Journal of Food Safety and Food Quality
Archiv für Lebensmittelhygiene

J. Food Saf. Food Qual. **2025**; 76(3): 38946
https://doi.org/10.31083/JFSFQ38946

Original Research

Exploration of Electron Beam Irradiation to Enhance the Quality and Safety of Refrigerated Chicken Patties

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Academic Editor: Corinna Kehrenberg
Submitted: 11 March 2025 Revised: 30 July 2025 Accepted: 4 August 2025 Published: 30 August 2025

Abstract

Purpose: This study aimed to evaluate the impact of electron beam irradiation on the microbiological, physicochemical, and sensory attributes of chicken patties stored at refrigeration temperatures (0–4 °C). **Methods**: Freshly prepared chicken patties were subjected to irradiation at 3.0, 3.5, and 4.5 kGy, while non-irradiated samples served as controls. A microbial analysis was performed, and the physicochemical parameters were assessed alongside a sensory evaluation of the samples. **Results**: The microbial analysis revealed the elimination of *Staphylococcus aureus* and a significant delay in the progression of the total viable count towards spoilage levels in the irradiated samples. The physicochemical parameters increased alongside storage time, with irradiated samples exhibiting a slower rate of deterioration compared to controls. The studied samples showed a progressive decline in appearance, texture, flavor, and overall acceptability across the storage period. The samples irradiated with 4.5 kGy exhibited the best microbiological, physicochemical, and sensory attributes for a refrigerated storage of up to 39 days. **Conclusion**: These findings provide evidence on the efficacy of electron beam irradiation at 4.5 kGy in reducing microbial load and preserving the physicochemical and sensory qualities of poultry products, thus contributing to the development of effective preservation strategies specifically for the tropical climate conditions of India.

Keywords: chicken patties; electron beam irradiation; physico-chemical; refrigeration temperature; sensory evaluation

1. Introduction

In the agricultural sector of India, poultry is one of the rapidly growing segments. India ranks 5th in meat production after China, USA, Brazil and Russia. With the country ranking fifth in global broiler meat production and second in egg production (FAOSTAT, 2024) [1], poultry products play a vital role in meeting domestic protein demands. Poultry meat is preferred by consumers worldwide due to its comparative affordability, richness in nutrients, low fat content, non-association with religious taboos, and the variety of processed poultry products commercially available. This demand is increasingly met by fresh poultry meat available for consumption through unorganized wet markets and meat vendors, along with value-added products like ready-to-eat/cook chicken patties, chicken patties, chicken wings, chicken kebabs, chicken sausages, etc. [2].

However, the growing scale of the industry, brings along with it challenges related to food safety. During production operations, processed poultry meat products are susceptible to contamination with potentially pathogenic microorganisms such as *Salmonella* spp., *Campylobacter* spp., *S. aureus*, *E. coli*, and *Listeria* spp. often introduced through equipments, handlers and the environment during processing. These microorganisms are responsible for millions of foodborne illnesses worldwide, with annual economic losses exceeding $3 billion in the United States alone. Among these, poultry meat was the cause of more than 3000 (about 12%) of the cases [3], thus, emphasizing the need for effective decontamination methods.

Despite the implementation of Good Manufacturing Practices (GMPs) and upgraded quality/safety management systems (like HACCP and ISO22000), the problem of post-processing contamination continues to compromise product safety. This necessitates the exploration of various non-thermal sanitization techniques. Among the options—such as high-pressure processing, pulsed light, and ultraviolet treatment (UV)—irradiation has emerged as a scientifically validated approach. In particular, electron beam (e-beam) irradiation is gaining attention due to its rapid processing time, minimal temperature rise, consumer acceptance, and lack of radioactive waste [4,5].

In May 1990, the Food and Drug Administration (FDA) approved the use of irradiation for controlling foodborne pathogens in poultry products [6]. The most commonly used irradiation sources are electron beams and gamma rays. When compared with Gamma irradiation method, which uses nuclear raw material and is at times subject to consumer disapproval, the electron beam offers high intensity dose rate, faster processing, less shielding requirement, while having an easy on and off operation mode

and can be applied in both directions, ensuring that the radiation is distributed evenly across the product [5,7]. This can be effectively used to eliminate organisms like *Listeria monocytogenes*, *Salmonella* spp., *Yersinia enterocolitica*, or *E. coli* O157:H7 [8]. Accelerators capable of producing electron beams with energies up to 10 MeV are used in electron beam irradiation and can penetrate up to 2 to 4 cm. While gamma irradiation can penetrate deeper, the moderate penetration depth of electron beams (up to 4 cm) is sufficient for processed meat products, such as chicken patties [6,7]. According to the Department of Atomic Energy, India, poultry—specifically chicken—is permitted to undergo irradiation at doses of up to 7 kGy for purposes such as microbial reduction and shelf-life extension. Therefore, irradiation with doses less than 7 kGy is generally considered safe for consumption. Whereas, the International Atomic Energy Agency (IAEA) deems food irradiated with electrons generated by a machine with energy less than 10 million electron volts (MeV) safe for human consumption.

In India, research on the impact of electron beam irradiation on processed poultry products, particularly under tropical storage conditions, remains sparse. Most existing studies have focused on raw poultry [7,9,10], with limited foray into processed items like chicken patties, which are gaining popularity. Furthermore, studies referencing the benefits of electron beams originate from regions other than India, without considering the tropical climate, which accelerates microbial spoilage of food, leading to economic losses across the supply chain. Therefore, this study aims to standardize Electron beam doses for the effective irradiation of chicken patties, evaluate their effects on the physicochemical, microbiological, and sensory quality, and determine the shelf life of the chicken patties at refrigeration temperatures in tropical climate conditions of India.

2. Materials and Methods

2.1 Procurement and Processing of Samples for Electron Beam Irradiation

Freshly prepared, ready-to-cook chicken patties were procured from HACCP and ISO-certified processing plants. Each 200 g product was aseptically packaged separately in sterile low-density polyethylene pouches. After being sealed with heat, the packages were delivered to the Board of Radiation and Isotope Technology (BRIT), Sector 20, Turbhe, Navi Mumbai. The chicken patties were divided into four groups of 50 patties each, with one group serving as the control, while the remaining three were subjected to electron beam irradiation at doses of 3.0, 3.5, and 4.5 kGy. One sample consisting of 5 chicken patties (200 gm each) was selected, and homogenized into a single composite sample. From this composite sample, the portions as required for the various tests were aseptically taken for further analysis. This process was repeated for 5 replicates in each group. Likewise, the same procedure was followed for analysis of samples in all control and treatment groups. Further, all the samples were analysed on 10 different intervals (0, 7, 9, 14, 21, 28, 31, 34, 37, 39 and 41st day) throughout the study. The packaged samples were placed in aluminium trays and exposed to radiation from a linear electron beam radiofrequency accelerator on both sides (Energy: 4.5 MeV, Beam Power: 15 kW, Pulsed Linear Accelerator–Electron Beam Accelerator Facility). The beam current was maintained between 0–4.5 mA, and irradiation was conducted at a conveyor velocity of 1.8 m/min. Dosimetry for the irradiation of these samples was carried out using a Radiochromogenic film dosimeter (B-3). Because of the electron beam's limited penetration power, the samples were arranged to have a maximum thickness of 3 cm. Throughout the experiment, the samples were kept at refrigeration temperatures (0–4 °C). Following irradiation, all treated samples were transported in an ice box to the institutes laboratory and stored in a refrigeration room at 0–4 °C until further analysis.

2.2 Microbial Analysis

For microbial analysis, 10 g of sample from each packet was weighed aseptically and transferred to 90 mL of sterile Normal Saline Solution (NSS) in stomacher bags for homogenization in a stomacher (Seward Stomacher 80, Fisher Scientific, Loughborough, Leicestershire, England) for 60 sec. Using 9 mL of sterile Normal Saline Solution (NSS), ten-fold serial dilutions were carried out, up to a 10^6 dilution. The Total Viable Count (TVC) was determined using the standard pour plate method, as outlined in IS 5402:2012. Furthermore, differential counts of specific pathogenic and spoilage organisms were evaluated in duplicate using various selective and differential media, using the spread plate technique. Method and media for the isolation and enumeration were as follows: *Staphylococcus aureus*-IS:5887 part 2-1976 method using Baird Parker agar, *Listeria monocytogenes*-IS 11290-1:1996 method using PALCAM agar, *Bacillus cereus*-IS:5887 part 6-2012 method using *Bacillus cereus* agar, *E. coli* IS:5887 part 1-1976 method using eosin methylene blue agar, *Salmonella* spp. -IS 5887 Part 3:1999 method using xylose lysine deoxycholate agar, *Pseudomonas aeruginosa* -IS 14843:2000 method using *Pseudomonas* isolation agar. The plates were incubated for 24 hours at 37 °C. The yeast and mould-IS:5403 part 1:1999 method using Sabouraud dextrose agar and incubated at 24–25 °C for 5–7 days. For further confirmation, the obtained isolates were subjected to biochemical tests as prescribed in the standards as mentioned above. The microbial analysis of the samples was performed at the storage time of 0, 7, 9, 14, 21, 28, 31, 34, 37, 39 and 41st day until spoilage of the samples were observed.

2.3 Physico-chemical Analysis

Estimation of pH, Thiobarbituric Acid and Tyrosine Value

The pH of all chicken patty samples was measured using a Labman pH meter (Model LMPH-10, Chennai,

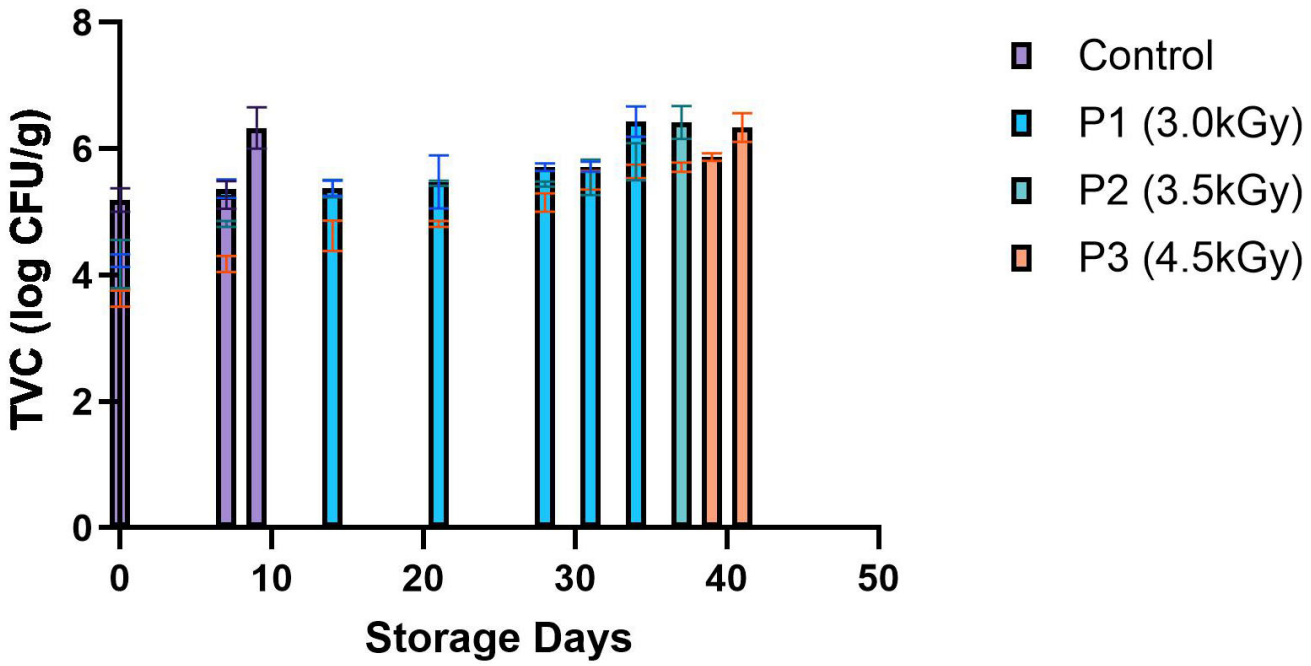

Fig. 1. Average microbiological count (log CFU/gm) and shelf-life of chicken patties treated with electron beam irradiation at the dose rate of 3.0, 3.5 and 4.5 kGy and stored at refrigeration temperature (0–4 °C). Control: non-irradiated chicken patties; P1: Chicken patties irradiated at the dose rate of 3.0 kGy; P2: Chicken patties irradiated at the dose rate of 3.5 kGy; P3: Chicken patties irradiated at the dose rate of 4.5 kGy. TVC, Total Viable Count.

Tamilnadu, India). Tyrosine values and the Thiobarbituric Acid (TBA) number of the control and electron beam-irradiated chicken patties were determined following the method outlined by Strange *et al*. [11], with slight modifications. For TBA number, equal volumes (3 mL each) of trichloroacetic acid (TCA) extract (prepared by mixing the sample with 20% TCA for 2 mins) and 2-thiobarbituric acid were mixed, heated at 100 °C for 30 minutes, cooled, and absorbance measured at 532 nm using a UV spectrophotometer. Whereas, for Tyrosine values, TCA extract was mixed with distilled water and NaOH, followed by Folin–Ciocalteu's reagent; after 30 minutes in the dark, absorbance was read at 660 nm and tyrosine content calculated using a standard curve.

2.4 Sensory Evaluation

A trained, institute-approved panel of 6 personnel scientifically evaluated the sensory properties of the irradiated chicken patties. The panel consisted of members of different age groups, sexes, the veterinary faculty, and the departmental staff. Each parameter in the sensorial analysis was evaluated by a 9-point descriptive scale [12] where 9- Like extremely, 8- Like very much, 7- Like moderately, 6- Like slightly, 5- Neither like nor dislike, 4- Dislike slightly, 3- Dislike moderately, 2- Dislike very much and 1- Dislike extremely. The products underwent testing and evaluation based on appearance, color, flavor, texture, juiciness, and overall acceptability. Following the assessment, the mean values for each parameter were determined. The surface color of the chicken patties was analyzed using a Color Difference Meter (Spectrophotometer Colourflex EZ-45, Reston, VA, USA), measuring Hunter color values L*, a*, and b*.

The chicken patty samples with a TVC above 6 log CFU/g, a pH above 6.3, a TBA value above 1 mg malonaldehyde/kg, and a Tyrosine value above 1 mg/100 g were considered spoiled and were not further considered in the study.

2.5 Statistical Analysis

A randomised block design within treatments was used to collect and analyse the experimental data for every storage day. The study consisted of 4 treatment groups with 5 patties each and 4 replicates in each storage interval. The results were analyzed by ANOVA in "WASP-Web Agri Stat Package-2.0", developed by the ICAR Research Complex, Goa, India.

3. Results and Discussion

3.1 Microbial Analysis

The microbiological quality of electron beam-irradiated and non-irradiated (control) chicken patties stored under refrigeration was assessed at various intervals to evaluate their shelf life. An increase in irradiation dose corresponds to a decrease in microbial count, as shown in Fig. 1. On day 0, the average TVC (log CFU/g) for the control samples was found to be 5.19 ± 0.17 and 4.23 ±

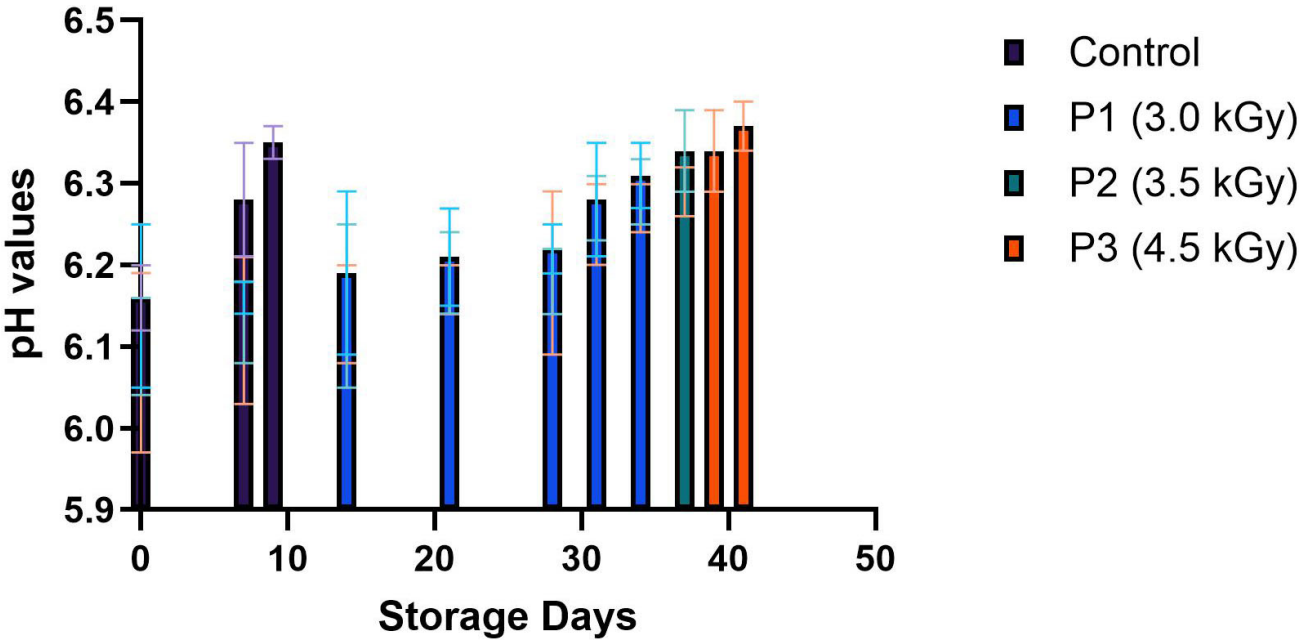

Fig. 2. Average of pH of chicken patties treated with electron beam irradiation at the dose rate of 3.0, 3.5 and 4.5 kGy and stored at refrigeration temperature (0–4 °C). Control: non-irradiated chicken patties; P1: Chicken patties irradiated at the dose rate of 3.0 kGy; P2: Chicken patties irradiated at the dose rate of 3.5 kGy; P3: Chicken patties irradiated at the dose rate of 4.5 kGy.

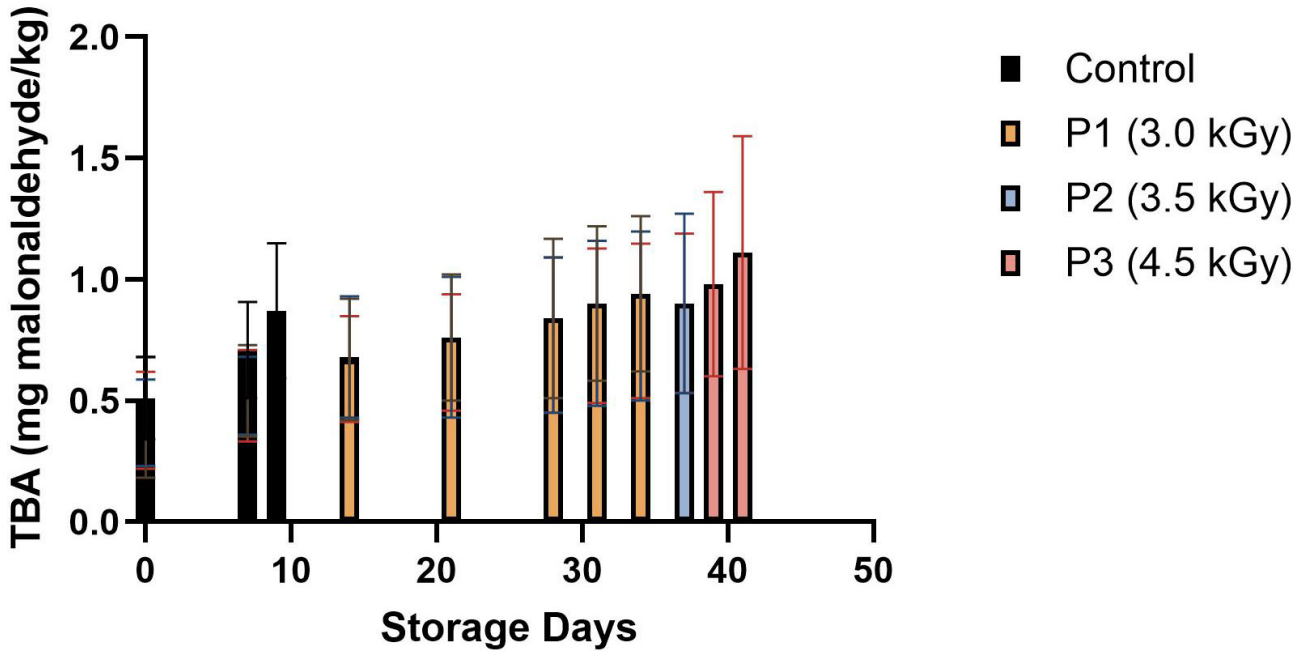

Fig. 3. Average TBA number (mg malonaldehyde/kg) of chicken patties treated with electron beam irradiation at the dose rate of 3.0, 3.5 and 4.5 kGy and stored at refrigeration temperature (0–4 °C). Control: non-irradiated chicken patties; P1: Chicken patties irradiated at the dose rate of 3.0 kGy; P2: Chicken patties irradiated at the dose rate of 3.5 kGy; P3: Chicken patties irradiated at the dose rate of 4.5 kGy. TBA, Thiobarbituric Acid.

0.10, 4.18 $\pm$ 0.39 and 3.63 $\pm$ 0.13, for EB dosage of 3.0, 3.5 and 4.5 kGy, respectively. All control (non-irradiated) chicken patty samples were fully spoiled by the 9th day of storage, with an average Total Viable Count (TVC) of 6.33 $\pm$ 0.35 log CFU/g. For comminuted poultry meat products such as chicken patties, Food Safety and Standards Authority of India (FSSAI) sets an upper permissible limit of 5×10^6 CFU/g (equivalent to 6.7 log CFU/g) for the Total Viable Count (TVC) above which the product is considered unacceptable for consumption. In contrast,

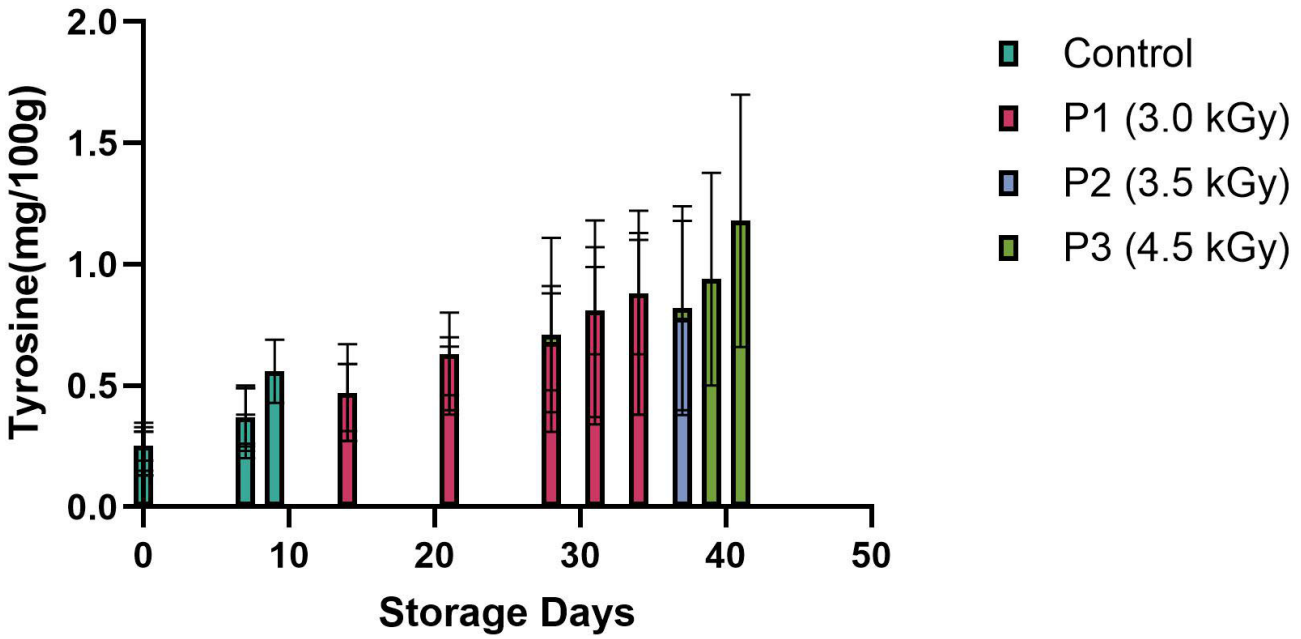

Fig. 4. Average of Tyrosine number (mg/100 g) of chicken patties treated with electron beam irradiation at the dose rate of 3.0, 3.5 and 4.5 kGy and stored at refrigeration temperature (0–4 °C). Control: non-irradiated chicken patties; P1: Chicken patties irradiated at the dose rate of 3.0 kGy; P2: Chicken patties irradiated at the dose rate of 3.5 kGy; P3: Chicken patties irradiated at the dose rate of 4.5 kGy.

samples treated with 3.0, 3.5, and 4.5 kGy reached spoilage on the 34th, 37th, and 41st days of storage, respectively, with average TVC values of 6.43 ± 0.24, 6.42 ± 0.26, and 6.34 ± 0.23 log CFU/g, respectively (Fig. 1). The reduction in the total viable count in the chicken patties samples observed in the present study agree with Li *et al.* [13], who reported a decrease in the microbiota after treatment with electron beam irradiation in ready-to-eat chicken claw samples, with an increase in irradiation dose. Ham *et al.* [14] observed a substantial decrease in the total bacterial count of beef patties as the irradiation dose increased. Likewise, Shin *et al.* [15] also reported that electron beam irradiation at 4 kGy led to a reduction in the microbial count of Bologna sausage.

The extended storage period of the samples up to 41 days at the effective dose rate of 4.5 kGy is in sharp contrast to the non-irradiated control samples wherein spoilage was observed on the 9th day of storage. The observed microbial inhibition is likely due to the ability of ionizing radiation to damage bacterial DNA and interfere with essential cellular processes [16]. Whereas, the initial count of *S. aureus* (log CFU/g) on the 0th day for the control chicken patties samples was 1.89 ± 0.20, and it further spoiled on the 9th day, with a corresponding average count of 3.22 ± 0.33.

None of the samples treated with 3.0, 3.5, and 4.5 kGy exhibited the presence of *S. aureus*. Similar reductions in *S. aureus* counts have been reported in previous studies. Deepika [17–19] and Khillare [20] observed a significant decline in *S. aureus* levels in pork sausages, salami, and raw pork samples following electron beam irradiation. Likewise, Cabeza *et al.* [8] found that treating ham slices with 2 kGy of electron beam irradiation led to a marked reduction in *S. aureus* counts. These findings align with the study by Chang *et al.* [21], who demonstrated that *S. aureus* in suspension culture was totally rendered inactive by 2 kGy of electron beam irradiation, whereas 4 kGy efficiently destroyed *S. aureus* cells in biofilms. Previous studies have reported that increasing the irradiation dose, particularly at higher levels, results in significant fragmentation of cellular components of *S.aureus* organisms. The bacterial inactivation maybe, therefore, attributed to the leakage of biomolecules like adenosine triphosphates (ATPs), nucleic acid and proteins occurring due to European Bioinformatics Institute (EBI) induced cell membrane damage [21]. All the control and irradiated chicken patties samples were also analyzed for detection of *E. coli*, *Salmonella* spp., *Pseudomonas* spp., *Listeria* spp., and *B. cereus* where none of the non-irradiated and irradiated chicken patties samples was found to be positive for these organisms. The control chicken patties samples showed average yeast and mold count as 2.62 ± 0.62 on the 9th day, whereas chicken patties samples treated with dosages 3.0, 3.5, and 4.5 kGy did not show any presence of yeast and mold count, thus indicating the safety of the product at its extended shelf-life.

3.2 Physico-Chemical Changes

A gradual increase in pH values was observed in all chicken patty samples during storage. As shown in Fig. 2, the initial pH values on day 0 for the control samples and those irradiated at 3.0, 3.5, and 4.5 kGy were 6.16 ± 0.04,

Table 1. Average sensory scores of chicken patties treated with electron beam at different dose rate and stored at refrigeration temperature (0–4 °C).

Parameters	Average sensory scores observed on different intervals (Days) at refrigeration temperature										
	Treatment	0	7	9	14	21	28	31	34	37	39	41
Appearance	Control	9.00 ± 0.00	6.20 ± 0.45	5.00 ± 0.01	ND	ND	ND	ND	ND	ND	ND	ND
	P1 (3.0 kGy)	8.00 ± 0.01	7.80 ± 0.00	ND	7.60 ± 0.55	7.40 ± 0.55^{b}	7.40 ± 0.55^{b}	7.00 ± 0.00	6.60 ± 0.89	ND	ND	ND
	P2 (3.5 kGy)	8.20 ± 0.45	8.20 ± 0.45^{b}	ND	8.00 ± 0.45	7.80 ± 0.55^{a}	7.60 ± 0.10^{a}	7.40 ± 0.00	7.20 ± 1.34	6.60 ± 0.55	ND	ND
	P3 (4.5 kGy)	9.00 ± 0.02^{a}	8.40 ± 0.55^{a}	ND	8.20 ± 0.00^{a}	8.00 ± 0.00	8.00 ± 0.00	7.80 ± 0.55	7.40 ± 0.89	6.80 ± 0.55	5.40 ± 0.55	4.80 ± 0.45
Flavour	Control	8.40 ± 0.55	5.40 ± 0.55	4.00 ± 0.02	ND	ND	ND	ND	ND	ND	ND	ND
	P1 (3.0 kGy)	8.20 ± 0.45	8.00 ± 0.00^{b}	ND	7.80 ± 0.45	7.40 ± 0.55	7.20 ± 0.45	7.00 ± 0.84^{b}	6.20 ± 0.45	ND	ND	ND
	P2 (3.5 kGy)	8.40 ± 1.10	8.20 ± 0.45^{b}	ND	8.20 ± 0.84^{b}	7.80 ± 0.45	7.60 ± 0.55	7.40 ± 0.89^{a}	7.00 ± 0.55	6.20 ± 0.45	ND	ND
	P3 (4.5 kGy)	9.00 ± 0.00^{a}	9.00 ± 0.00^{a}	ND	8.80 ± 0.45^{a}	8.60 ± 0.45^{a}	8.20 ± 0.55	7.80 ± 0.55^{a}	7.60 ± 0.55	7.00 ± 0.00	5.00 ± 0.00	4.60 ± 0.55
Texture	Control	8.60 ± 0.89	5.60 ± 0.89^{c}	4.40 ± 0.89	ND	ND	ND	ND	ND	ND	ND	ND
	P1 (3.0 kGy)	8.80 ± 0.45	8.20 ± 0.45^{b}	ND	7.80 ± 0.45^{b}	7.80 ± 0.45^{b}	7.60 ± 0.55^{b}	7.20 ± 0.55	7.00 ± 0.71	ND	ND	ND
	P2 (3.5 kGy)	8.80 ± 0.45	8.20 ± 0.45^{b}	ND	8.00 ± 0.00^{a}	7.80 ± 0.45^{b}	7.40 ± 0.45^{ab}	7.00 ± 0.00	6.60 ± 0.55	6.20 ± 0.84	ND	ND
	P3 (4.5 kGy)	8.60 ± 0.55^{b}	8.00 ± 0.00	ND	8.00 ± 0.00^{a}	8.00 ± 0.00^{a}	8.00 ± 0.00^{a}	7.80 ± 0.45	7.80 ± 0.45	6.80 ± 0.45	5.20 ± 0.45	4.80 ± 0.45
Juiciness	Control	8.40 ± 0.55^{b}	6.40 ± 0.55^{c}	4.40 ± 0.89	ND	ND	ND	ND	ND	ND	ND	ND
	P1 (3.0 kGy)	8.00 ± 0.00^{c}	7.80 ± 0.45^{b}	ND	7.60 ± 0.55	7.40 ± 0.55	7.00 ± 0.55	6.60 ± 0.84	6.20 ± 0.84	ND	ND	ND
	P2 (3.5 kGy)	8.40 ± 0.55^{b}	8.20 ± 0.45^{a}	ND	8.00 ± 0.00^{a}	7.80 ± 0.55	7.60 ± 0.55	7.00 ± 0.00^{b}	6.80 ± 1.22	5.40 ± 0.55	ND	ND
	P3 (4.5 kGy)	8.60 ± 0.55^{a}	8.20 ± 0.45^{a}	ND	8.00 ± 0.00^{a}	7.80 ± 0.00	7.60 ± 0.45	7.20 ± 0.45^{a}	7.00 ± 1.34	6.20 ± 0.45	5.80 ± 0.45	4.60 ± 0.55
Overall acceptability	Control	8.60 ± 0.55^{a}	6.40 ± 0.55	5.40 ± 0.89	ND	ND	ND	ND	ND	ND	ND	ND
	P1 (3.0 kGy)	8.40 ± 0.45	7.80 ± 0.45	ND	7.80 ± 0.45	7.60 ± 0.55^{b}	7.40 ± 0.55^{b}	7.20 ± 0.84	6.60 ± 0.55	ND	ND	ND
	P2 (3.5 kGy)	8.40 ± 1.00	8.20 ± 0.00^{a}	ND	8.00 ± 0.00	7.80 ± 0.45^{b}	7.60 ± 0.45^{ab}	7.40 ± 0.55^{a}	6.80 ± 0.89	6.20 ± 0.45	ND	ND
	P3 (4.5 kGy)	8.60 ± 0.55^{a}	8.40 ± 0.55^{a}	ND	8.00 ± 0.00	8.00 ± 0.00^{a}	7.80 ± 0.00^{a}	7.40 ± 0.45	7.20 ± 0.55^{a}	6.40 ± 0.55	5.60 ± 0.55	4.80 ± 0.45

Note: Means in the same column with the different superscript letters are significantly different ($p \leq 0.05$).

P1, Chicken patties treated with electron beam irradiation at the dose rate of 3.0 kGy; P2, Chicken patties treated with electron beam irradiation at the dose rate of 3.5 kGy; P3, Chicken patties treated with electron beam irradiation at the dose rate of 4.5 kGy; Control, Non-irradiated Chicken patties; ND, Not done.

Table 2. Average colour scores of chicken patties treated with electron beam irradiation at dose rate of 3.0, 3.5 and 4.5 kGy and stored at refrigeration temperature (0–4 °C).

Storage interval (Days)	Average colour scores observed for chicken patties treated with electron beam technology and stored at refrigeration temperature (0–4 °C)											
	L*				a*				b*			
	Control	P1 3 kGy	P2 3.5 kGy	P3 4.5 kGy	Control	P1 3 kGy	P2 3.5 kGy	P3 4.5 kGy	Control	P1 3 kGy	P2 3.5 kGy	P3 4.5 kGy
0	59.72 ± 3.01	59.34 ± 1.69	59.73 ± 1.41	60.51 ± 1.32	7.04 ± 1.18	6.85 ± 1.28	6.69 ± 1.36	5.62 ± 0.44	25.98 ± 2.07	26.10 ± 1.97	25.81 ± 2.25	24.36 ± 1.19
7	63.75 ± 0.37	62.27 ± 1.89	62.63 ± 1.72	62.50 ± 2.35	4.55 ± 0.90	4.50 ± 0.18	4.49 ± 0.52	4.91 ± 0.22	22.02 ± 1.12	22.58 ± 1.23	21.75 ± 0.62	23.37 ± 0.18
9	63.80 ± 0.94	-	-	-	4.52 ± 0.85	-	-	-	21.75 ± 1.58	-	-	-
14	ND	63.70 ± 1.76	63.51 ± 0.90	62.03 ± 2.82	ND	4.26 ± 1.08	4.39 ± 1.07	4.67 ± 1.07	ND	22.35 ± 1.06	21.74 ± 1.77	21.89 ± 2.15
21	ND	63.95 ± 1.31	63.62 ± 2.31	62.54 ± 1.51	ND	3.92 ± 0.75	4.37 ± 1.20	4.49 ± 0.22	ND	21.94 ± 1.99	21.53 ± 2.15	21.63 ± 0.56
28	ND	64.14 ± 1.67	63.76 ± 2.55	63.36 ± 0.91	ND	3.72 ± 1.37	4.29 ± 1.51	4.33 ± 1.18	ND	21.62 ± 0.16	21.11 ± 1.68	21.57 ± 2.22
31	ND	64.94 ± 1.18	64.31 ± 2.61	63.84 ± 2.59	ND	3.67 ± 0.39	3.55 ± 0.43	3.72 ± 0.96	ND	21.59 ± 0.34	20.81 ± 0.81	21.25 ± 1.21
34	ND	65.48 ± 1.42	64.79 ± 1.91	63.89 ± 1.80	ND	3.53 ± 0.27	3.22 ± 0.34	3.55 ± 0.89	ND	21.14 ± 0.54	19.88 ± 1.09	20.94 ± 0.95
37	ND	ND	65.08 ± 1.45	64.47 ± 0.85	ND	ND	2.67 ± 0.27^{b}	3.30 ± 0.35^{a}	ND	ND	19.03 ± 0.43^{b}	20.84 ± 0.81^{a}
39	ND	ND	ND	64.86 ± 0.83	ND	ND	ND	3.26 ± 0.27	ND	ND	ND	20.53 ± 0.71
41	ND	ND	ND	64.99 ± 2.45	ND	ND	ND	3.13 ± 0.24	ND	ND	ND	20.01 ± 0.39

Note: Means in the same rows with the different superscript letters are significantly different ($p \leq 0.05$).

P1, Chicken patties treated with electron beam irradiation at the dose rate of 3.0 kGy; P2, Chicken patties treated with electron beam irradiation at the dose rate of 3.5 kGy; P3, Chicken patties treated with electron beam irradiation at the dose rate of 4.5 kGy; Control, Non irradiated Chicken patties; ND, Not done.

6.15 ± 0.11, 6.10 ± 0.06, and 6.08 ± 0.11, respectively. Spoilage was observed in the control and samples irradiated at 3.0, 3.5, and 4.5 kGy on the 9th, 34th, 37th, and 41st day, respectively, corresponding to pH values of 6.35 ± 0.02, 6.31 ± 0.04, 6.34 ± 0.05, and 6.37 ± 0.03. The observed increase in pH of chicken patty samples aligns with the findings of Deepika [17–19] and Khillare [20], who reported a similar pH increase in control and irradiated pork sausage, salami, and raw pork samples stored under refrigeration throughout the storage period. However, this was in contrast to a study conducted by Wahyono *et al*. [22] where the pH remained unchanged after Electron Beam irradiation on pork samples. This rise in the pH could possibly be due to microbial degradation of proteins and amino acids, forming compounds such as ammonia and amines [23].

The TBA values observed on 0th day for control and irradiated chicken patties at the dose of 3.0, 3.5, and 4.5 kGy were 0.51 ± 0.17, 0.43 ± 0.25, 0.41 ± 0.18 and 0.42 ± 0.20, respectively. These values increased to 0.87 ± 0.28, 0.94 ± 0.32, 0.90 ± 0.37 and 1.11 ± 0.48 on the 9th, 34th, 37th, and 41st day, respectively (Fig. 3). The increase in TBA values in both irradiated and non-irradiated chicken patty samples during the storage period was consistent with the findings of Ham *et al*. [14] and Trindade *et al*. [24], who reported a similar rise in Thiobarbituric acid reactive substances (TBARS) values in processed meat products and beef burgers following electron beam irradiation as storage time progressed. The elevated TBA value in this study indicates the increase in the malonaldehyde value which is an oxidative product of poly unsaturated fatty acid present in the meat, thus suggestive of spoilage of the chicken patties [25].

The average tyrosine values (mg/100 g) of control and irradiated chicken patties samples at the dose rate of 3.0, 3.5, and 4.5 kGy on 0 days were 0.25 ± 0.06, 0.22 ± 0.09, 0.24 ± 0.11 and 0.24 ± 0.09, respectively. The tyrosine values gradually increased to 0.56 ± 0.13, 0.88 ± 0.25, 0.78 ± 0.40 and 1.18 ± 0.52 on 9th, 34th, 37th and 41st day (Fig. 4). The increase in tyrosine values observed in this study is consistent with the findings of Rane *et al*. [5], who reported a similar rise in tyrosine values in chicken nuggets as the storage period progressed. Since it assesses the amount of tyrosine and tryptophan found in the non-protein extract of meat, the tyrosine value serves as a marker of proteolysis of the meat [26]. The growth of spoilage bacteria in the meat leads to both lipolytic and proteolytic changes, resulting in the buildup of breakdown products like free amino acids and aldehydes. Notably, both elevated tyrosine and TBA values with declining sensory scores in the current study, particularly in terms of odor, taste, and overall acceptability suggests a direct relationship between biochemical spoilage markers and sensory deterioration.

3.3 Sensory Evaluation

The sensory scores of irradiated and control chicken patties exhibited a progressive decline across all attributes as storage time increased. Table 1 presents the sensory scores obtained for both control and irradiated chicken patty samples. The colour values of irradiated and control chicken patties at different refrigeration storage intervals are presented in Table 2. The L* values showed an increasing trend over the storage period, while the a* values of irradiated samples decreased with extended storage duration. Significant differences were observed in b* values between the treatment and control groups, with a further decline throughout refrigeration storage. The findings of the current study are consistent with those of Johnson *et al*. [27], who reported that chicken frankfurters treated with electron beam irradiation at 3 kGy maintained their sensory qualities with minimal changes during refrigerated storage for up to 32 days. Remarkably, a previous study reported that the sensory evaluation of irradiated and frozen minced turkey meat showed acceptable sensory scores even after storage up to 6 months [28]. Similar to the present study, no significant differences were found in the sensory evaluation scores between control and irradiated ground beef samples, with a 1 kGy dose exerting minimal impact on tenderness, juiciness, beef flavor, and aroma [29]. Similarly, the L* values for the present study increased throughout storage, which concurs with Rane *et al*. [5] who reported an increase in L* value in irradiated chicken nuggets. The findings of the present study are consistent with those of Wahyono *et al*. [22], who reported a decrease in the a* values of irradiated pork during storage. However, in contrast to our results, Carcel *et al*. [4] observed an increase in the a* values of electron-beam-irradiated chicken steaks and hamburgers with higher irradiation doses. The decline in b* values observed in this study aligns with the findings of Du *et al*. [9], who reported a similar decrease in the b* values of electron beam-irradiated cooked chicken breast fillets over time. Conversely, Carcel *et al*. [4] noted an increase in the b* values of electron beam-irradiated chicken steak and hamburgers with higher irradiation doses. These color changes, particularly the increase in lightness (L*) and decline in redness (a*), may be due to pigment oxidation and structural modifications induced by irradiation and prolonged storage [30].

4. Conclusion

Among all the electron beam irradiation dosages tested, 4.5 kGy proved to be the most effective in extending the shelf life of chicken patties by up to 41 days at refrigerator storage temperatures (0–4 °C). These findings conclude that electron beam irradiation is highly effective in reducing the microbial load in chicken patties, contributing to enhanced safety during refrigerated storage in tropical regions like India, and may be considered as a supplementary method to extend the product shelf life. Furthermore, future

research may focus on the long-term impact of irradiation on nutritional quality and scalability for commercial applications, with sensory evaluation studies involving a larger group of participants.

Availability of Data and Materials

The data mentioned in the article will be available with the corresponding author.

Author Contributions

All authors contributed substantially to the preparation of the manuscript. SR, RK, AS: Performed the research work; RZ and VV: designed the research study; KPR and SAK: provided assistance in treating the samples with Electron Beam; NP and ST: conducted a detailed review of literature, drafted the initial manuscript draft and contributed to the acquisition and interpretation of data in the study; All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

Not applicable.

Acknowledgment

Not applicable.

Funding

The MAFSU-Mumbai centre acknowledges the ICAR-All India Co-ordinated Research Project on Post Harvest Engineering and Technology, Government of India, New Delhi for providing financial assistance to conduct the research.

Conflict of Interest

The authors declare no conflict of interest.

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