Food Science and Applied Biotechnology, 2022, **5**(2), 160-172

Food Science and Applied Biotechnology
e-ISSN: 2603-3380

Journal home page: www.ijfsab.com
https://doi.org/10.30721/fsab2022.v5.i2



OPEN ACCESS

Research Article

A meta-analysis of the effect of gamma irradiation on chicken meat quality: Microbiology and colour

Krasimir Dimov[1]✉, Teodora Popova[2]

[1] *Agricultural Academy, Department of Food Technologies, Institute of Cryobiology and Food Technologies, Sofia, Bulgaria*
[2]*Agricultural Academy, Institute of Animal Science-Kostinbrod, Kostinbrod, Bulgaria*

Abstract
A meta-analysis of the effect of gamma irradiation on the microbial status and colour in raw chicken meat was performed. A total of 14 studies were selected and data about the total viable count (TVC), coliforms (TCC), instrumental colour measurements - lightness (L*), redness (a*) and yellowness (b*) was extracted for evaluation in gamma treated and untreated meat. Due to the high between study heterogeneity, the meta-analysis was conducted through random-effects model applied on the raw mean difference (effect size) for each outcome of interest. The results of the meta-analysis showed that gamma irradiation considerably decreased TVC and TCC (P<0.001). Gamma rays also significantly diminished L* (P=0.013), but increased a* and b* (P<0.001). The meta-regression models showed that the dose of the radiation contributed to the overall effect of irradiation TVC (P=0.006), TCC (P=0.074) and a*(P=0.007). The effect of gamma rays on TVC was further influenced by storage (P=0.007), while package affected the increase of a* (P=0.100).

Keywords: meta-analysis, gamma irradiation, chicken meat, microbiology, colour

Abbreviations
TVC – total viable count; TCC – total coliform count; OxyMb – oxymyoglobin; MetMb – metmyoglobin; COMb – carboxymyoglobin

✉*Corresponding author: Krasimir Dimov, Agricultural Academy, Department of Food Technologies, Institute of Cryobiology and Food Technologies, 53"Cherni vrah" blvd. 1407, Sofia, Bulgaria, tel.: +359 887988561; E-mail: krasimir.dimov@ikht.bg*

Article history:
Received 28 March 2022
Reviewed 4 May 2022
Accepted 8 July 2022
Available on-line 13 October 2022

https://doi.org/10.30721/fsab2022.v5.i2.185
© 2022 The Authors. UFT Academic publishing house, Plovdiv

Introduction

The consumption of chicken meat is increasing faster than any other one, turning it into the most consumed meat for 2021(OECD, 2021). This is due to its high nutritious value, easy access and low price (Kralik et al. 2017). Although chicken meat is a good nutrition choice, when raw it is often contaminated with microorganisms, some of which pathogenic. As reported by an extensive systematic review of Gonçalves-Tenório et al. (2018), pathogens such as *Salmonella* spp., *Listeria monocytogenes*, *Staphylococcus aureus* and *Campylobacter* were found at the end of processing and retail display of chicken meat, also in both packed and unpacked products. Furthermore, the authors found that although chilling and freezing can substantially reduce the propagation of pathogens, these preservation methods might not be able to fully inactivate them. Pathogenic microflora is a serious hazard for the food safety and shelf life and different preservation technologies have been applied to restrict them. One of the methods that has proved to be successful in preserving foods is irradiation. It is the process of exposing food and food packaging to ionizing rays. The latter does not cause any harm to human health when applied in doses up to 10 kGy (Lacroix 2005). Three are the sources of radiation approved to be used on foods: gamma rays emanated from radioactive forms of cobalt (Cobalt 60) or cesium (Cesium 137); X-rays that are high energy photons generated into a tube through high voltage, and Electron beam (or e-beam) that is a stream of high-energy electrons sent from an electron accelerator into food. Of all three sources, gamma rays have been the most widely used. Irradiation has been applied for direct microbial inhibition in foods since 1940s (Lawrie 2006; Zhou et al. 2010). As stated by Sebranek et al. (2014), FDA approved using irradiation to control *Salmonella* and other harmful bacteria in chicken, turkey and other fresh and frozen uncooked poultry meats in May 1990 with limits of radiation amounts of 3 kGy (Arvanitoyannis and Tserkezou 2010). The application of gamma irradiation for inhibition of pathogenic and spoilage microflora in chicken meat has been subject of many studies. However, an inevitable influence of the irradiation has been observed in regard of the quality characteristics such as colour, which is one of the most important parameters impacting the decision of the consumers to buy meat (Mancini and Hunt 2005). Some reviews concerning the effect of irradiation on meat quality, including poultry also exist (Brewer 2004). However, they do not apply quantitative methods for evaluation of the studied effects of the irradiation. Meta-analysis allows to quantitatively estimate the effects as calculated from the results of individual studies, that might even present conflicting results (Fernandez-Duque 1997), taking into account the variation between studies. Furthermore, it makes possible to describe the overall strength of the effect, and the circumstances that make it stronger or weaker (DeCoster 2009). According to Carriquiry et al. (2008), meta-analysis might be particularly useful when small sample sizes limit the statistical power of individual studies to detect differences. The aim of this meta-analysis was to quantify the effect on the gamma irradiation on the microbiological status and colour in raw chicken meat.

Materials and Methods

Selection of the studies

An exhaustive computerized literature search was performed using Scopus, Web of Science, Pubmed databases, publisher websites and Google search engine to select the studies assessing the effect of gamma irradiation on the microbial status and colour of raw chicken meat. Key words and combinations such as "gamma irradiation", "chicken", "poultry", "meat", "instrumental colour", "meat quality", "microbiology" were used. The studies included in the meta-analysis were published as peer-reviewed papers in English. Each observation in the meta-analysis corresponded to the mean of each treatment group. As additional criteria for inclusion of the meta-analysis, the studies had to provide any measure of variation such as standard deviation (SD), standard error (SE), variation coefficient for each group (CV), mean square error (MSE) or root mean square error (RMSE).

Description of the data sets

Initially, a data set of 19 studies corresponding to the required criteria was obtained, that reported results from microbial analysis and/or instrumental colour measurement. Further, after careful examination, 4 studies were excluded from the data set for reporting data without variation measurement or using bulk sample. One study was

excluded due to duplicate data. Final data set included 14 studies that provided appropriately the data and the measures of the variation of the outcomes. After setting a minimum of six studies for any outcome as requirement for estimation of the effect of treatment, total viable count (also referred as total aerobic count), total coliforms, L*, a* and b* were the outcomes considered for the meta-analysis. In all the studies microbial analysis was performed on uninoculated samples, except Shankar et al. (2022) who conducted experiment through inoculation with *E. coli* to evaluate the effect of gamma irradiation on the microflora survival in meat samples. Instrumental colour measurements were done through Hunter or Minolta colorimeters. The values of the parameters were presented as CIELAB coordinates. Islam et al. (2019) reported experiments with meat from indigenous chickens. Javanmard et al. (2006), Rima et al. (2019), Kanatt et al. (2015), Xiao et al. (2011), Bhoir et al. (2019) specified using broiler meat. Breast meat was used by Kanatt et al. (2015), Balamatsia et al. (2006), Chouliara et al. (2008), Bhoir et al. (2019), Millar et al. (1995), while thighs was used by Torgby-Tetteh et al. (2014), Xiao et al. (2011), Shankar et al. (2022). Chicken meat was mostly commercially obtained from local markets (Islam et al. 2019; Arshad et al. 2019; Rima et al. 2019; Khalid et al. 2021; Torgby-Tetteh et al. 2014; Al-Bachir et al. 2013; Bhoir et al. 2019), farm (Kanatt et al. 2015), poultry or slaughtering plants (Javanmard et al. 2006; Balamatsia et al. 2006; Chouliara et al. 2008; Shankar et al. 2022; Millar et al. 1995). Xiao et al. (2011) reported experimental design with raising of the birds. Studies on different doses of radiation and type of packaging (Chouliara et al. 2008; Kanatt et al. 2015; Arshad et al. 2019) presenting the results for each condition was treated as separate studies. In studies reporting results on different intervals of storage, the latter were averaged for each type of storage (refrigerated or frozen) according to the applied dose.

Statistical analysis

Statistical analysis was conducted using JASP v. 0.16.1 software (JASP team 2022). Since the primary studies used the same outcome and units of measure, the meta-analysis was done on the raw difference in means (raw mean difference). According to Borenstein et al. (2009), the main advantage of the raw mean difference is that it is intuitively meaningful, either inherently or because it is widely used. Meta-analysis can be carried out through fixed- or random-effects model. According to Borenstein et al. (2010) under the fixed-effect model it is assumed that there is one true effect size that underlies all the studies in the analysis, and that all differences in observed effects are due to sampling error. By contrast, under the random-effects model the true effect is presumed to vary from study to study, and includes between-study variability (true heterogeneity) as well as sampling error. The presence of the true heterogeneity between studies was identified by the Q test. Random-effects model was opted for this meta-analysis due to heterogenous data. The method of restricted maximum likelihood (REML) was applied to estimate heterogeneity variance as recommended by Langan et al. (2019). Quantification of the heterogeneity was done using I^2 index (Higgins and Thompson 2002), describing the proportion of total variation across the studies that is due to heterogeneity. Whenever values of I^2 were greater than 50% indicating substantial heterogeneity, meta-regression was applied to explore the sources of heterogeneity. Covariates included in the model were dose of gamma irradiation (continuous), storage (categorical, refrigerated compared to frozen) and package (categorical, aerobic compared to any other, including vacuum, or modified atmosphere). The covariates were tested for significance at $P<0.10$. The individual estimated effect sizes within studies were visualized by forest plots, which were constructed for each outcome variable. In the forest plots after the reference, indicators have been used as follows: dose of irradiation, kGy; package (AP – aerobic, VP – vacuum, MAP1 – modified atmosphere, 30%CO_2/70%N_2, MAP2-70%CO_2/30% N_2); storage (refrigerated R, 0-4°C or frozen F, -18 to - 20°C). If the kind of package was missing, it was accepted as aerobic. A positive value of the effect size indicates that meat treated with gamma irradiation presents higher value of the variables of interest, while a negative value indicates that control samples are superior to the treated ones.

Results and Discussion

Effect of gamma irradiation on the microbial status of raw chicken meat

Total viable count and total coliforms were the outcomes of interest in this study in regard to microbial status (Table 1). Gamma irradiation improved the microbial status of the raw chicken meat by decreasing TVC (P<0.001). The random-effects model showed that the observed mean differences ranged -4.97 to -0.74 (Fig.1).

All the studies showed negative estimates, with overall effect size -2.54 (95%CI: -2.96, -2.12), indicating lower TVC in the gamma irradiated meat.

Table 1. Effect size estimates of gamma irradiation on the TVC and TCC of raw chicken meat

Outcome	Effect size (95% CI)	Standard error	df	Z test (P value)	Q (P value)	I^2 (%)
TVC (log CFU/g)	-2.54 (-2.96; -2.12)	0.22	29	-11.82 (<0.001)	5836.15 (<0.001)	98.80
TCC (log CFU/g)	-1.08 (-1.32; -0.84)	0.12	13	-8.73 (<0.001)	242.97 (<0.001)	96.35

The meta-analysis revealed substantial heterogeneity between studies (98.80%), that could be explained by the inclusion of the covariates in the model. The overall effect of the gamma irradiation on the TVC in the raw chicken meat samples was affected significantly by the dose (P=0.006) and the storage (P=0.007) of the meat, as the latter had higher contribution (- 1.19 *vs.* -0.33) (Table 2).

Gamma irradiation had similar effect in regard to coliforms. The estimated average mean difference was -1.08 (95% CI: -1.32, -0.84) showing reduction of the coliforms in the irradiated chicken meat (Table 1, Fig. 2). The dose of the gamma irradiation influenced the overall effect on this trait (P=0.074) (Table 2).

According to Sedeh et al. (2007), gamma irradiation of foods can be used as one of the most efficient methods to reduce their microbial contamination. As stated by Correa et al. (2019), in addition to inactivation of bacterial metabolism, when applied in sufficient doses, gamma irradiation can kill bacteria. The studies selected for evaluation in this meta-analysis presented data on gamma irradiation of the chicken meat when subjected to refrigerated or frozen storage. As seen from the forest plot (Fig.1), the mean differences in TVC between the gamma irradiated and untreated raw chicken meat were more pronounced in refrigerated samples, than frozen.

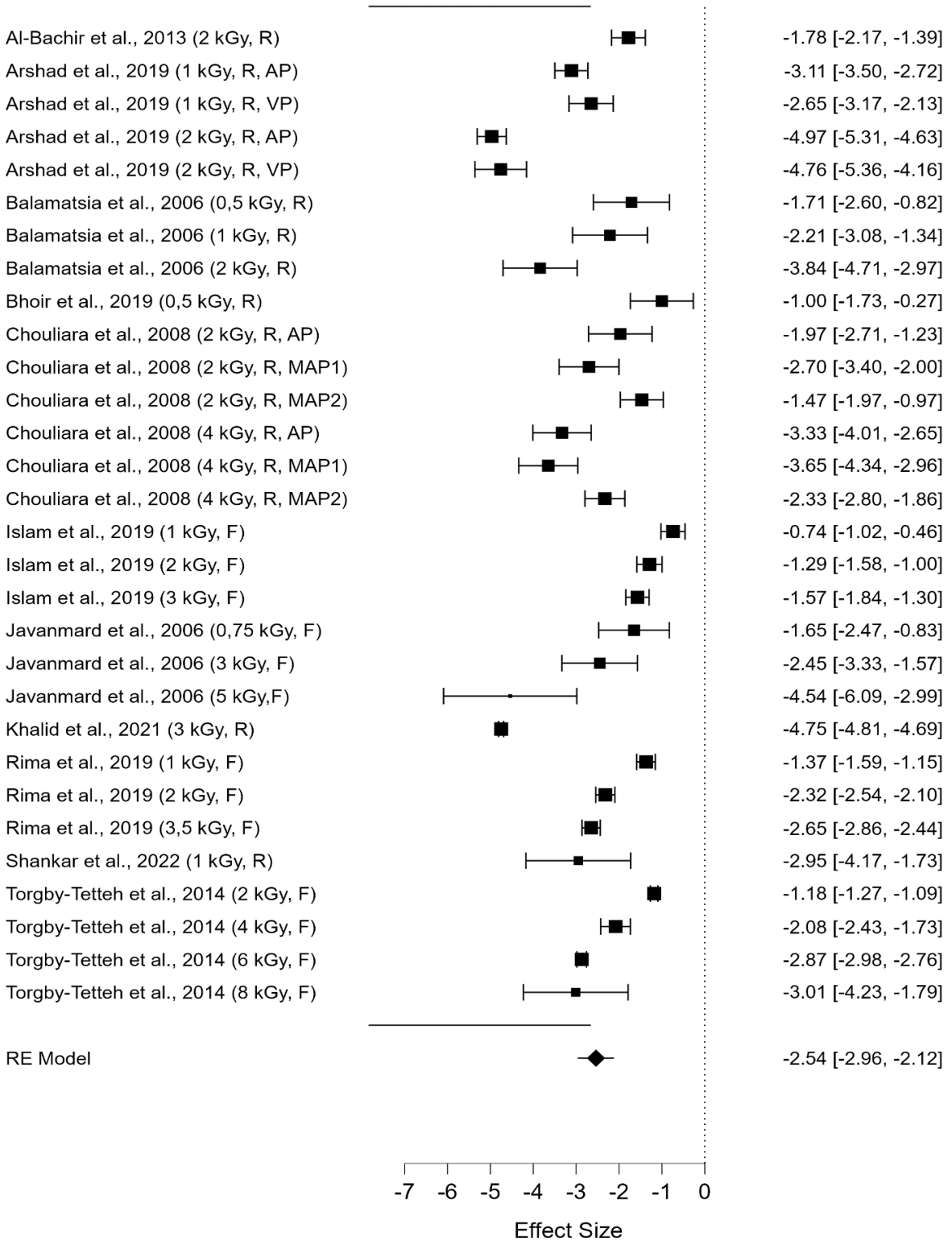


Figure 1. Forest plot of the random-effects models of the effect of gamma irradiation on TVC in raw chicken meat

Table 2. Significant covariates affecting the effect of gamma irradiation on the microbial status in chicken raw meat

Covariates	Coefficient (95% CI)	Standard error	Z test	P
TVC				
Dose	-0.33 (-0.10, -0.56)	0.12	2.77	0.006
Storage	-1.19 (-0.33, -2.05)	0.44	2.72	0.007
TCC Dose	-0.45(-0.95, 0.04)	0.25	-1.78	0.074

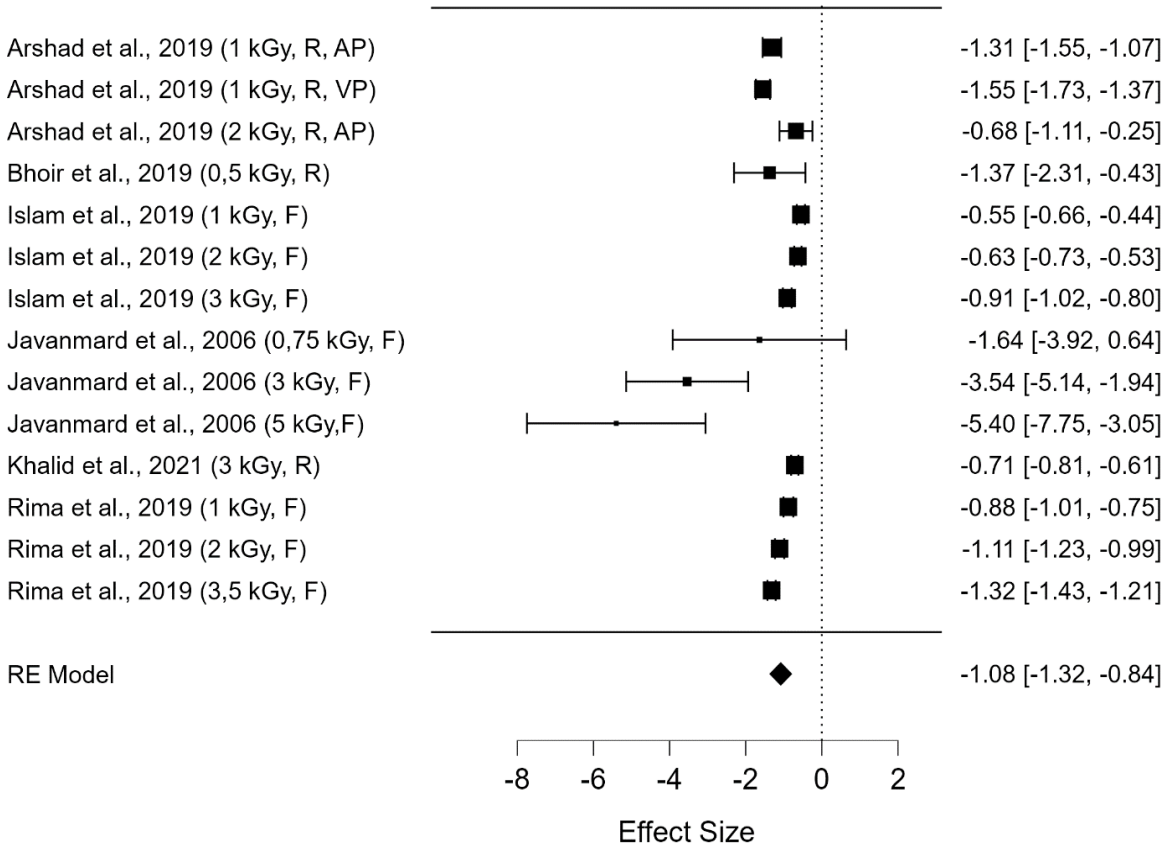


Figure 2. Forest plot of the random-effects models of the effect of gamma irradiation on TCC in raw chicken meat

This might be explained with the bacterial growth that continues under refrigerated conditions and the increase of the microbial populations with time (Dourou et al. 2021). Similar increase in the microorganisms of the untreated meat was observed in the studies included in the meta-analysis, which makes the effect of the gamma irradiation stronger, when treatment is applied together with refrigeration. On the other hand, during freezing, microorganisms suffer multiple damages that may cause their inactivation and death directly or later during frozen storage (Erkmen and Faruk Bozoglu 2016). In this case gamma irradiation is applied for initial inhibition of the microorganisms and its effect is weaker due to synergy with freezing.

An important factor affecting the microbial status of the treated meat is the dose of gamma irradiation. The negative coefficients for this covariate determined for TVC and TCC showed that the increase of the dose leads to decrease of the

microbial population in the irradiated meat. This corresponded to the lower TVC in the refrigerated raw chicken meat irradiated with medium and high dose and the frozen meat treated with high dose of gamma rays.

Unlike the TVC, storage did not contribute to the observed effect of gamma irradiation on the TCC in the raw chicken meat, however, the dose was significant covariate. For most of the studies reporting this outcome, the observed mean difference fell within the range of -0.55 to -1.37. In comparison to the other studies included in the meta-analysis, substantial differences between gamma treated and untreated samples were reported by Javanmard et al. (2006). According to the authors, irradiation and frozen storage were more effective than either treatment alone for decrease of TVC and coliforms.

Effect of gamma irradiation on the colour of chicken meat

Gamma rays decreased significantly the lightness (L*, P=0.013), and increased the redness (a*) and yellowness (b*) (P<0.001) in the raw chicken meat (Table 3). The estimated average mean difference for L*, according to the random-effects model was -1.94 (95% CI: -3.47, -0.41). The mean differences across studies ranged from -7.17 to 3.75, with 88 % reporting negative differences showing decreased L* values after gamma irradiation (Fig. 3).

Chouliara et al. (2008), however reported higher L* in chicken meat irradiated with low and medium dose. The meta-regression model (Table 4) showed that the heterogeneity between studies, and hence the overall effect could be explained with the dose of the treatment. The negative coefficient (-0.82) showed that the higher the dose of irradiation, the values of L* decrease. Furthermore, the gamma rays treatment showed substantial influence on the redness a* and yellowness b* of the raw chicken meat. The estimated average mean differences for both parameters were positive (Table 3).

The overall effect of gamma irradiation on a* was 1.12 (95% CI: 0.57, 1.67), with majority of the estimates being positive (Fig.4).

The only exception was Chouliara et al. (2008), who reported decreased redness in raw chicken meat treated with 2 kGy and packed in modified atmosphere containing CO_2 and N_2. The overall effect of gamma rays on b* was 1.07 (95 %CI: 0.57,1.57). 88% of the estimates were positive as well (Fig.5), except the estimate observed in Kanatt et al. (2015) showing decreased yellowness of chicken meat after irradiation with high dose (5 and 10 kGy).

Table 3. Effect size estimates of gamma irradiation on L*, a* and b* of raw chicken meat

Outcome	Effect size (95% CI)	Standard error	df	Z test (P value)	Q (P value)	I^2 (%)
L*	-1.94 (-3.47, -0.41)	0.78	15	-2.48 (0.013)	103.10 (<0.001)	85.58
a*	1.12 (0.57,1.67)	0.28	15	3.98 (<0.001)	244.66 (<0.001)	92.73
b*	1.07 (0.57,1.57)	0.25	15	4.20 (<0.001)	757.93 (<0.001)	95.86

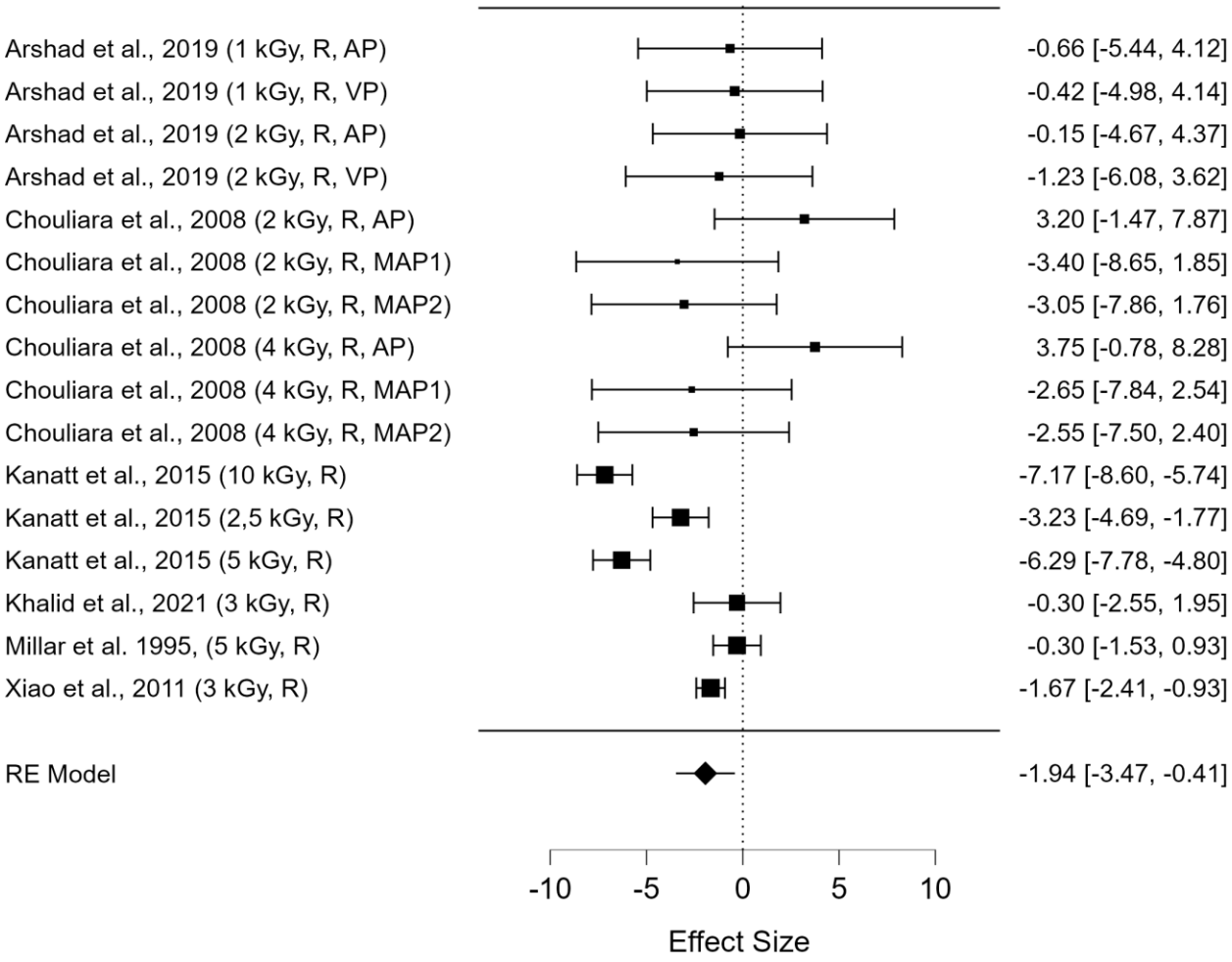


Figure 3. Forest plot of the random-effects models of the effect of the gamma irradiation on L* in raw chicken meat

Table 4. Significant covariates affecting the effect of the gamma irradiation on colour in chicken raw meat

Covariates	Coefficient (CI 95%)	Standard error	Z test	P
L* Dose	-0.82(-1.39, -0.24)	0.29	-2.80	0.005
a* Dose	0.27 (0.07, 0.47)	0.10	2.68	0.007
Package	0.76 (-0.14, 1.66)	0.46	1.65	0.100

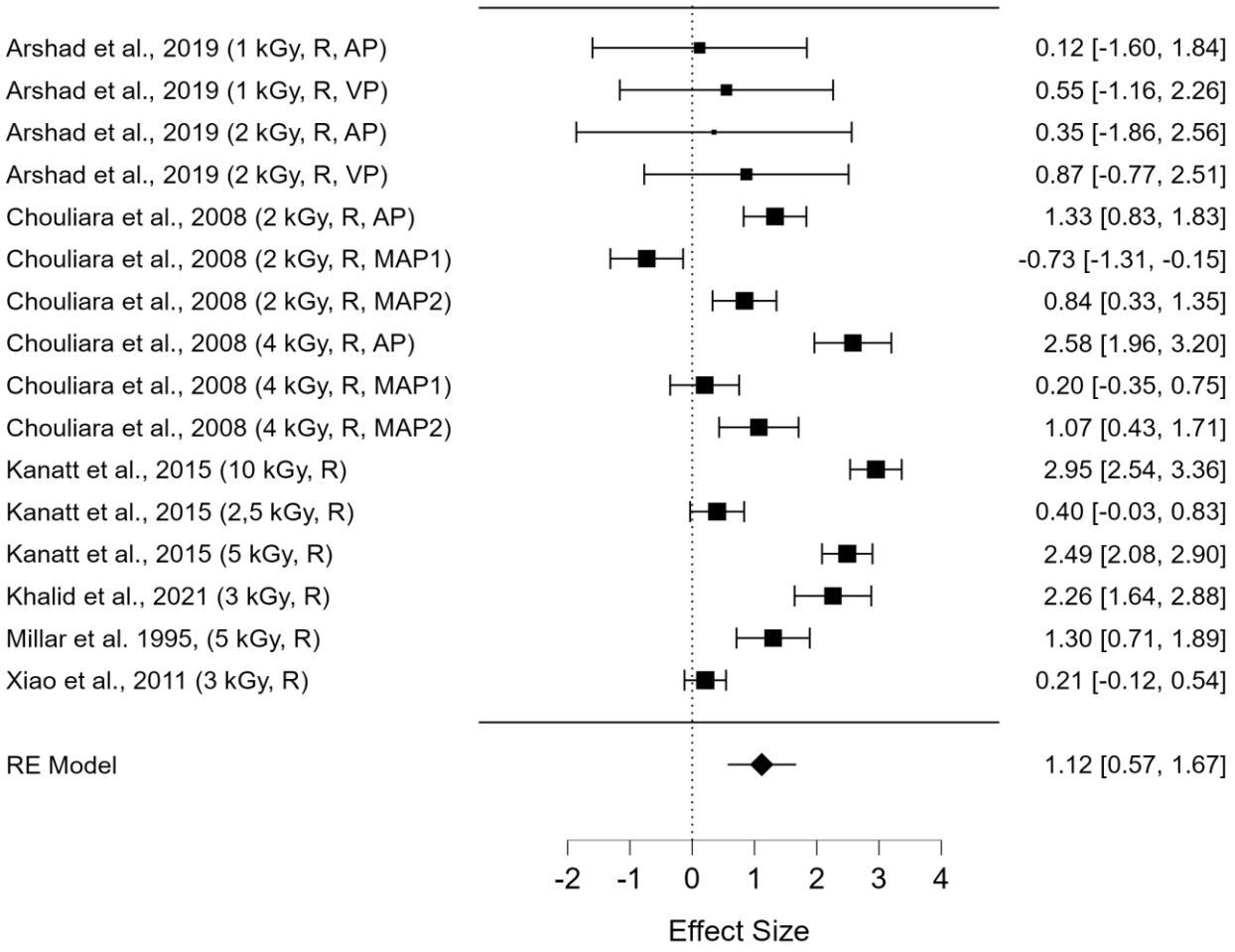


Figure 4. Forest plot of the random-effects model of the gamma irradiation on a* in raw chicken meat

According to the meta-regression model, the dose of the gamma irradiation contributed significantly to the effect on a* (P=0.007). The positive coefficient of the dose (0.27) corresponded to the substantial increase in this parameter in the meat irradiated with high dose (over 3 kGy). The package also contributed to the effect of the gamma irradiation in the chicken meat as seen from the positive regression coefficient 0.76 (P=0.100).

The principal pigment of meat is myoglobin and the impact of gamma irradiation on its molecule is responsible for the changes in meat colour. According to Lee and Song (2002), gamma irradiation can alter considerably the molecular structure of myoglobin in meat. It can lead to splitting of the ordered structure of the protein molecules, and can also cause degradation, cross-linking and aggregation of the polypeptide chains. Early studies (Saterlee et al. 1972) reported that the effect of gamma irradiation on meat colour depended on the form of myoglobin and showed that irradiated metmyoglobin (MetMb) produces red pigment, believed to be oxymyoglobin (OxyMb), thus increasing a* values. Furthermore, the process depended on pH (higher at pH 8.5-7.5 than 6) and the formation of the red pigment was dose dependent. On the other hand, Sørheim et al. (1999) observed higher a* values in beef and pork packed in modified atmosphere containing low concentrations of carbon monoxide (0.4%). Carbon monoxide is one of the major radiolytic gases arising from irradiated foods.

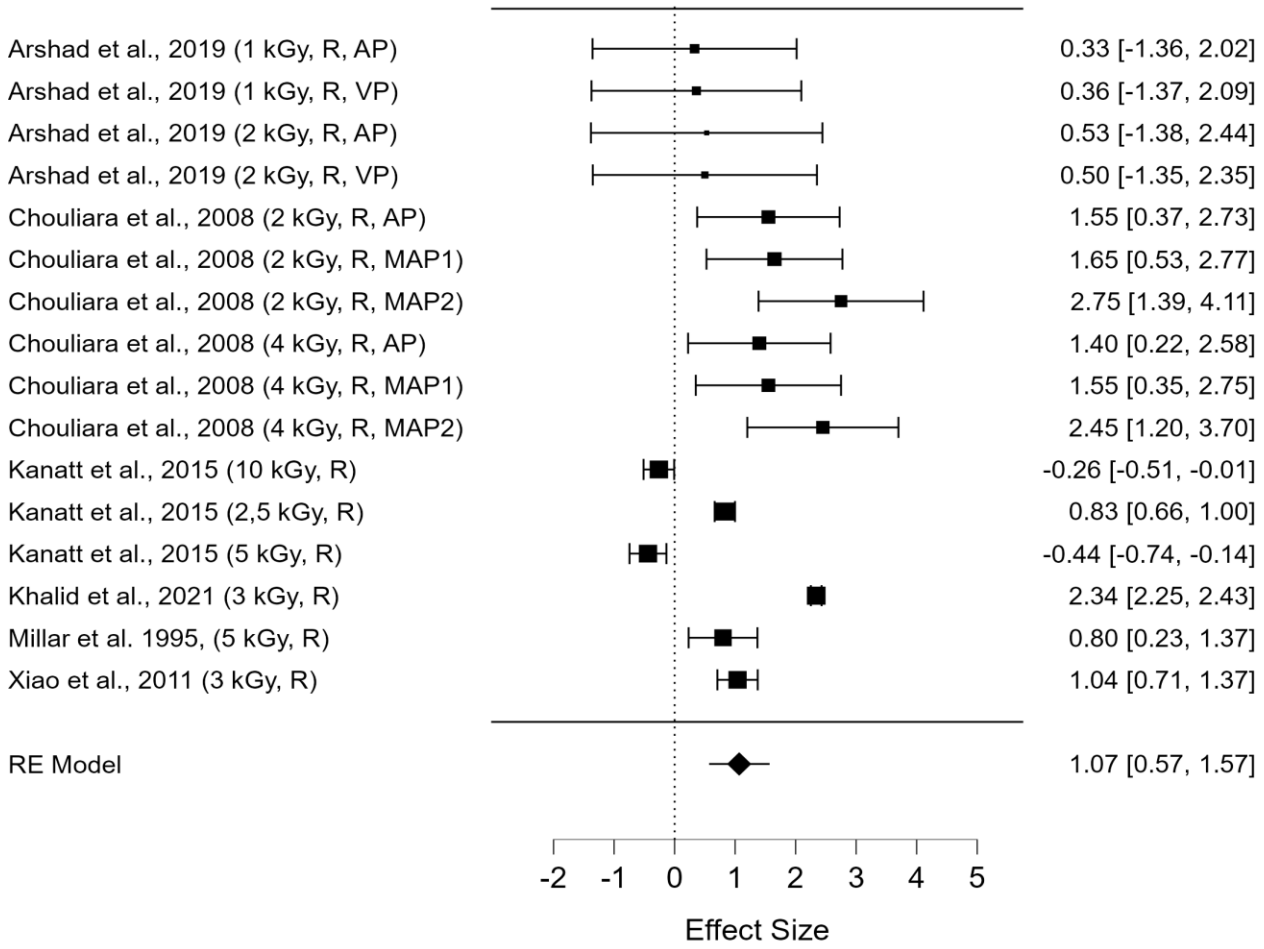


Figure 5. Forest plot of the random-effects model of the gamma irradiation on b* in raw chicken meat

It has been proposed as a marker for irradiated meat by Furuta et al. (1992). Hence, it might be suggested that the increased a* values might be due to formation of carboxymyoglobin (COMb).

Meat contains significant amount of water undergoing radiolysis at gamma irradiation. As a results, aqueous electrons and highly reactive radicals such as hydroxyl radicals are produced (Thakur and Singh 1994). The latter can recombine to produce H_2O_2 in aqueous or oil emulsion systems. According to Harel and Kanner (1985), when activated by H_2O_2, the heme pigments act as strong prooxidants. The reaction of MetMb with H_2O_2 generates ferric peroxide. Both oxy-and ferric peroxide forms of Mb have similar absorbance maxima in the visible region and they can generate a visibly red color (Brewer et al. 2004).

The hydroxyl radicals are strong initiators of lipid oxidation. In an extensive review, Faustman et al. (2010), reported that lipid and myoglobin oxidation are related and the oxidation of one of these induces the formation of chemical species that can provoke oxidation of the other. The authors stated that during lipid oxidation a wide range of primary and secondary products are generated. They can adduct to histidine, lysine, and cysteine residues in myoglobin through alkylation and hence induce its oxidation (Wang et al. 2021). When the central iron atom within the heme group of myoglobin is oxidized, the ferrous heme iron is converted to its ferric form, resulting in change from OxyMb to MetMb, which is responsible for meat discoloration (Faustman et al. 2010).

Rowe et al. (2004) showed that early *post-mortem* irradiation in beef increased oxidation in myofibrillar and sarcoplasmic proteins. They found significant decrease in L* in fresh irradiated beef and after storage of 14 days, as well as decrease in

a* and b* values throughout the whole storage period after irradiation.

Nanke (1998), demonstrated that irradiation induced OxyMb pigment in vacuum packaged pork, whereas in beef it led to formation of both Oxy-and MetMb like pigments. Furthermore, it was shown that colour changes appeared to be independent of myoglobin concentration. In a recent study, Rodriguez et al. (2020) demonstrated increased MetMb accumulation with increased doses of gamma irradiation in beef. This was also confirmed by Khalid et al. (2021) in irradiated chicken meat. The authors observed considerable decrease in the percentage of myoglobin but increase in MetMb after irradiation with 3 kGy. In line with this, Nisar et al. (2020) observed decrease in the percentage of myoglobin in aerobic and vacuum packaged chicken meat. Moreover, they demonstrated significant increase in both OxyMb and MetMb of the irradiated meat regardless of the package, however influenced by the duration of storage.

Conclusions

The meta-analysis helped us to evaluate and summarize the knowledge about the effect of the gamma irradiation on the microbial status and colour of raw chicken meat. It showed that the treatment with gamma rays reduced substantially the microflora as expressed by TVC and TCC. As a result of radiation meat was darker with lower L*, but increased a* and b* values. High variability existed between the studies, that was partially explained by including covariates, such as the irradiation dose, method of storage and packaging. It revealed that the higher dose of rays was associated with lower TVC and TCC, however storage also contributed to the overall effect on this parameter in TVC. The increase of the dose of radiation decreased L* and increased a* of the raw chicken meat.

References

Al-Bachir, M. Microbiological load and quality characteristics of irradiated chicken meat. *Arab Gulf Journal of Scientific Research*, 2013, 31(1): 59-67.

Arshad, M.S., Amjad, Z., Yasin, M., Saeed, F., Imran, A., Sohaib, M., Anjum, F. M., Hussain, S. Quality and stability evaluation of chicken meat treated with gamma irradiation and turmeric powder. *International Journal of Food Properties*, 2019, 22(1): 154-172. https://doi.org/10.1080/10942912.2019.1575395

Arvanitoyannis, I., Tserkezou, P. Legislation on Food Irradiation (EU, US, Canada, Australia, Brazil). In: *Irradiation of Food Commodities* (I. Arvanitoyanis, Ed.). Academic Press, 2010, pp. 3-20. https://doi.org/10.1016/B978-0-12-374718_1.10001-X

Balamatsia, C.C., Rogga, K., Badeka, A., Kontominas, M.G., Savvaidis, I.N. Effect of low-dose radiation on microbiological, chemical, and sensory characteristics of chicken meat stored aerobically at 4 degrees C. *Journal of Food Protection*, 2006, 69(5): 1126-1133. https://doi.org/10.4315/0362-028x-69.5.1126

Bhoir, S.A., Jhaveri, M., Chawla, S.P. (2019). Evaluation and predictive modeling of the effect of chitosan and gamma irradiation on quality of stored chilled chicken meat. *Journal of Food Process Engineering*, 2019, 42(7): e13254. https://doi.org/10.1111/jfpe.13254

Borenstein, M., Hedges, L.V., Higgins, J.P.T., Rothstein, H.R. Introduction to meta-analysis. Chichester, UK: John Wiley & Sons, Ltd., 2009.

Borenstein, M., Hedges, L.V., Higgins, J.P.T., Rothstein, H.R. A basic introduction to fixed-effect and random-effects models in meta-analysis. *Research Synthesis Methods*, 2010, 1(2): 97-111. https://doi.org/10.1002/jrsm.12

Brewer, S. (2004). Irradiation effects on meat color – a review. *Meat Science*, 2004, 68(1): 1-17. https://10.1016/j.meatsci.2004.02

Carriquiry, M., Weber, W.J., Crooker, B.A. Administration of bovine somatotropin in early lactation: A meta-analysis of production responses by multiparous Holstein cows. *Journal of Dairy Science*, 2008, 91(7): 2641-2652. https://doi.org/10.3168/jds.2007-0841

Chouliara, E., Badeka, A., Savvaidis, I., Kontominas, M.G. Combined effect of irradiation and modified atmosphere packaging on shelf-life extension of chicken breast meat: microbiological, chemical and sensory changes. *European Food Research and Technology*, 2007, 226(4): 877-888. https://doi.org/10.1007/s00217-007-0610-3

Correa, W., Brandenburg, J., Behrends, J., Heinbockel, L., Reiling, N., Paulowski, L., Schwudke, D., Stephan, K., Martinez-de-Tejada, G., Brandenburg, K., Gutsmann, T. Inactivation of bacteria by γ-irradiation to investigate the interaction with antimicrobial peptides, *Biophysical Journal*, 2019, 117 (10): 1805-1819. https://doi.org/10.1016/j.bpj.2019.10.012

De Coster, J. Meta-Analysis Notes, 2009. Retrieved on 12.03.2022 Available at http://www.stat-help.com/notes.html

Dourou, D., Spyrelli, E.D., Doulgeraki, A.I., Argyri, A.A., Grounta, A., Nychas, G.E., Chorianopoulos, N.G., Tassou, C.C. Microbiota of chicken breast and thigh fillets stored under different refrigeration temperatures assessed by next-generation sequencing. *Foods*, 2021, 10(4): 765. https://doi.org/10.3390/foods10040765

Erkmen, O., Bozoglu, T.F. Chapter 3 – Food Preservation by low temperatures. In: Food Microbiology: Principles into Practice (First Edition) (O. Erkmen, T. Faruk Bozoglu, Eds.). *Food Microbiology: Principles into Practice*, 2016, pp. 34-43, Print ISBN: 9781119237761, Online ISBN: 9781119237860. https://doi.org/10.1002/9781119237860.ch29

Faustman, C., Sun, Q., Mancini, R., Suman, S.P. Myoglobin and lipid oxidation interactions: mechanistic bases and control. *Meat Science*, 2010, 86(1): 86-94. https://doi.org/10.1016/j.meatsci.2010.04.025

Fernandez-Duque, E. Comparing and combining data across studies: alternatives to significance testing. *Oikos*, 1997, 79(3): 616. https://doi.org/10.2307/3546906

Furuta, M., Dohmaru, T., Katayama, T., Toratani, H., Takeda, A. Detection of irradiated frozen meat and poultry using carbon monoxide gas as a probe. *Journal of Agricultural and Food Chemistry*,1992, 40(7): 1099-1100. https://doi.org/10.1021/jf00019a001

Gonçalves-Tenório, A., Silva, B. N., Rodrigues, V., Cadavez, V., Gonzales-Barron, U. Prevalence of pathogens in poultry meat: a meta-analysis of European published surveys. *Foods*, 2018, 7(5): 69. https://doi.org/10.3390/foods7050069

Harel, S., Kanner, J. Muscle membranal lipid peroxidation initiated by H_2O_2-activated metmyoglobin. *Journal of Agriculture and Food Chemistry*, 1985, 33(6): 1188-1192. https://doi.org/10.1021/jf00066a042

Higgins, J.P.T., Thompson, S.G. Quantifying heterogeneity in meta-analysis. *Statistics in Medicine*, 2002, 21(11): 1539-1558. https://doi.org/10.1002/sim.1186

Islam, A., Sadakuzzaman, M., Hossain, M.A., Hossain, M.M., Hashem, M.A. Effect of gamma irradiation on shelf life and quality of indigenous chicken meat: Irradiation on chicken meat. *Journal of the Bangladesh Agricultural University*, 2019, 17(4): 560-566. https://doi.org/10.3329/jbau.v17i4.44626

Javanmard, M., Rokni, N., Bokaie, S., Shahhosseini, G. Effects of gamma irradiation and frozen storage on microbial, chemical and sensory quality of chicken meat in Iran. *Food Control*, 2006, 17(6): 469-473. https://doi.org/10.1016/j.foodcont.2005.02.008

Kanatt, S.R., Chawla, S.P., Sharma, A. Effect of radiation processing on meat tenderization. *Radiation Physics and Chemistry*, 2015, 111(6): 1-8. https://doi.org/10.1016/j.radphyschem.2015.02.004

Khalid, W., Arshad, M.S., Yasin, M., Imran, A., Ahmad, M.H. Quality characteristics of gamma irradiation and kale eaf powder treated ostrich and chicken meat during storage. *International Journal of Food Properties*, 2021, 24(1): 1335-1348. https://doi.org/10.1080/10942912.2021.1963274

Kralik, G., Kralik, Z., Grčević, M., Hanžek, D. Quality of chicken meat. In: *Animal Husbandry and Nutrition* (B. Yücel, T. Taşkin, Eds). IntechOpen, London, 2017. https://doi.org/10.5772/intechopen.72865

Lacroix, M. Irradiation of foods. In: *Emerging Technologies for Food Processing* (Sun, D.-W., Ed.). Academic Press, 2005, pp.353-386, ISBN: 0-12-676757-2.

Langan, D., Higgins J.P.T., Jackson, D., Bowden, J., Veroniki, A. A., Kontopantelis, E., Viechtbauer, W., Simmonds, M. A comparison of heterogeneity variance estimators in simulated random-effects meta-analyses. *Research Synthesis Methods*, 2019 10(1): 83-98. https://doi.org/10.1002/jrsm.1316

Lawrie, R.A. Chapter 9 – The Storage and Preservation of Meat: III Direct microbial inhibition. In: *Lawrie's Meat Science (Seventh Edition)* (R.A. Lawrie, D.A. Ledward, Eds.). Woodhead Publishing Series in Food Science, Technology and Nutrition, 2006, pp. 264-278, Print ISBN: 9781845691592, eBook ISBN: 9781845691615. https://doi.org/10.1533/9781845691615.264

Lee, Y., Song, K.B. Effect of gamma-irradiation on the molecular properties of myoglobin. *Journal of Biochemistry and Molecular Biology*, 2002, 35(6): 590-594. https://doi.org/10.5483/bmbrep.2002.35.6.590

Mancini R., Hunt M. Current research in meat color. *Meat Science*, 2005, 71(1): 100-121. https://doi.org/10.1016/j.meatsci.2005.03.003

Millar, S.J., Moss, B.W., MacDougall, D.B., Stevenson, M.H. The effect of radiation on the CIELAB colour co-ordinates of chicken breast meat as measured by different instruments. *International Journal of Food Science and Technology*, 1995, 30(5): 663-674. https://10.1111/j.1365-2621.1995.tb01413.x

Nanke, K.E. Effects of ionizing radiation on pork, beef, and turkey quality. PhD thesis by Iowa State University, USA, 1998.

Nisar, M.F., Arshad, M.S., Yasin, M., Khan, M.K., Afzaal, M., Sattar, S., Suleria, H.A.R. Evaluation of gamma irradiation and moringa leaf powder on quality characteristics of meat balls under different

packaging materials. *Journal of Food Processing and Preservation*, 2020, 44(10): e14748. https://doi.org/10.1111/jfpp.14748

OECD Data, 2021 https://data.oecd.org/. Rima, F., Sadakuzzaman, M., Hossain, M., Ali, M., Hashem, M. Effect of gamma irradiation on shelf life and quality of Broiler meat. *SAARC Journal of Agriculture*, 2019, 17(1): 149-159. https://doi.org/10.3329/sja.v17i1.42768

Rodrigues, L.M., Sales, L.A., Fontes, P.R., Torres Filho, R.A., Andrade, M.P.D., Ramos, A.L.S., Ramos, E.M. Combined effects of gamma irradiation and aging on tenderness and quality of beef from Nellore cattle. *Food Chemistry*, 2020, 313(5): 126137. https://doi.org/10.1016/j.foodchem.2019.126137

Rowe, L.J., Maddock., K.R., Lonergan, S.M., Huff-Lonergan, E. Influence of early postmortem protein oxidation on beef quality. *Journal of Animal Science*, 2004, 82(3): 785-793. https://doi.org/10.2527/2004.823785x

Satterlee, L.D., Brown, W.D., Lycometros, C. Stability and characteristics of the pigment produced by gamma irradiation of metmyoglobin. *Journal of Food Science*, 1972, 37(2): 213-217. https://doi.org/10.1111/j.1365-2621.1972.tb05819.x

Shankar, S., Karboune, S., Salmieri, S., Lacroix, M. Development of antimicrobial formulation based on essential oils and gamma irradiation to increase the shelf life of boneless chicken thighs. *Radiation Physics and Chemistry*, 2022, 192(3): 109893. https://doi.org/10.1016/j.radphyschem.2021.109893

Sebranek, J.G., Dikeman, M., Devine, C.E. Irradiation. In: *Encyclopedia of Meat Sciences (Second Edition)* (M. Dekeman, C. Devine, Eds.). Academic Press, 2014. Pp. 140-144. https://doi.org/10.1016/B978-0-12-384731-7.00135-5

Sedeh, F.M., Arbabi, K., Fatolahi, H., Abhari, M. Using gamma irradiation and low temperature on microbial decontamination of red meat in Iran. *Indian Journal of Microbiology*, 2007, 47(1): 72-76. https://doi.org/10.1007/s12088-007-0013-y

Sørheim, O., Nissen, H., Nesbakken, T., The storage life of beef and pork packaged in an atmosphere with low carbon monoxide and high carbon dioxide. *Meat Science*,1999, 52(2): 157-164. https://doi.org/10.1016/S0309-1740(98)00163- 6

Thakur, B.R., Singh, R.K. Food irradiation-chemistry and applications. *Food Reviews International*, 1994, 10(4): 437-473. https://doi.org/10.1080/87559129409541012

Torgby-Tetteh, W., Adu-Gyamfi, A., Odai, B.T., Appiah, V. Combined effect of irradiation and frozen storage on survival of viable bacteria and inoculated Escherichia Coli in chicken. *Journal of Food and Nutrition Sciences*, 2014, 2(3): 53-57. https://doi.org/10.11648/j.jfns.20140203.11

Wang, Y., Li, S., Rentfrow, G., Chen, J., Zhu, H., Suman, S.P. (2021) Myoglobin post-translational modifications influence color stability of beef longissimus lumborum. *Meat and Muscle Biology*, 2021, 5(1): 1-21. https://doi.org/10.22175/mmb.11689

Xiao, S., Zhang, W.G., Lee, E. J., Ma, C.W., Ahn, D.U. Effects of diet, packaging, and irradiation on protein oxidation, lipid oxidation, and color of raw broiler thigh meat during refrigerated storage. *Poultry Science*, 2011, 90(6): 1348-1357. https://doi.org/10.3382/ps.2010-01244

Zhou, G.H., Xu, X.L., Liu, Y. Preservation technologies for fresh meat – A review. *Meat Science*, 2010, 86(1): 119-128. https://doi.org/10.1016/j.meatsci.2010.04.033