RADIATION DOSE MEASUREMENTS PERTAINING TO FOOD IRRADIATION APPLICATIONS: CHALLENGES AND FUTURE ROADMAP

Bhaskar Sanyal[1,2*] and S. Gautam[1,2]
[1]Food Technology Division, Bhabha Atomic Research Centre, Mumbai, India
[2]Homi Bhabha National Institute, Mumbai, India

Email: sanyal@barc.gov.in, sgautam@barc.gov.in

Abstract

Radiation processing is a well-established technology with the potential to mitigate food losses and ensure food safety during postharvest storage. Accurate dosimetry, the measurement of radiation energy absorbed by food, is essential to achieve the desired objectives and comply with international trade requirements. Radiation sources used for food irradiation include radionuclides (Cobalt-60 or Cesium-137) and linear accelerators (generating electron beams with energies less than 10 MeV or X-rays with energies less than 7.5 MeV). The radiation facilities are operated with standardized parameters ensuring operational and radiological safety by the trained personnel. This chapter discusses the fundamentals of radiation dosimetry, challenges faced in dose measurements specific to food irradiation applications, research and development outcomes to address these issues, recent developments in dosimetry, and a future roadmap.

1. Introduction

Nuclear energy has a large number of non-power applications. One such prominent application is processing of food using ionizing radiation to address the food losses during postharvest storage. India is one of the largest producers of agri-produce such as grains, fruits and vegetables. However, a large fraction of these produce gets wasted during the extended period of storage. This happens either due to the inherent perishability of the food or due to the attack of microbes, pests and insects. Based on the extensive R&Ds carried out across the globe, radiation technology has been found as one of the safest and proven method to overcome the wastage of agricultural produces. In India, the development of radiation technology was initiated in the early 60s. Over the last 60 years, BARC has put in considerable research efforts, developed protocols and established radiation dose optimization for a variety of food and allied products.The protocols have also been published as a part of Government of India Gazette notification under DAE Food Irradiation rule 2012[1]. International statutory organizations including WHO, FAO, IAEA, Codex Alimentarius commission have approved different sources of ionizing radiation for food processing. These include gamma radiation emitting radioisotopes (Co^{60} and Cs^{137}), X-rays and electrons generated by linear accelerators operating up to maximum permissible energy levels of 7.5 MeV and 10 MeV, respectively. Subsequently, these sources were also approved by the Food Safety and Standards Authority of India (FSSAI) for radiation food processing of food.

The radiation effects in food are due to the amount of absorbed energy. The determination of this quantity known as absorbed dose constitutes radiation dosimetry which is the crucial parameter to achieve the desired objectives. In view of the stringent requirement of absorbed dose, food irradiation is highly regulated process in regard to the absorbed dose. Therefore, accurate dosimetry methods should not be overlooked to avoid obvious legal and economic consequences. Inadequate processing of foods not only may lead to an economic loss but also reduces confidence of the stakeholders including consumers in the food irradiation technology. Accurate dosimetry is also essential to comply with the internationally accepted procedures for the food being radiation processed for trade in the international markets. Operational parameters of the irradiation facility and the characteristics of the food products are the major factors influencing absorbed dose to the product. Special emphasis is required on the parameters such as type of radiation, distribution pattern of the source, speed of the conveyor, bulk density of the food to ensure the intended objective. The minimum absorbed dose must be delivered and the maximum allowed dose must not be exceeded.

Specific and stringent requirements in radiation processing of food lead to limited choice of dosimeters, accurate calibration and process control. Some of the specific needs of food irradiation are a) radiation processing at lower doses (< 10 kGy) and in certain instances <1 kGy for phytosanitary applications, b) dose delivery with dose rate < 1 kGy/h, c) radiation processing of high-density commodities, and d) irradiation of fish and meat products at frozen and chilled temperatures. Hence, precise exposure to radiation dose to the food products in commercial irradiation facility is of paramount importance to meet the purpose.This chapter discusses the fundamentals of interaction of radiation with matter, dosimetry, challenges faced in dose measurements specific to food irradiation applications, research and development outcomes to address these issues with recent developments, and a future roadmap.

2. Interaction of radiation with matter

During radiation processing, ionizing radiations such as X- rays, gamma rays and electrons are interacting with a matter in random fashion producing secondary particles.These particles further interact with the medium and give rise to bunch of secondary particles. Photons such as γ rays from radioisotopes and X rays from linear accelerator, predominantly interact with the processes a) Photoelectric effect, b) Compton scattering, and c) Pair production.

In photoelectric effect, the photon transfers its full energy to bound atomic electron and dislodge the electron.The emitted electron is called photoelectron. The probability of this effect is governed by the bound electrons of the interacting medium and the energy of the incident photon. On the other hand, in Compton scattering a gamma ray interacts with a free or weakly bound electron and transfers part of its energy to the electron. The impinging electromagnetic radiation is scattered and deviated from its initial direction. Pair production takes place when the energy of the incoming photon is > 1.022 MeV which is twice of the electronic rest mass (0.511MeV) in presence of strong nuclear field. This process creates electron - positron pair.

The interaction of charged particles with matter is different from the photon interaction. Charged particles lose their energies by successive collision with the interacting particles of atoms in the matter. Excitation and ionization take place following the trajectory of the secondary electrons inside the interacting medium. Majority of these secondary electrons are carrying reduced energies and getting scattered. For monoenergetic radiation, the energy deposition is maximum near the surface of the medium. This region is termed as buildup area and the depth depends on the type of the medium and energy of the incident radiation. Subsequently the deposition of energy is decayed following an exponential path based on the radiation attenuation property of the interacting medium as shown in Fig. 1[2,3].

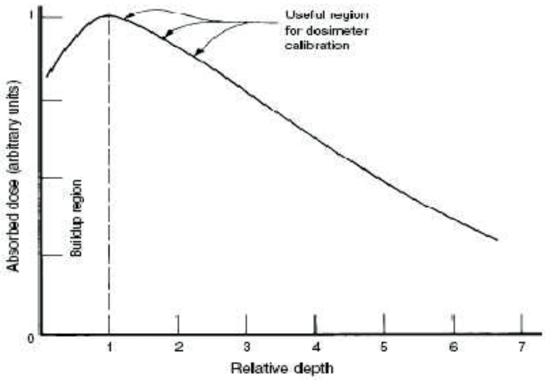

Fig. 1 Deposition of the absorbed doseas a function of thickness (depth) in a medium indicating the buildup zone which is the depth required to achieve charge particle equilibrium and the useful region for the calibration of the dosimeter[3]

3. Fundamentals of radiation absorbed dose

Dosimetry is a branch of applied physics where radiation energy absorbed in the medium is estimated experimentally, using computation, or a combination of both. The quantity 'absorbed dose' is the most important quantity in radiation processing of food to obtain an accurate information on the efficacy of the ionizing radiations. Dosimetry is the only tool which provides information to the regulatory agencies for the acceptance of the food commodities ensuring accurate dose delivery to the foods within the stipulated dose range.

Absorbed dose

The effects (physical, chemical and biological) of ionizing radiation do not solely depend on the energy transferred to the medium, but on the energy absorbed by it. The quantity absorbed dose (D) is defined by the amount of energy absorbed per unit mass of the matter at the point of interest.

$$D = \overline{d\varepsilon} / dm \qquad (1)$$

Where, $\overline{d\varepsilon}$ is the mean energy absorbed by the medium and dm is the mass of interest.

The SI unit of absorbed dose is gray (Gy) and the CGS unit is rad.

1 Gy = 1 J/kg = 100 rad

Radiation attenuation characteristics are different for different materials for any given irradiation conditions. Therefore, it is required to convert the absorbed dose in other materials of user interest using following relation.

$$D_M = D_D \times (\mu_{en}/\rho)_M / (\mu_{en}/\rho)_D \qquad (2)$$

Where, D_M is the dose absorbed by the medium,

D_D is the dose absorbed by the dosimeter,

$(\mu_{en}/\rho)_M$ is the energy attenuation coefficient of the medium, and

$(\mu_{en}/\rho)_D$ is the energy attenuation coefficient of the dosimeter.

The medium is generally considered as water for food because food is considered to be water equivalent.

4. Dosimeters for radiation processing of food

Various dosimetry systems are available for different applications in the area of radiation processing. Their intrinsic accuracy forms the basis of the classification of dosimeters. Such classification shows a typical traceability chain starting at the top position with primary standards. Four classes of dosimetry systems based on their zone of employment are:

a. Primary standard dosimeter: Primary standard dosimeter enables absolute dose measurements with reference to base SI units (mass, length, time, electric current) and fundamental physical constants. National Standards Laboratories operate them. The primary standard dosimeters are ionization chambers and calorimeters. The overall uncertainty of these systems is ± 1% (2σ).

b. Reference standard dosimeter: A Reference standard dosimeter is one with a high metrological quality and is used as a standard to calibrate other dosimeters in the lower level of the traceability chain. In case of reference standard system, the change due to radiation must be accurately measurable and must have a well-defined functional relationship with the absorbed dose. The overall uncertainty is ± 1% (2σ).The commonly used dosimetry systems are Fricke solution, ceric-cerous dosimeter, and alanine with electron paramagnetic resonance (EPR) as measurement method.

c. Transfer standard dosimeter: They are used as mailing dosimeters for calibration because of easy transportability and capability to ensure traceability. This class of systems are used to carry out dose inter-comparison studies among various laboratories and irradiation facilities. Examples are alanine, ceric-cerous sulphate solution etc.

d. Routine dosimeter: These are used for process control during irradiation of food commodities.These systems are different from otherswith respect to their accuracy. However, they are simple, cost-effective and convenient systems.The effects of factors such as irradiation temperature, dose rates etc. on a routine dosimeter are normally complex. Therefore, frequent calibration of this dosimeter with respect to higher dosimeters is necessary to obtain accurate dosimetry. The overall uncertainty is ± 10% (2σ). Materials like polyethylene strip, films, solutions, dyes, polycrystals or amorphous systems are utilized for routine dosimetry.

The dosimetry systems available for applications in radiation processing of food is shown in Table 1. A suitable dosimeteris identified in view of application and required accuracy as per the criteria based on the Standard Guide ASTM E1261, 2000[4]

Table 1. Dosimeters and their useful dose ranges

Materials	Type of radiation	Measurement method	Dose Range (Gy)	ASTM No.
Radiochromic Film	Electron/ Photons (γ and X-rays)	Spectrophotometer	$1 - 1.5 \times 10^5$	51275
Polymethyl methacrylate	Photons (γ and X-rays)	Spectrophotometer	$10^2 - 1.5 \times 10^5$	51276
Radiochromic Optical wave guide	Photons (γ and X-rays)	Spectrophotometer	$1 - 10^5$	51310
Dichromate	Photons (γ and X-rays)	Spectrophotometer	$2 \times 10^3 - 5 \times 10^4$	51401
Ethanol chlorobenzene solution	Photons (γ and X-rays)	Spectrophotometer, colour titration, high frequency conductivity	$10 - 2\ \mathrm{x} 10^5$	51538
Alanine	Electron / Photons (γ and X-rays)	Electron Paramagnetic Resonance spectrometer	$1 - 10^5$	51607
Calorimetric	Electron	Calorimeter	$10^2 - 5 \times 10^4$	51631
Cellulose tri acetate	Electron / Photons (γ and X-rays)	Spectrophotometer	$5 \times 10^3 - 3 \times 10^5$	51650
Fricke solution	Photons (γ and X-rays)	UV spectrophotometer	$20 - 4 \times 10^2$	51026
Ceric-Cerous Sulfate	Photons (γ and X-rays)	Potentiometry	$5 \times 10^2 - 5 \times 10^4$	51208

5. R&Ds and Challenges in food irradiation dosimetry

Radiation measurement is important for quality assurance program of an irradiation facility. Radiation processing of food possess very special requirements leading to limited choice of materials as dosimeters. In addition, irradiation at subzero conditions (chilled and frozen) for the fish and meat products has the requirement to measure the radiation dose with a system which can register dose at sub-ambient temperatures. The majority of the aqueous systems used in food irradiation applications such as ceric cerous sulphate and Fricke dosimeters cannot be employed at sub-ambient temperature because of the self-freezing of the systems. Radiation absorbed dose is also dependent on the density of the product and a significant variation in densities of the food and wide dose range further adding to the dose measurement challenges. Therefore, a single dosimetry system is not sufficient and research and development is essential to develop new dosimeters to address these challenges.

5.1. Studies on solid state systems for food irradiation dosimetry using thermoluminescence

5.1.1 Studies on polycrystalline phosphor

Thermoluminescence (TL) materials are used for personnel and environmental dosimetry in general, but not very often in the dose range of food irradiation applications. In case of personnel monitoring, patient dosimetry, and environmental monitoring $CaSO_4$: Dy has been established as a useful thermoluminescence dosimeter (TLD). Considerable quantity of commodities namely sea foods are required to be irradiated at chilled (0º ± 3ºC) or frozen (-10 ± 4ºC) temperature in the dose range of 4.0 -7.0 kGy. Various high dose measurement methods exist, but they are either not cost-effective or improper for low temperatures dose estimation. On the other hand, solid-state thermoluminescence dosimeters are cheaper with user-friendly measurement methods. In radiation protection applications, the dosimetry TL peak (240ºC) of $CaSO_4$:Dyphosphor is linear up to 10 Gy[5]. Supralinear dose response has been reported in the dose range of 10 Gy to 5.0 kGy at ambient temperature of irradiation[6]. The concentration of dysprosium normally used is 0.1 mol % and the saturation of TL response could be because of the inadequate numbers of the available trapping centers to trap the radiation-induced charge carriers[7]. To address these issues, increased concentration (0.2 mol %) of dysprosium was chosen to prepare a $CaSO_4$ based TL phosphor. Bakshi et al, 2002[8] reported that the thermal treatment of $CaSO_4$:Dy in the range of 400 – 700ºC enhances the response of high temperature peak. In view of this, effort was made to understand the behavior of the untreated and thermally annealed $CaSO_4$: Dy (0.2 mol %) phosphor upon exposure at sub-zero conditions. TL and EPR correlation studies helped to understand the TL characteristics of the phosphor subjected to pre-irradiation annealing. The dose range was chosen as 0.5 to 7.0 kGy. The phosphor was subjected to different pre-irradiation thermal treatments at 700 to 900°C to enhance the sensitivity of the low temperature TL peak at 142°C. An improved linear dose response of the glow peak (142◦C) at sub-zero irradiation was observed. The results revealed that thermally modified $CaSO_4$:Dy can be considered as an efficient dosimeter capable of low-temperature dose measurements useful for food irradiation[9].

In order to further simplify the preparation of the $CaSO_4$:Dy phosphor at user level avoiding pre-irradiation thermal treatments $CaSO_4$: (Dy, Bi) phosphor was prepared through recrystallization method. The TL sensitivity reduction with increase in Bi_3+ co-dopant in the phosphor was correlated with the quenching of TL by Bi_3^+ ions rather than the reduction in the concentration of the above defect centers[10]. Electron Paramagnetic Resonance spectroscopy (EPR) was employed to investigate the radiation induced radical ions formed. It was also observed that EPR signal intensities of SO_4^- and SO_3^-reduced drastically at 250°C annealed phosphor confirming the role of the defect centers in the dosimetric TL peak. Bi_3^+ co-doped $CaSO_4$:Dy phosphor also exhibited its potential in sub-ambient dose measurements.

5.1.2 Studies on Amorphous systems

The studies showed that the luminescence method may be a promising area of research to measure high radiation doses delivered during different irradiation applications. Polycrystals as host matrices of the dosimeters showed limitations in the high dose measurements. Solid state amorphous systems could be of paramount importance for this specific application in the dose range of 20 Gy to 25 kGy because of their inherent inertness toward radiation. The limited sensitivity of amorphous materials like glass to register radiation-induced information is because of their disordered structure with no long-range symmetry. On the other hand, in the case of crystal the atoms are organized in a regular and periodic lattice. The atoms are so systematically arranged that the prediction of large number of atoms in all directions is possible except for occasional crystal defects. This spatial regularity is called long-range order and possibly responsible for their sensitivity toward ionizing radiation leading to saturation in luminescence characteristics at high dose ranges. In case of glass the atoms are arranged randomly because glass is essentially a super-stiff liquid. Its atoms are agglomerated in a sloppy fashion and their mobility is restricted resulting incapability to form a more orderly distribution. Materials reach at this amorphous state when hot liquid glass is cooled very fast. Glasses have various chemical and physical properties and they can be prepared by suitably altering their components. The major glasses are a) Commercial glass (soda-lime glass), b) Lead glass, c) Borosilicate glass, and d) Glass fiber. In order to exploit these structural properties of glass to develop radiation measuring devices several studies are being carried out worldwide. A few such studies are also being carried out with the objective to synthesize solid state systems. This study also includes identification of suitable dopants, understanding of luminescence mechanisms and evaluation of all dosimetric properties as elaborated below.

MnO doped calcium fluoroborophosphate glasses were synthesized. The samples were irradiated to γ-ray doses in the range 250–1000 Gy and their thermoluminescence (TL) characteristics were analyzed. The TL glow curves exhibited an intense peak at about 200 °C. It was observed that a gradual increase of MnO concentration in the glass matrix resulted in a decrement in the integral TL output. This could be because of different valence states of Mn ions in the glass matrix. The quenching effect was observed as a major player in measuring the high radiation doses without saturating the PMT of the reader. The TL response of integral TL output exhibited perfectly linear dose response in the range of 250–1000 Gy[11]. In another study, lead aluminosilicate glass was prepared with doping dysprosium ($PbO–Al_2O_3–SiO_2$: Dy^{3+}) to assess its thermoluminescence properties. The concentration of Al_2O_3 was varied (5–10 mol%) to understand its role in TL output after exposure to γ-rays dose till 5 kGy. It was observed that the TL emission was enhanced with increasing Al_2O_3 concentration till 3.0 mol% for any fixed dose, and beyond this concentration, quenching of TL was significant. The dose response of TL emission showed linear behavior in the dose range of 0.5 - 4 kGy. The glow curves were characterized by a dosimetric peak at 180°C[12]. In dosimetry, one of the desired characteristics of the dosimeter is to have an effective atomic weight equivalent to tissue or water (Z_{eff}= 7.3). In order to further improve the dosimetric response with energy independent behavior having Z_{eff} near tissue a glass system composed of lithium borate ($30Li_2O–70B_2O_3$) was synthesized to studyTL response. To enhance the TL characteristics 0.5 wt% of Dy_2O_3 was added prior to the glass making. No significant change in density and glass transition were observed after incorporation of Dy_2O_3. However, optical properties such as photoluminescence, absorption and band gap exhibited measurable changes. The samples emitted TL glow with peaks at around 136 and 152 °C after gamma irradiation in the dose range of 0.5–5 kGy with a linear dose response[13]. In order to study the effect of transition metal ions as dopants lithium borate glass was also synthesized using 0.5 wt% CuO and EuO. The glass with Dy_2O_3 as dopant exhibited most enhanced thermoluminescence with linear dose response. Kinetic parameters were also investigated for Dy_2O_3 doped glasses to understand TL mechanism. Electron paramagnetic resonance spectroscopy was carried out to understand the electron and hole pair generation process upon irradiation and the results were correlated with TL characteristics to understand its probable mechanism. Lithium Borate glass with Dy^{3+} dopant was found to be one of the potential glasses to measure high radiation doses suitable for food irradiation and industries associated with materials processing[14]. However, the studies on time kinetics of TL emission suggested further compositional improvements are required to ensure signal stability.

5.2 Challenges in routine dosimetry

In routine dosimetry periodical determination of the absorbed doses into the product of the irradiation volume is carried out in all the irradiation facilities. Different dosimeters are being employed for the measurements of the radiation doses in the range of 0.02 to 25 kGy. Based on the purpose of irradiation two dose limits namely Dose minimum (D_{min}) and Dose maximum (D_{max}) are defined for each class of food products to ensure dose delivery within the given range. The dose uniformity ratio (DUR) is defined by the ratio of the upper dose limit to the lower dose limit. In a commercial food irradiation facility, the process container and the source configuration are fixed. Hence, the bulk density of the process load is the major parameter influencing non uniformity in the dose distribution. The behavior of D_{max}, D_{min} and DUR with different media having variable bulk densities was investigated in a category IV irradiator where radiation was imparted on both the sides of the product container[15]. The results suggested that the D_{min} should be measured using the actual process load to avoid variation in bulk densities between dummy and actual processing materials. DUR exhibited a continuous enhancement with the increase of density. It was noteworthy that the geometry of the individual food commodity influences the final absorbed dose to the products.

6. Future roadmap of radiation dose measurement in food

6.1 Radiochromic compounds for food irradiation dose measurements

Radiation preservation of food is commercially being carried out using Cobalt 60 based irradiation facilities. However, with increasing need of higher process rate and radiation processing of perishable foods at subzero temperatures linear accelerators are gaining interest as preferable option. Therefore, accurate measurements of absorbed dose are necessary to achieve the desired objective of radiation processing. The leuko-dyes are colorless and develop colour when irradiated and can be used as the basis of dosimeters. Radiochromic systems in the forms of film and liquid are required for accelerator and radionuclide-based irradiation facilities, respectively. In radiochromic dosimeters, chemical reactions take place resulting optical bands. A spectrophotometer or photometer is used to measure the absorbance in these optical bands induced by radiation[16]. A wide dose range starting from 1 Gy to 25 kGy can be measured using radiochromic dosimeters. This is widely utilized as a routine dosimeter not only for the phytosanitary application but also to measure absorbed doses in the food irradiated to achieve different objectives. In view of this, there are enough scope of research for synthesis of various radiochromic dyes indigenously and subsequent preparation of thin films for radiation measurements. A leuco crystal radiochromic dye based thin film has been developed and acceptable efficacy was observed in dosimetry useful for radiation processing of food.

There is a need to develop simple and cost-effective dosimeter as an import substitute for phytosanitary application of food. Dosimeters like Fricke, ceric-cerous sulphate, optichromic are in use to measure absorbed doses within their respective operational range. Fricke is a well-established reference standard dosimeter that covers the dose range of 20 – 400 Gy. Ceric–cerous sulphate (3 mM) dosimeters can measure doses starting from 500 Gy. The dose range of measurement for ceric-cerous (15 mM) dosimeters starts from 8 kGy. Optichromic wave-guide systems are available in the low dose range but they are required to be imported and show non-reliability during storage. No cost-effective single dosimeter is available in the dose range of 25 to 1000 Gy in India. Reliable, user-friendly and cost-effective dosimeter in the low dose range is the need of the hour. An indigenous dye-based dosimeter has been developed and validated. This new system has immense potential of deployment for the measurements of low dose radiation processing of food. This dosimeter is an aqueous system used for measuring gamma radiation doses in Cobalt-60 irradiation facilities and may not be suitable for electron beam facilities. In this field, there is immense scope to do research to synthesize radiosensitive dye molecules and dosimetric characterization for subsequent deployment in the commercial domain.

6.2 Dosimetry for surface decontamination of foods using low energy radiation

There is an increasing demand on food processing industries to mitigate their impact in the environment. A novel option using low energy beams has been initiated for food and agricultural products to mitigate environmental impact.The industries associated with food processing are looking for in-line mechanism to eliminate microorganisms available either on the surface or in some superficial segments of the foods. The efficacy of the radiation surface treatment using low energy electron beam for food commodities such as spices, herbs, or grains are being studied[17]. A deeper understanding on the interactions of low energy electron beam (LEEB) and low energy x-ray (LEEX) sources is essential to explore their efficacy in radiation treatment of foods. In this case, one of the major challenges is to measure the energy imparted on the surface and penetration depth of the low energy beam. Established methods employed to measure absorbed dose in10 MeV linear accelerators are not suitable for low energy electron beam due to the considerable thickness of the measurement systems. Thin dosimetric foil could be a potential candidate to address this issue with various inherent challenges such as development of dosimeters capable of surface dose measurement and monitoring dose distribution confined in the surface. Applications of computational dosimetry based on Monte Carlo simulation may be of major interest to estimate the surface dose and subsequent validation using a thin radiochromic film[18].

7. Conclusion

An ideal dosimeter should have some desired characteristics which includes a) reproducible dose response over a wide dose range, b) adequate precision, c) suitable pre and post-irradiation stability, d) energy independency of the incident radiation, e) dose rate independency, f) independency on small compositional changes, and g) user-friendly with low cost. Therefore, a dedicated and sustainable research is essential to develop dosimeters for achieving the desired goals. In addition, dose measurement in radiation processing of food has unique requirements and systematic studies are the need of the hour to address the specific challenges. Machine sources (LINAC) have enhanced dose rates leading to increased process rates. Therefore, there is an increasing demand of these sources especially for the perishable food commodities to be processed at sub-ambient temperature. Aqueous dosimeters are not suitable to measure radiation dose in LINAC operating in electron-beam mode. Synthesis of novel solid-state systems in thin film shape and subsequent dosimetric characterization is of paramount interest for electron-beam dose measurements. On the other hand, luminescence technique is another potential area of research to measure higher doses delivered during radiation processing applications. Dosimeters made of crystalline materials exhibit saturation in dose estimation at higher doses and therefore development of amorphous systems is gaining importance. Computational dose estimation and thin-film dosimeter are also gaining importance as appropriate options for surface dose measurements of food using low energy accelerators.

References

1. Atomic Energy (Radiation Processing of Food and Allied Products) Rules, 2012
2. Rizzo, F X. Irradiator design calculational techniques based on centre line depth dose distributions, International Journal of Radiation Engineering 1971, 1, 549–584.
3. IAEA Technical Reports Series No. 409. 2002. Dosimetry for food irradiation. International Atomic Energy Agency, Vienna.
4. ASTM Standard guide ASTM E1261. 2000. Selection and Calibration of Dosimetry Systems for Radiation Processing. Annual Book of ASTM Standards. Vol. 12.02, ASTM, Philadelphia, PA.

5. Campos, L.L.; Lima, M.F. Dosimetric properties of CaSO4:Dyteflon pellets produced at IPEN. Radiation Protection Dosimetry 1986, 14, 333-335.
6. ASTM Standard, 51956. 2005 (E). Standard practice for use of thermoluminescence dosimetry (TLD) systems for radiation processing.
7. Mathur, V.K.; Lewandowski, A.C.;Guardala, N.A.; Price, J.L. High dose measurements using thermoluminescence of CaSO4: Dy. Radiation. Measurements1999, 30, 735-738.
8. Bakshi, A.K.; Pradhan, A.S.; Srivastava, K.;Kolambe, D.H. New parameters of annealing and re-use of TLDs based on CaSO4:Dy phosphor. Radiation. Protection Dosimetry 2002, 100, 293-296.
9. Sanyal, B.;Natarajan, V.; Chawla, S. P.;Sharma, A. TL and EPR studies of $CaSO_4$: Dy phosphor to investigate its efficacy in measurement of food irradiation dose at sub-ambient temperature. Radiation measurements 2010, 45, 899 – 905.
10. Bakshi, A. K.; Sanyal, B.; Joshi, V. J.;Bhide, M. K.; Natarajan, V.; Sharma, A. EPR-TL correlation studies on bi co-doped $CaSO_4$: Dy phosphor. Applied Radiation and Isotope 2011, 69, 254 – 260.
11. Swamy B. J. R.; Sanyal B.; Gandhi Y.; Kadam, R. M.; Natarajan, V.; Raghava Rao P.;Veeraiah N. Thermoluminescence study of MnO doped borophosphate glass samples for radiation dosimetry. Journal of Non-Crystalline Solids 2013, 368, 40-44.
12. Rao, M. S.; Sanyal, B.;Bhargavi, K.;Kityk, I. V.;Veeraiah, N. Influence of induced structural changes on thermoluminescence characteristics of γ–ray irradiated PbO–Al2O3–SiO2: Dy3+glasses. Journal of Molecular Structure 2014, 1073,174–180.
13. Sanyal, B.; Goswami, M.; Shobha, S.;Prakasan, V.; Chawla, S. P.; Krishnan, M.; Ghosh, S. K. Synthesis and characterization of Dy3+ doped lithium borate glass for thermoluminescence dosimetry. J Non-Crystalline Solids 2017, 475, 184 - 189.
14. Sanyal, B.; Goswami, M.; Shobha, S.;Prakasan, V.; Krishnan, M.; Ghosh, S. K. Thermoluminescence and Electron Paramagnetic Resonance study on rare earth/transition metal doped lithium borate glasses for dosimetry applications. Journal of Luminescence 2019, 216, 116725, 1 – 9
15. Sanyal, B.; Prakasan, V.; Chawla, S. P.; Ghosh, S. K. A study to assess the role of bulk density of process load in Co60 based food irradiation facility. BARC News Letter (Jan-Feb) 2017, 17-19.
16. ISO/ASTM 51275:2013 (E). 2013. Practice for use of a radiochromic film dosimetry system.
17. Jahn, M.;Röder, O.;Tigges, J. Electron treatment of cereal crop seeds – overview and appraisal of field trials. Mitteilungenaus der BiologischenBundesanstaltfür Land- und Forstwirtschaft. 2005, 399, 66 – 128.
18. Matsui, S.; Mori, Y.; Nonaka, T.; Hattori, T.;Kasamatsu, Y.;Haraguchi, D.; Watanabe, Y.; Uchiyama, K.; Ishikawa, M.Energy deposition evaluation for ultra-low energy electron beam irradiation systems using calibrated thin radiochromic film and Monte Carlo simulations. Review of scientific instruments 2016, 87, 053309.