compounds (Table 3a). There was no considerable difference in the initial protein oxidation levels between the irradiated muscle foods without active packaging and those packed with biopolymers (61% vs 64.7%). As mentioned earlier, the studies eligible for this *meta*-analysis applied biopolymers with no remarkable antioxidative effects for the packaging of muscle foods. However, packaging muscle foods with biopolymer + active compounds were more efficient than without active packaging. Packaging prevents the initial protein oxidation with biopolymer since the protein carbonyl levels were 3.02 and 3.20 folds lower in the irradiated samples packed with biopolymer + active compounds than those without active packaging and with biopolymer packaging, respectively. The antioxidative effects of plant-based products, such as essential oils or extracts added as active compounds to the biopolymers before packaging muscle foods, can justify this issue (Aziz & Karboune, 2018). The components of plant-based products can quench the free radicals produced during ionizing radiation by donating hydrogen atoms or electrons, hence decreasing the initial level of protein oxidation in the muscle foods packed with biopolymer + active compounds (Domínguez et al., 2018; Krishnaiah et al., 2011; Pateiro et al., 2018; Umaraw et al., 2020).

Our subgroup analysis demonstrated that the protein carbonyl levels significantly increased in irradiated muscle foods without active packaging and biopolymer packaging by 32.7% ($R^* = 1.327$) and 21.6% ($R^* = 1.216$) during the storage period, respectively. A significant reduction of 10.1 % ($R^* = 0.899$) was found in the protein carbonyl level of the irradiated samples packed with biopolymer + active compounds during the storage period (Table 3b). It was found that biopolymer packaging was more efficient than without active packaging in slowing down protein oxidation in irradiated muscle foods during storage because the protein carbonyl level was 1.51 times lower in the irradiated samples packed with biopolymers compared to those without active packaging. It might be due to the barrier properties of the irradiated biopolymers because irradiation, even at low doses, caused molecular crosslinking of the biopolymers and increased their barrier properties (Jamshidi & Lacroix, 2018). Our result showed that packaging muscle foods with biopolymer + active compounds are the best approach to slow protein oxidation in muscle foods during the storage period because most of the studies eligible for this *meta*-analysis added potent antioxidants like essential oils or extracts, as active compounds, to the biopolymers. In addition, irradiation under conditions to produce molecular crosslinking of the biopolymers increased their capacity to retain bioactive compounds and allowed the gradual and continuous release of such compounds into the muscle foods during the storage period (Hossain et al., 2019; Jamshidi & Lacroix, 2018). It has been reported that there is a positive correlation between lipid and protein oxidation in muscle foods (Hasani-Javanmardi, Fallah, & Abbasvali, 2021; Hematyar, Rustad, Sampels, & Kastrup Dalsgaard, 2019; Pirastehfard, Fallah, & Habibian Dehkordi, 2021). The active compounds added to the biopolymers restricted the progress of lipid oxidation during storage time. Hence retarding protein oxidation can be justified (Dini et al., 2020; Fallah et al., 2022).

3.6. Inter-study heterogeneity

The results of inter-study heterogeneity are presented in Supplementary Data, Tables S1a, b for microbial and S2a, b for chemical parameters. High heterogeneity (Cochrane Q-test's $P < 0.001$, $I^2 > 94\%$) was found for overall estimates of all microbial and chemical parameters except initial TVN (Cochrane Q-test's $P = 0.992$, $I^2 = 0.0\%$).

Considering initial microbial parameters, the inter-study heterogeneity (Cochrane Q-test's $P > 0.050$, $I^2 < 50\%$) was found in the subgroup of chicken for TMB, subgroups of red meat and biopolymer for TSB, subgroups of red meat and > 2.5 kGy for ENB, and subgroups of red meat, without active packaging, and biopolymer for LAB (Supplementary Data, Table S1a). For microbial parameters during the storage period, the subgroups of seafood and > 2.5 kGy for LAB demonstrated low inter-study heterogeneity (Supplementary Data, Table S1b).

Regarding initial chemical parameters, low inter-study heterogeneity (Cochrane Q-test's $P > 0.050$, $I^2 < 50\%$) was found for all subgroups of TVN and the subgroup of chicken for TBARS (Supplementary Data, Table S2a). For chemical parameters during the storage period, the subgroup of biopolymer for TVN and the subgroup of chicken for TBARS demonstrated low inter-study heterogeneity (Supplementary Data, Table S2b).

3.7. Publication bias

The results for publication bias of microbial and chemical parameters are shown in Supplementary Data, Fig. S1a, b and Fig. S2a, b, respectively. Based on Begg and Egger tests, no publication bias was found for the microbial and chemical parameters.

3.8. Knowledge gaps and future needs

The current study has some limitations as follows: (*a*) The selected studies applied various natural active compounds, such as plant extracts or essential oils, in the coating solutions or films; however, the components of these active ingredients did not determine in some studies (Kang et al., 2007; Lacroix et al., 2004; Ouattara et al., 2001, 2002; Shahhosseini et al., 2019; Shankar et al., 2019); (*b*) The selected studies did not evaluate the release kinetics of active compounds from the coating solutions or films; (*c*) The effect of irradiation on the crosslinking of biopolymers and release kinetics of active compounds from the coating solutions or films did not assess in the selected studies; (*d*) The proximate composition and other intrinsic factors of food models did not evaluate by most of the selected studies. The factors above, regarded as

knowledge gaps, can affect the treatments' antioxidant and/or antimicrobial activities; therefore, future studies should assess these factors.

Several studies evaluated the combined effect of biopolymer-based active packaging and ionizing radiation on the microbial flora of muscle foods (Abdeldaiem et al., 2018; Lacroix et al., 2004; Shankar et al., 2019; Zhang et al., 2017); however, few studies assessed this effect on inactivation of inoculated food-borne pathogenic or spoilage microorganisms (Dini et al., 2020; Nortjé et al., 2006; Ouattara et al., 2001). In addition, no survey was conducted on the combined effect of biopolymer-based active packaging and ionizing radiation on the quality and safety of ready-to-eat muscle food products that are popular among consumers worldwide.

4. Conclusions and perspectives

This study demonstrated that radiation processing of muscle foods reduced the initial counts of TMB, TSB, ENB, and LAB by 57.8%, 49.3%, 60.2%, and 16.7%, respectively. Moreover, irradiation caused reductions of 53.7 %, 36.6 %, 77.9 %, and 30.9 % in the TMB, TSB, ENB, and LAB counts of muscle foods during the storage period, respectively. Irradiation did not affect the initial level of TVN while decreasing its increasing rate during the storage period. The initial levels and increasing rates of lipid and protein oxidation increased after the radiation processing of muscle foods. It was found that packaging of muscle foods with biopolymer + active compounds before irradiation was more effective compared to biopolymer packaging and without active packaging in decreasing the initial counts and growth rates of microbial flora. Although lipid and protein oxidation increased in irradiated muscle foods without active packaging or packed with biopolymers at the initial time and after the storage period, such indices decreased in the irradiated muscle foods packed with biopolymer + active compounds during the storage period. From an industrial standpoint, packaging of muscle foods with biopolymer + active compounds, especially plant-based ones, synergistically acts with ionizing radiation to decrease the counts of microbial flora and increase the shelf-life of muscle foods; therefore, lower radiation doses can be applied, which reduces the radiation costs and minimizes the adverse effects of irradiation on muscle foods. In addition, this type of packaging is the best approach to control oxidative processes, which are the main adverse effects of the ionizing radiation of muscle foods. Few studies have been performed on combining ionizing radiation and active packaging to preserve muscle foods in recent years. We recommend other researchers to conduct more studies in this field while taking into account the limitations of previous studies to reach more accurate results.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodchem.2022.134960.

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