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Understanding Phytosanitary Irradiation Treatment of Pineapple Using Monte Carlo Simulation

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Abstract

Purpose: Pineapple is now the third most important tropical fruit in world production after banana and citrus. Phytosanitary irradiation is recognized as a promising alternative treatment to chemical fumigation. However, most of the phytosanitary irradiation studies have dealt with physiochemical properties and its efficacy. Accurate dose calculation is crucial for ensuring proper process control in phytosanitary irradiation. The objective of this study was to optimize phytosanitary irradiation treatment of pineapple in various radiation sources using Monte Carlo simulation. **Methods:** 3-D geometry and component densities of the pineapple, extracted from CT scan data, were entered into a radiation transport Monte Carlo code (MCNP5) to obtain simulated dose distribution. Radiation energy used for simulation were 2 MeV (low-energy) and 10 MeV (high-energy) for electron beams, 1.25 MeV for gamma-rays, and 5 MeV for X-rays. **Results:** For low-energy electron beam simulation, electrons penetrated up to 0.75 cm from the pineapple skin, which is good for controlling insect eggs laid just below the fruit surface. For high-energy electron beam simulation, electrons penetrated up to 4.5 cm and the irradiation area occupied 60.2% of the whole area at single-side irradiation and 90.6% at double-side irradiation. For a single-side only gamma- and X-ray source simulation, the entire pineapple was irradiated and dose uniformity ratios (Dmax/Dmin) were 2.23 and 2.19, respectively. Even though both sources had all greater penetrating capability, the X-ray treatment is safer and the gamma-ray treatment is more widely used due to their availability. **Conclusions:** These results are invaluable for optimizing phytosanitary irradiation treatment planning of pineapple.

Keywords: Phytosanitary irradiation, Monte Carlo, MCNP, Pineapple

Introduction

Agricultural produce is a basic need of humanity and its production has become increasingly internationalized over the past century. Thus, the countries have been aware that destructive pests in agricultural commodities gained entry to a country from which it was previously absent, because it can cause significant economic and ecological damage. It is estimated that the loss caused by these pests globally is about $1.4 trillion or 5% of the world gross national product (Pimentel et al. 2007).

Phytosanitary treatments eliminate, sterilize, or kill pests in exported commodities to prevent their introduction and establishment into the new areas. Most phytosanitary treatments currently in use involve subjecting traded commodities to heat (~46℃), cold (~1℃) or chemical fumigants to acutely kill regulated pests. However, commodity tolerance is often the main limiting factors on the use of heat or cold treatments of fresh produce. Moreover, fumigants which have been toxic broadly on the environment and traded fresh produce will be phased out in the near future (UNEP, 2012). Irradiation is very effective against pests (insects and mites), cost competitive and fast, compared with other methods. Irradiation generally does not significantly reduce commodity quality, and even it can be applied to the commodity after packaging.

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Food irradiation treatment initiates by passing the food in front of a source of gamma rays from Cobalt- 60 or machine generated X-ray or electron beams. Ionizing energy in irradiated treatments breaks chemical bonds within DNA and other molecules, thereby disrupting normal cellular function, resulting in killing microbial pathogens or preventing reproduction of insects. Food irradiation has been endorsed by FAO/ WHO/IAEA as having significant strategic importance for the future of food safety worldwide. Currently, almost 19,000 tons of tropical fruits are irradiated each year in 6 countries to control quarantine pests (Hallman, 2011).

The absorbed dose in irradiated treatments is the amount of energy imparted to a given material. The SI unit of absorbed dose is the gray (Gy); one Gy is defined that 1 Joule of energy is absorbed in 1 kg of substance. Since the absorbed dose is directly related to the desired effects in a specific food, the suitable and accurate dose measurement must not be underestimated. Over-dosage is costly while under-dosage can have huge safety implications.

The dose uniformity ratio, DUR, the ratio of the maximum dose (Dmax) to the minimum dose (Dmin), is a useful concept for quality assurance of irradiation treatment. This ratio should be as close to 1 as possible; i.e. the dose should be very uniform. In practice, when irradiation is done on a commercial scale, a majority of the fruits receives significantly greater than the maximum dose required for quarantine security; much of it two times or more (Hallman and Martinez, 2001; Heather and Hallman, 2008).

In order to minimize this ratio, we have to obtain accurate dose distribution of the commodity. When using conventional dosimetry technique, it is difficult to know exactly how much energy absorbed in each element of the whole target, because of the dosimeter's geometry limitation. Furthermore, a real food produce is more likely to deteriorate during dose measurement.

The term *Monte Carlo* is used to describe to a problem where a probabilistic analogue to a given mathematical problem is set up and solved by stochastic sampling. The Monte Carlo method is one of the most universally used approximate numerical techniques in physical science, computational biology, and applied statistics (Elishakoff, 2001). This simulation approach also has been mostly used for dose calculation in the field of health physics (Andreo, 1991; Mackie, 1990). In Monte Carlo simulations, the particle tracks or histories are generated by simulating the random nature of particle interactions with the medium; Monte Carlo "solves" a transport problem by simulating particle histories rather than by solving an equation.

3D scanner or machine vision system has been used to obtain geometrical characteristics of the food products (Du and Wun, 2006; Goni et al., 2009; Uyar and Erdogdu, 2009); however, neither can provide their internal information which is a critical factor in radiation simulation.

Computed Tomography (CT) scan is an advanced method for nondestructively evaluating a cross section of an object. Geometrical and density information for accurate dose calculation in Monte Carlo simulation can be obtained by using multi-sliced CT scan data. The CT scan data has been used for dose calculation of various food product for food safety purpose: apple (Kim et al., 2006), broccoli head (Kim et al., 2008), chicken (Kim et al., 2007), etc. However, no literature is available regarding dose simulation of food product for phytosanitary irradiation purpose.

Thus, the objective of this study was to understand irradiation treatment of pineapple in various radiation sources (electron beam, X-ray, and gamma-ray) using Monte Carlo simulation and CT scan data so that its phytosanitary irradiation treatment can be optimized.

Materials and Methods

3-D geometric modeling of pineapple using CT data

The pineapple, having a pine-cone shape, has a high juiciness and vibrant tropical flavor. Its world production increased more than fivefold over the last 40 years (FAOSTAT, 2012). The pineapple is mostly cultivated in Southeast Asia, and it is an excellent source of manganese and vitamin C according to the USDA Nutrient Database. A pineapple ('Smooth Cayenne'), purchased from a local food market, was stored in a cold chamber at 4℃ and 95% relative humidity.

When samples are scanned using a CT scanner, each pixel on the slice image is assigned a numerical value (CT number). e.g. fat is about -200 to -5, and water is about -5 to 5, which is related to the densities of the scanned materials. A total of 25 slice images (0.8-cm thickness) was obtained from the pineapple using 24-cm field of view (pixel size = 0.47 mm) in a Universal HD350E X-ray

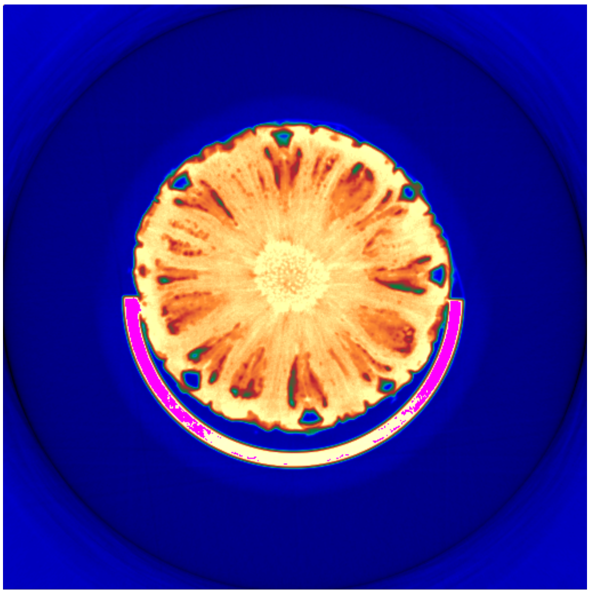

Figure 1. A original CT image of a pineapple (FOV = 24 cm).

CT scanner (Universal System, Dolon, OH). Figure 1 shows one of the CT images of the pineapple. A sample holder, made of plastic material, has higher CT number than the pineapple whose CT numbers do not vary much itself. We can see several air pockets near the rind and small air passages in the internal part.

Each slice of CT data (512 x 512 matrixes) was processed using the MATLAB Image Processing Toolbox (Mathworks, Natick, MA). The artifacts on the original CT slices, such as sample holder, were removed and the target product was then segmented out from the background. The 2-D slice CT data was made into a 99 x 97 voxel array, in which the y, z resolution was 0.14 cm and the slice thickness (x direction) was 0.8 cm; the voxel size was adjusted in considering the simulation time. The 3-D volume array was constructed by combining pixels in the y, z plane and by duplicating the slices along the x direction.

Monte carlo simulation

The MCNP5 (Monte Carlo N-Particle, Version 5), developed at Los Alamos National Laboratory, was used to simulate radiation interaction in the pineapple. In this Monte Carlo simulation, the incident particles (electrons or photons) in a target are tracked. By tracing a large number of particle histories, it is possible to track the interactions of individual particles in their passages through the matter and to obtain distributions of many desired physical quantities. The particle tracks are finished either when they leave the region of interests or when the energy becomes smaller than an energy cutoff, which is the energy where particles are assumed to be effectively stopped and absorbed in the medium (Cashwell and Everett, 1959).

Dose distribution of pineapple was obtained at four different radiation sources: 2 MeV electron beam, 10 MeV electron beam, 5 MeV X-rays, and 1.25 MeV gamma-rays. Low-energy (2 MeV) electron beam has been noticed for a surface pasteurization treatment (Kim et al., 2006). High-energy (10 MeV) electron beam is widely used in most of the commercial irradiators. 5 MeV X-rays, also being available in the irradiators, are generated when 5 MeV electrons strike a metallic target. Most electron accelerators have a 5-MeV X-ray irradiator as in tandem. The gamma-rays, 1.25 MeV, are obtained from ^{60}Co radionuclide sources. Unlike electron beams, these X-rays and gamma-rays penetrate the matter more easily, which is good for treatment of thicker samples.

In the simulation, each source particle was emitted in a plane, distributed evenly, and entered the target perpendicularly. The target geometry was made by using CT data and its voxel densities were calculated with the relationship between CT number and electron density (Matsufuji et al., 1998).

The atomic composition of pineapple was calculated using the data from the USDA National Nutrient Database for Standard Reference (USDA, 2013). The contents of the common element (H, C, N, and O) in the pineapple are 10.4, 5.4, 0.1, and 84.0% by mass respectively; its total mass is up to 99.9%. The mineral (Ca, Mg, P, and K) content is only 0.1% by mass.

The simulation was run on a Windows PC (3.20 GHz CPU, 32.0 GB RAM) with Cygwin platform. The CPU time was approximately 13 hours for 10^6 histories. Generally, Monte Carlo results represent an average of the contribution from many histories sampled during the simulation (Brown, 2003). Therefore, a total of $10^6 - 10^7$ histories were used in our simulations to reduce the statistical uncertainty to about 5 % or less.

Results and Discussion

Dose distribution of pineapple at 2 MeV electron beam

Electrons, negative in charge, interact with other electrons or nucleus of practically every atom as they

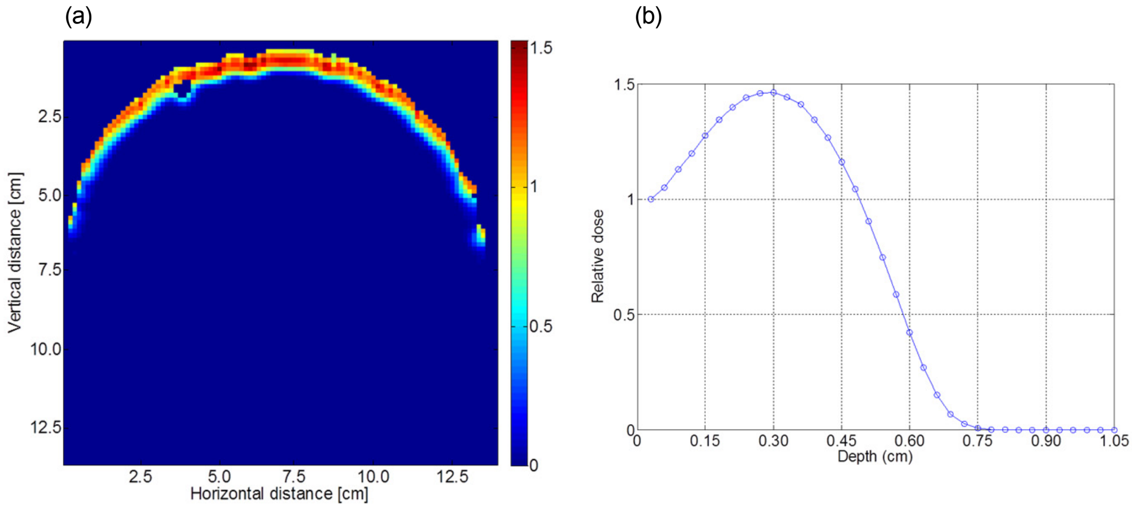

Figure 2. Dose distribution of a pineapple at 2 MeV electron beam. (a) in top-to-bottom beam direction; (b) a depth-dose curve of a pineapple at 2 MeV electron beam.

pass through the matter. Thus, unlike gamma- or X-rays, their penetration depth is very limited and is closely related to their kinetic energy.

Figure 2 shows dose distribution of pineapple at 2 MeV electron beam calculated with MCNP simulation results. The absorbed dose was presented in the incident surface up to 0.75 cm of the depth, which is well beyond the outer rind (Fig. 2(a)). The figure 2(b) clearly shows a buildup region, that is, the dose is 40% higher at 0.3-cm depth from the entrance (around 1.4 kGy compared to 1.0 kGy). In general, in the case of incident electron beams, the secondary electrons generated from collisional energy losses interact the matter with their own kinetic energy, and they contribute to the buildup dose (Attix, 1986).

This low energy (2 MeV) electron beam treatment is very efficient for controlling insect eggs laid just below the fruit surface. In addition, it could preserve the internal fruit quality. In order to irradiate the lower part of the pineapple, either the beam direction was changed to upward or the pineapple could be rotated by 180 degrees so that the lower part could be exposed to the upper beam.

Dose distribution of pineapple at 10 MeV electron beam

In general, the penetration depth at high energy (e.g., 10 MeV) electron beam is much longer than the value at low energy (e.g., 2 MeV) electron beam. Thus, the high energy electron beam is more efficacious for controlling pests presented in deeper area; the caterpillars that emerge from the eggs seek out and bore into fruit where they continue to feed and develop.

The penetration depth in the middle of pineapple is approximately 4.5 cm (Fig. 3(a)). Assuming that the entrance dose is 1.0 kGy, as electrons move deeper and undergo interactions with other electrons, the maximum dose (1.3 kGy) is reached at roughly half of the penetration depth (2.2 cm). The dose then rapidly fall until it goes to zero (Fig. 3(b)). However, this penetration depth becomes shorter as electrons enter the pineapple, being away from its center. As the incident beam angle increases, the backscattering yield increases as well, resulting in decreasing the dose build-up region (Rosenstein et al., 1972). Thus, the dose near the surface is significantly increased.

Here, we can notice that the absorbed dose does not reach the core of the pineapple, in which browning could be induced under the irradiation at the dose of 300 Gy and above (Limohpasmanee et al., 2005). Overall, the dose was shown in 60.2% of the cross section area. Control of electron's penetration depth depending on the pineapple size is highly desirable to disinfest quarantine pests and to preserve fruit quality as well.

In order for a pineapple to be fully irradiated, two sided irradiations are required in 10 MeV electron beam (Fig. 4). For industrial applications, the conveyor loaded with samples can be exposed to the electron beam from top and bottom direction simultaneously. In two sided irradiation, the dose was distributed down to 4.5 cm from the surface over the whole pineapple, and its region was

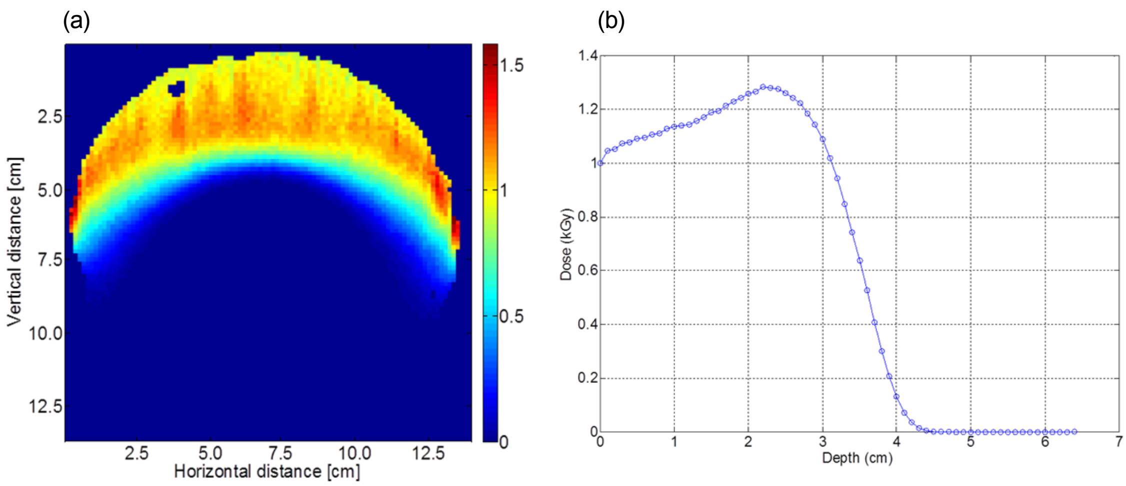

Figure 3. Dose distribution of a pineapple at 10 MeV single electron beam. (a) in top-to-bottom beam direction; (b) a depth-dose curve of a pineapple at 10 MeV electron beam.

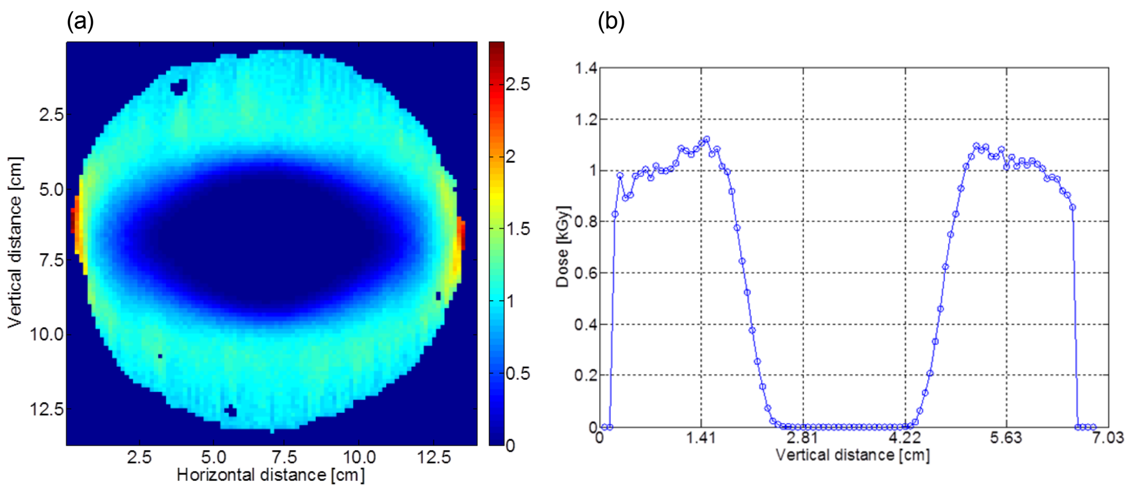

Figure 4. Dose distribution of a pineapple at 10 MeV double electron beam. (a) in top-to-bottom and bottom-to-top beam direction; (b) dose distribution along the vertical direction at horizontal point (7.5 cm).

increased to 90.6% of the whole area. However, the edge regions in which beam overlap occurs receive doses that are approximately a factor of two higher than the dose intended. This problem could happen in cylinder-shaped samples (Miller, 2005). In order to decrease those high doses, we can surround the pineapple both top and bottom with conformal absorbers, made of plastic material (e.g., high density polyethylene (HDPE)). The other approach is rotation of the pineapple so that the dose variation could be reduced, resulting in acceptable product from a quality perspective.

Dose distribution of pineapple at 1.25 MeV gamma rays

The gamma rays used in food processing are obtained from ^{60}Co radionuclide sources whose kinetic energy is 1.25 MeV. Because of its greater penetrating capability, the gamma rays are mainly used for processing of relatively thick or dense products.

Figure 5(a) shows the dose distribution of pineapple when the gamma rays flow toward the left side. The dose was 0.78 kGy when the gamma-ray photons were entering the pineapple, and it increased up to 0.87 kGy not far from the surface. It then kept decreasing until they left the pineapple, in which the dose was 0.42 kGy. The gamma rays lose their kinetic energy in few large interactions; thus, the resulting depth-dose distribution resembles an approximately exponential curve (Fig. 5 (b)). Even in this case, we can see a short range (1.13 cm) of buildup region due to the secondary electrons generated from interactions

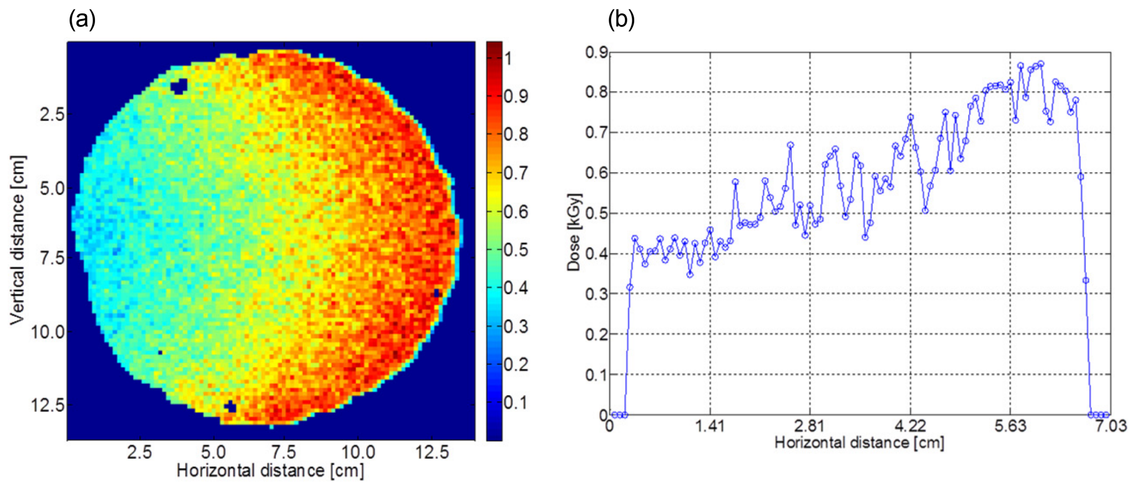

Figure 5. Dose distribution of a pineapple at 1.25 MeV gamma rays. (a) at right-to-left beam direction; (b) dose distribution along the horizontal direction at vertical point (7.5 cm).

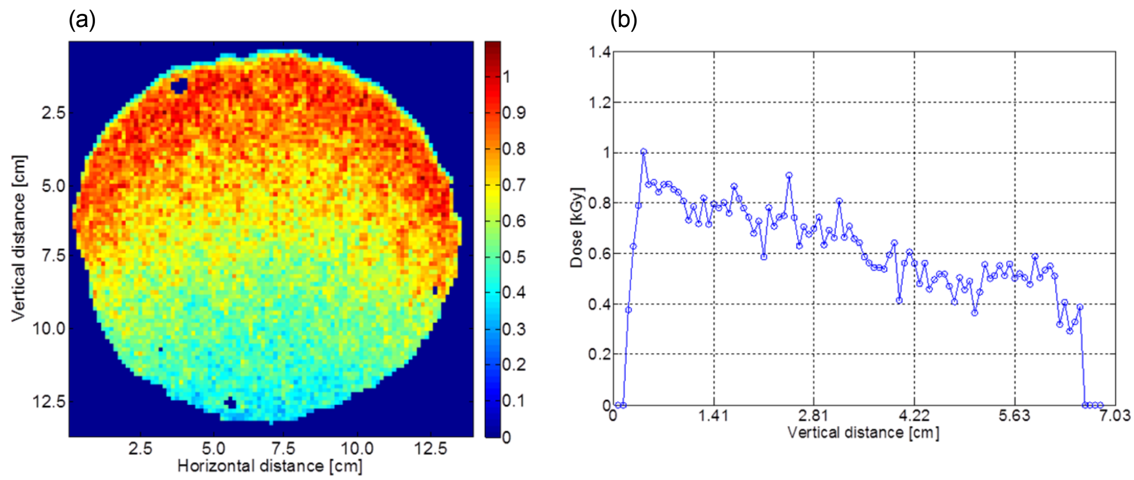

Figure 6. Dose distribution of a pineapple at 5 MeV X-rays. (a) top-to-bottom beam direction; (b) dose distribution along the vertical direction at horizontal point (7.5 cm).

of gamma rays with the matter.

The dose uniformity ratio of pineapple at 1.25 MeV gamma rays was 2.23. Although a low dose uniformity ratio, e.g. less than 1.5, is highly desirable in food irradiation treatment, many food product applications can be tolerable a higher uniformity ratio of 2 or even 3 (IAEA, 2002). However, the rotation of the pineapple, which makes the other side exposed to the radiation source, would decrease the dose uniformity ratio; i.e., the pineapple would be irradiated more uniformly.

Dose distribution of pineapple at 5 MeV X-rays

X-rays in food irradiation processing are generated by allowing an electron beam to strike a metallic target. The X-ray energy production is proportional to the electron's kinetic energy and the atomic number of the target (Attix, 1986). In fact, 5 MeV is the kinetic energy of the electron before hitting the metallic target, such as Tungsten (W) or Tantalum (Ta). Unlike the radionuclide source, which emits nearly mono-energetic photons, these X-rays have a broad energy spectrum. The actual average kinetic energy of the X-rays generated is 1.14 MeV, which is far less than the incident electron energy (Kim et al., 2006).

Figure 6(a) shows the dose distribution of the pineapple when 5 MeV X-rays were directed downward. It is very similar to the one at 1.25 MeV gamma rays except the beam direction; the dose was distributed over the whole pineapple and it decreased exponentially as the X-rays proceeded into the pineapple. The dose uniformity ratio, 2.19, did not much differ from the one at 1.25 MeV gamma rays.

However, the radiation yield, the fraction of electron energy spent in generating X-rays, was only 8.2% at 5 MeV X-rays (Meissner et al., 2000). In practice, the electron beam or the gamma rays generated from radionuclide sources has been more widely used than X-rays in food irradiation treatment. Even though the kinetic energy of X-rays has been allowed to 7.5 MeV several years ago (CFR, 2004), its radiation yield was still quite low (13.3%).

Since X-rays, like an electron beam, are generated from electron accelerators, it is safer than the gamma rays in catastrophic accidents (e.g., earthquake). In addition, combined with the electron beams, the X-rays treatment would irradiate sample more effectively; the electron beam will be used to reduce low dose region in X-rays irradiation.

Conclusions

In this study, we simulated the dose distribution of the pineapple at various radiation sources for phytosanitary treatment purpose. At low energy (2 MeV) electron beam, the penetration depth was only 0.75 cm, which is good for surface treatment. Assuming that quarantine pests are distributed into the whole pineapple, 2-sided high-energy (10 MeV) electron beams are required for an efficient treatment. The gamma- and X-rays both penetrated the pineapple easily, and doses were exponentially decreased. The dose uniformity ratios were also very similar: 2.23 at gamma rays and 2.19 at X-rays. However, in the industrial application, where mostly treated in pallet load, X-rays or gamma-rays would be more effective than electron beams because of their larger penetration depth. These simulation results provide invaluable information for planning phytosanitary irradiation treatment for pineapples.

The phytosanitary irradiation of fruits is a promising treatment for assuring their safety and quality and even for allowing them oversea marketing. The accurate dose calculation is crucial for irradiation planning and quality control. In general, the validation of the simulated results using the real experiment is needed for improving its reliability. However, no phantom, which is a substitute instead of the real sample in radiation experiment, is available for pineapple currently. Even though a phantom composed of paraffin wax, chloroform, and methyl yellow was developed for a real apple (Kim et al., 2006), it has not used widely because of the laborious process of making it.

In practice, radiochromic thin film dosimeters have been used to identify the location of extreme doses for irradiation treatment. Since most food products have high moisture content and they are easily perishable, once cut to put dosimeters between them, its use is very limited. Thus, it needs to develop a versatile phantom for food products and a method to predict quality changes of food product quantitatively as well. In addition, once we evaluated and detected the depth and location where quarantine pests lay eggs, we can maximize radiation effects and minimize quality change by precisely controlling penetration depth.

The phytosanitary irradiation is gaining in use worldwide, and prompt actions for supplying safe foods and dealing with environmental problems are required urgently.

Conflict of Interests

The authors have no conflicting financial or other interests.

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