Hue University Journal of Science: Natural Science
Vol. 131, No. 1B, 73–79, 2022

pISSN 1859-1388
eISSN 2615-9678

Depth-dose distribution in potatoes with low-energy X-rays

Nguyen Thi Nguyet Ha*, Tamikazu Kume, Nguyen An Son, Nguyen Thi Minh Sang, Pham Thi Ngoc Ha, Nguyen Danh Hung, Cao Van Hai, Nguyen Quang Kien, Nguyen Huu Duc, Do Thi Le

Dalat University, 1 Phu Dong Thien Vuong St., Dalat, Vietnam

* Correspondence to Nguyen Thi Nguyet Ha <hantn@dlu.edu.vn>

(*Received: 8 September 2021; Accepted: 18 November 2021*)

Abstract. Irradiation is known as a handful measure to inhibit potato sprouting, kill harmful bacteria, and increase preservation. The absorbed dose is one of the essential characteristics of the irradiation process. In this study, the depth-dose distributions in potatoes and polymethyl methacrylate were investigated under low-energy X-ray irradiation by using the Fricke dosimeter and Gafchromic film dosimeter. The dose rates required for the rays to penetrate in polymethyl methacrylate were compared with those in potatoes. Polymethyl methacrylate could be used as a phantom in measuring the depth dose delivered in potatoes. The difference in depth-dose distribution in potatoes between one-sided and double-sided irradiation was also investigated. The calculated dose uniformity ratio values are 5.8 and 1.9 for potatoes irradiating one-sided and double-sided.

Keywords: depth-dose distribution, gafchromic film dosimeter, low-energy X-rays, potato

1 Introduction

The application of radiation technology in the food industry has been investigated since the late nineteenth century [1, 2] and widely implemented in numerous countries [3]. The detailed depth-dose distribution in the irradiated samples is required for food radiation processing. Dosimetry is a reliable technique for measuring and calculating the dose. According to the intrinsic accuracy and usage, there are four types of dosimetry systems: (1) primary standards (ion chamber, calorimeters); (2) reference standards (alanine, Fricke, and other chemicals); (3) transfer standards (thermoluminescent dosimeter); (4) routine dosimeters (process monitoring, radiochromic films) [4, 5].

Because of various appealing characteristics, such as reliability, accuracy, near tissue equivalent, and high sensitivity of all kinds of ionizing radiation, radiochromic dosimetry films have been widely employed for the quantitative measurement of absorbed dose in different materials in radiation processing, including sterilization of food and medical devices [6, 7]. Radiochromic films were used to study the X-ray depth-dose distribution in bulk biological samples [8]. Ishizaka et al. utilized a radiochromic film to calculate relative intensity distribution by using gamma-ray irradiation [9]. The dose delivered to polymethyl methacrylate and polyethylene was determined by using a radiochromic film with a 10 MeV electron accelerator [10].

Potato is a common food in the world and provides various benefits for people’s health. However, sprouting and harmful bacteria species are the main problems of potato preservation. For inhibiting sprouting, the irradiation technique has been applied since the 1950s [11] and developed

DOI: 10.26459/hueunijns.v131i1B.6514

until recently. There have been works on the effect of irradiation on potato sprout inhibition [12-15]. Some studies reported using radiation for micro pathogen killing or bacteria inactivation purposes [16, 17].

According to the Codex General Standard for irradiation of food [18], there are three types of radiation used for food irradiation: gamma rays (^{60}Co and ^{137}Cs), electron beams with energy less than 10 MeV, and X-rays with energy less than 5 MeV. Among them, gamma rays from ^{60}Co, high-energy electron beams, and X-rays are commonly used for commercial irradiation. Nowadays, low-energy X-ray devices have been used for non-bulky food and small-scale irradiation. The advantages of these devices are as follows: low-energy X-rays do not require heavy shielding and can be fitted in-house. The low-energy X-ray irradiator is reliable, compact, and cost-effective. In addition, it can avoid the disposal issue associated with radioisotopes and can be easily transported to storage places. Therefore, low-energy X-rays are attractive and provide an alternative technology that could be developed in the food industry.

This study aims to investigate the depth-dose distribution in potatoes with low-energy X-rays to determine optimum irradiation conditions for potato preservation.

2 Materials and method

2.1 Materials

Materials for this study are potato Solanum tuberosum L. PO3 and polymethyl methacrylate (PMMA).

Potato Solanum tuberosum L. PO3 (abbreviated PO3) is a late blight-resistant potato variety selected and developed by the Potato, Vegetable & Flower Research Center. Potato tubers without mechanical damage to the surface were collected from a farm in Da Lat, Lam Dong, Vietnam. After harvesting, the potatoes were cleaned with a soft brush. Each tuber has an average weight of around 150 g. The average size is about 70 mm in diameter (D) and 50 mm in height (H).

Polymethyl methacrylate is frequently used for food irradiation as an organic phantom because it has a similar water composition to potatoes [19]. Therefore, the potato was simulated by the PMMA phantom in the present research.

2.2 X-ray irradiator

The X-ray irradiation system model MBR-1618R-BE was used in this study (Fig. 1). The size of the irradiator is 1600 (height) × 800 (depth) × 730 (width) mm. The irradiator operates with different tube voltage values (35–160 kV) and tube currents (1–30 mA) with a maximum power of 3 kW. The irradiation time and dose are set according to a tablet connected with the irradiator [20].

The irradiation area differs depending on the distance from the X-ray focal point to the turntable (Fig. 2); the irradiation angle is 40°. The operation condition of the X-ray irradiator was adjusted at the tube voltage of 160 kV, the tube current of 18.7 mA, and the distance of 250 mm from the X-ray source to the surface of materials put on the turntable.

Fig. 1. X-ray irradiation system model MBR-1618R-BE (right) and the cooler (left)

Hue University Journal of Science: Natural Science
Vol. 131, No. 1B, 73–79, 2022

pISSN 1859-1388
eISSN 2615-9678

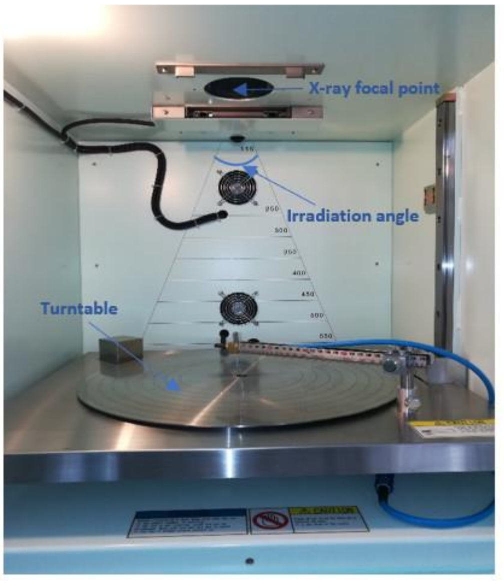

Fig. 2. Irradiation chamber

2.3 Dosimeter

In this experiment, a Fricke dosimeter and a radiochromic film (Gafchromic HD-V2 film) dosimeter were used.

The Fricke dosimeter is commonly used as a reference standard to calibrate other dosimeters, such as a radiochromic film [19]. It has been primarily applied to measure the absorbed dose in the low-dose range for potato sprout inhibition [21]. It is based on the oxidation of ferrous ions (Fe^{2+}) in the aqueous sulfuric acid solution to ferric ions (Fe^{3+}) by ionizing radiation. The absorbed dose (dose in water) was determined by measuring the change in absorbance of the irradiated solution at the 304 nm wavelength (the peak of the absorption spectrum).

The Ashland Gafchromic™ dosimetry media, type HD-V2, was used for the dose distribution measurement inside potatoes and PMMA. It is a thin film dosimeter (109 μm) with a recommended dose range of 10–1000 Gy. The film comprises a 12 μm thick active layer containing an active component, a marker dye, stabilizers, and other components, giving the film its energy-independent response. The active layer is coated on a clear, 97 μm polyester substrate [22].

For evaluating the depth-dose distribution in potatoes and the PMMA, a large film sheet was cut into small pieces (10 × 20 mm) that were covered with a thin plastic film (0.05 mm thickness). Then, these covered film pieces were sandwiched among potato slices and PMMA plates (the thickness of each potato slice and each PMMA plate is 5 and 1.47 mm). Eventually, the potato/PMMA phantom had total thickness, including the thickness of covered film pieces (Fig. 3). After exposure, the films were kept for at least 24 hours, and the colour change was scanned with the scanner Epson. Then, the dose response was analyzed from the scan images with the Film QA Pro software, and the measured dose response was used to calculate the dose [23]. This simulation system was irradiated at the centre of the turntable for 25 min and repeated three times to get an average value.

(a) (b)

Fig. 3. Experimental setup for potatoes (a) and PMMA phantom (b)

The experiments were undertaken in the air at an ambient temperature of 22–25 °C and relative humidity of 60–75%.

3 Results and discussion

3.1 Gafchromic film calibration

The Ashland Company provides a high-quality dependence equation between dose and dose response (red, green, and blue value) of a

Gafchromic film on a colour scanner. To get a good equation, we used a Fricke dosimeter as a standard. The dose rate obtained with the Fricke dosimeter was used to estimate the dose absorbed by the film.

The dose rate measured with the Fricke dosimeter is 16.83 Gy·min^{-1} at the 160 kV tube voltage and 30 mA current of the X-ray irradiator. To build the calibration equation, we irradiated eight film pieces at different times (1–8 min, 1 min step), corresponding to different absorbed doses. The dose response of the scanned irradiated films at different doses is presented in Fig. 4 (in the lower right corner). The calibration curves for the colour channels fitted by following the recommended function are in the upper right corner of the figure [23]

$$X(D) = A + B/(D - C) \quad (1)$$

where $X(D)$ is the red, green, and blue value of the film at dose D, and A, B, and C are the equation parameters to be fitted. The parameters of the fitting equation and R squared (R^2) values are given in Table 1.

Table 1 and Fig. 4 reveal that the green channel with the highest R^2 value of 0.9957 is the most appropriate option. Then, the depth dose delivered to the potato and PMMA was calculated with the green response value of the irradiated film and the corresponding parameters A, B, and C.

Table 1. Parameters of fitting equation

Parameter	Red	Green	Blue
A	$-1.39 \cdot 10^4$	$-9.04 \cdot 10^4$	$-0.77 \cdot 10^4$
B	$2.01 \cdot 10^6$	$5.83 \cdot 10^7$	$1.54 \cdot 10^6$
C	–39.34	–427.94	–79.27
R^2	0.9550	0.9957	0.9722

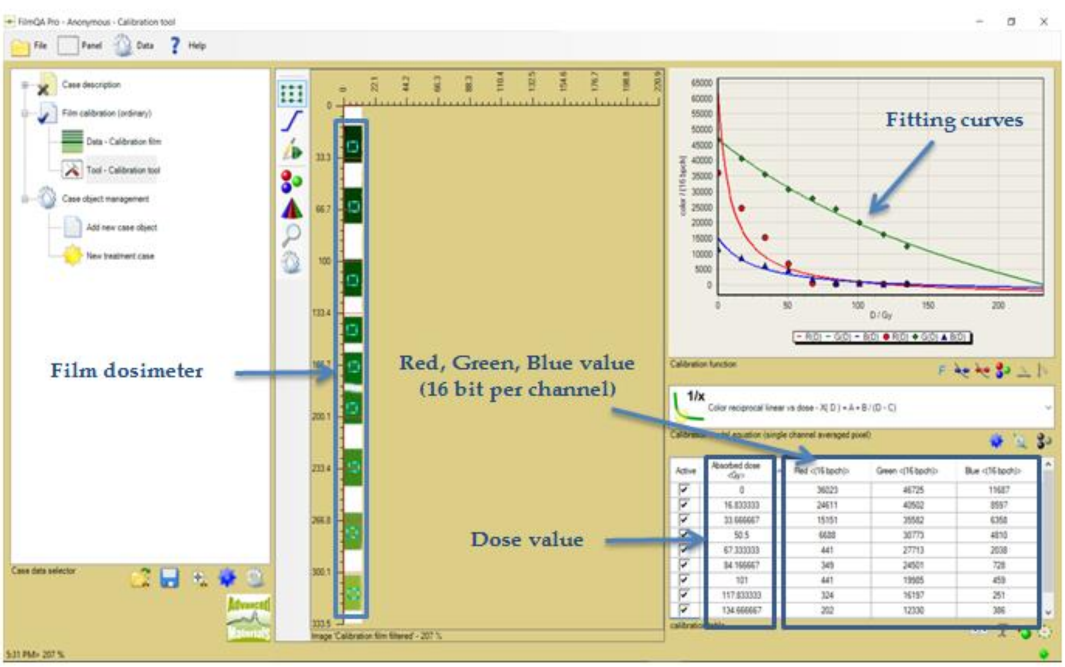

Fig. 4. Calibration of the Gafchromic™ film HD-V2 to different colour channel readings with Film QA Pro software

pISSN 1859-1388
eISSN 2615-9678

3.2 Depth-dose distribution in potato and PMMA with low-energy X-rays

The calculated depth-dose distribution in the potato and PMMA is shown in Table 2 and Table 3. The precision was evaluated according to the coefficient of variation (CV), which is the ratio of the standard deviation to the mean (average). The mean values and the standard deviation were calculated with the Excel software. The CV is less than 6% and is affected by the factors such as the operation of the X-ray tube, the appearance of a very small gap between the film sheet and potato/PMMA, and the colour reading process.

Figure 5 shows the depth-dose rate distribution in potatoes and PMMA. In general, the dose penetration depth curves follow an exponential decay with an R^2 value of 0.9573 for PMMA and 0.9059 for potatoes. The exponential form is consistent with the physical law of the decay curve in materials.

Table 2. Depth-dose distribution in potatoes

Thickness (mm)	Dose (Gy)	Dose rate (Gy·min⁻¹)	CV (%)
0	205.79	8.23	2.23
5.26	111.55	4.46	4.46
10.47	90.64	3.63	5.70
15.68	77.29	3.09	1.63
25.89	61.88	2.48	0.95
41.10	47.37	1.89	1.96
46.30	41.46	1.66	2.75
51.51	35.62	1.42	5.87

Table 3. Depth-dose distribution in PMMA

Thickness (mm)	Dose (Gy)	Dose rate (Gy·min⁻¹)	CV (%)
0	204.17	8.17	0.15
7.61	126.67	5.07	0.30
15.18	96.47	3.86	0.25
22.74	81.59	3.26	0.42
37.66	64.16	2.57	0.56
59.94	42.29	1.69	1.22
67.50	37.66	1.51	0.99
75.07	30.69	1.23	0.87

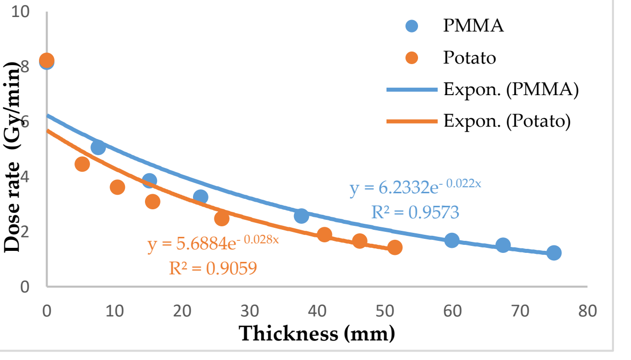

Fig. 5. Depth-dose rate distribution in potatoes and PMMA

As shown, the dose rates at the surface of potatoes and PMMA are similar at 8.23 and 8.17 Gy·min⁻¹. Then, the absorbed dose rate in potatoes decreases faster with the increase of thickness than in PMMA. Therefore, the graph for potatoes is below that for PMMA. It is probably due to the greater density of PMMA (1.18 g·cm⁻³) compared with that of potatoes (1.03 g·cm⁻³). Besides, it should be noticed that in the first few millimetres in the samples, the dose rates of PMMA and potatoes decrease faster with the exponential law. The reason is that the X-ray spectrum is not mono-energetic. The lower-energy part of X-rays with a low penetration into the samples is strongly absorbed in the first few millimetres, causing a rapid reduction of the dose rate. Afterwards, the dose rate decreases gradually as the depth increases and has a value of 1.42 Gy·min⁻¹ at a depth of 51.51 mm for potatoes and 1.69 Gy·min⁻¹ at the 59.94 mm depth for PMMA.

The difference in dose rates in PMMA and potatoes was calculated through the fitted equations shown in Fig. 5. The rate for PMMA is 1.5 times smaller than that for potatoes (for thickness up to 50 mm – the average thickness of a potato tuber). This difference is acceptable. Thus we used PMMA as a phantom to measure the depth-dose distribution in potatoes. It is difficult to measure the dose at every millimetre inside the potatoes, but it is possible with PMMA.

The dose uniformity ratio (DUR), defined as the ratio of the maximum to minimum absorbed dose, is an essential parameter for food processing. The allowed DUR values are 2 or even 3 for most food products [4, 5]. Table 2 indicates that the DUR for potatoes is 5.8, beyond the allowed value. The factors influencing DUR can be one-sided or double-sided irradiation. For the former, the potato is exposed on the top or bottom surface. For the latter, after irradiation on the top surface, each potato is turned to the opposite side and continued to be irradiated under the same condition. The difference between one-sided and double-sided irradiation for the potato with low-energy X-rays is displayed in Fig. 6. The DUR value is 1.9 for potatoes when irradiating double-sided, and this value is within the allowed range.

The results indicate that the dose rate that allows the rays to penetrate the bottom surface of the potato is 1.42 $Gy{\cdot}min^{-1}$ in one-sided irradiation and 9.65 $Gy{\cdot}min^{-1}$ in double-sided irradiation. When the potato is irradiated one-sided for 10 minutes, the absorbed dose at the backside is 14.2 Gy, lower than the standard dose for sprout inhibition of potatoes (60–150 Gy). This value could be compensated in double-sided irradiation with 96.5 Gy. So, both-sided irradiation needs less time and, consequently, has higher efficiency than single-sided irradiation.

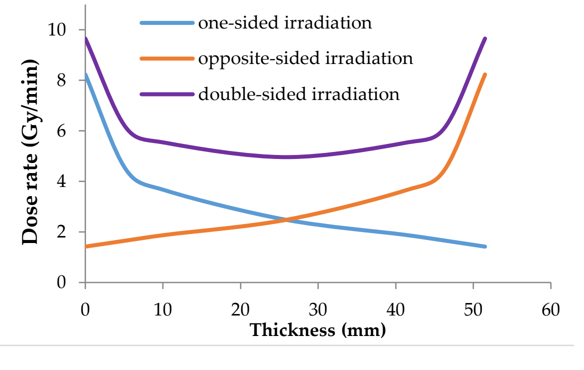

Fig. 6. Depth-dose rate distribution in potato for double-sided irradiation with low energy X-rays

As the low-energy X-rays could not strongly penetrate inside the sample, the depth-dose distribution in potatoes is critical information. From this information, the required depth at which the dose reaches the necessary value for potato preservation could be determined.

4 Conclusion

In this study, the depth-dose distribution of low-energy X-rays in potatoes and PMMA was investigated with an HD-V2 Gafchromic film dosimeter. The dose rate for PMMA is 1.5 times lower than that for potatoes. Being suitable for food and easy to handle, PMMA could be used as a phantom in measuring the depth dose delivered in potatoes. Besides, the present work provides efficiency information on double-sided and one-sided irradiation.

The measurements of this study were carried out at a tube voltage of 160 kV, a current of 18.7 mA, and a distance of 250 mm from the X-ray focal point to the samples. To get more information and obtain optimum irradiation conditions, one should conduct further studies with other values of tube voltage, tube current, and different distances between the focal point and the exposed area.

Funding statement

This research is funded by the Ministry of Education and Training of Vietnam under the project code: B2020-DLA-02.

References

1. Josephson ES. An Historical Review of Food Irradiation. J Food Safety. 1983;5:161-165.
2. Diehl JF. Safety of Irradiated Foods. New York : Marcel Dekker; 1990.

pISSN 1859-1388
eISSN 2615-9678

3. Kume T, Todoriki S. Food irradiation in Asia, the European Union and the United States: A Status Update. Radioisotopes. 2013;62(5):291-299.
4. IAEA. Technical Reports Series: Dosimetry for food irradiation. Vienna: IAEA; 2002. №: 409.
5. Rosana GM. Irradiation of Food. Virginia: Virginia tech publishing; 2020.
6. Casolaro P, Campajola L, Breglio G, Buontempo S, Consales M, Cusano A, et al. Real-time dosimetry with radiochromic films. Scientific Reports. 2019;9(1):5307.
7. Casolaro P. Radiochromic Films for the Two-Dimensional Dose Distribution Assessment. Appl Sci. 2021;11(5):2132.
8. Marshall AT. X-ray Depth Distribution (φ(ϱz)) Curves for X-ray Microanalysis of Frozen-Hydrated Bulk Biological Samples. Micron (1969). 1982;13(3):317-8.
9. Ishizaka T. Measurement Method of Ion-Beam Ralative Intensity Distribution using gamma-ray Irradiation response function of Gafchromic Film HD-V2. Radioisotopes. 2017;66:251-258.
10. Kishor M, Igor J. Measurements of electron depth-dose distribution in thick plastics and effects of accumulated charge. Radiat Phys Chem. 1996;47(3):487-490.
11. Sparrow H, Christensen E. Improved storage quality of potato tubers after exposure to Cobalt-60 gamma. Nucleonics. 1954;12(8):16-17.
12. Kume T, Tachibana H, Aoki S, Sato T. Effective gamma-ray dosage and dose rate in sprout inhibition of potatoes. JAERI-M. 1976.
13. IAEA. Irradiation of bulbs and tuber crops – A compilation of technical data for its authorization and control. Vienna: IAEA; 1997.
14. Rezaee M, Almasi M, Farahani AM, Minaei S, Khodadadi M. Potato sprout inhibition and tuber quality after post-harvest treatment with gamma irradiation on different dates. Journal of Agricultural Science and Technology. 2011;13:829-842.
15. Alimov AS, Bliznyuk UA, Borchegovskays PU, Varzar SM, Elansky SN, et al. Using accelerated electron beams for the radiation processing of foodstuffs and biomaterials. Bulletin of the Russian Academy of Sciences: Physics. 2017;81(6);743-747.
16. Fellows PJ. Food processing technology: Principles and practice, 3rd edit., T Boca Raton: Taylor &Francis; 2009.
17. WHO. High-dose irradiation: wholesomeness of food irradiated with doses above 10kGy. Report of a Joint FAO/IAEA/WHO Study Group: No. 890 (WHO Technical Report Series); 1999.
18. International Food Standards. Codex STAN 106-1983 - FAO/WHO Codex Alimentarius Commission. 2003.
19. Mehta K, O'Hara K. Dosimetry for Food Processing and Research Applications. Food Irradiation Research and Technology ; 2006. p. 105-25.
20. Hitachi Power Solutions Co. Operation. Manual X-ray Irradiation System MBR-1618R-BE. Hitachi Inspire the Next. 2018.
21. Kume T, Tachibana H, Takehisa M. Fricke dosimetry in low dose range for sprout inhibition. Radioisotopes. 1981;30(10);560-562.
22. Gafchromic™ dosimetry media, type HD-V2. Technical Sheet and User Guide. http://www.gafchromic.com/documents/gafchromic-hdv2.pdf.
23. Micke A, Lewis DF, Yu X. Multichannel film dosimetry with nonuniformity correction. Medical Physics. 2011;38(5):2523-2534.