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Improving phytosanitary irradiation treatment of mangoes using Monte Carlo simulation

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ABSTRACT

Mango is a popular tropical fruit, comprising approximately half of all tropical fruits produced worldwide. Phytosanitary irradiation is a promising treatment as an alternative to fumigation. Most of the irradiation, however, is done in pallet loads, resulting in non-uniform dose distribution in fruits. Therefore, accurate dose calculation is needed to ensure proper process control to minimize quality changes. Our objective was to evaluate phytosanitary irradiation treatment for mangoes in pallet loads. Mango's 3D geometry, ellipsoid shape, based on Computed Tomography data, was used to simulate dose distributions in mangoes using radiation transport code (MCNP5). To calculate average doses at different depths, mango flesh was divided into 20 segments from the surface to the seed. Mango was divided into 0.05-cm vertical sections to calculate doses along the major axis. Radiation energy was 1.25 MeV from a Cobalt-60 source. For one-directional irradiation, doses from the surface to the mango seed had a build-up region at the outermost region (up to 0.13 cm) with only 78% of the average dose. An average dose at the outermost segment up to the center of the fruit (0.37 kGy) was significantly less than 0.56 kGy at the middle shell and 0.54 kGy at the innermost shell. Adding 0.1-cm of plastic wrap (PVC) and edible coating to improve dose distribution, the doses at the outermost segment were 0.52 and 0.51 kGy, respectively. These results are crucial since most insects lay eggs just under the produce's skin. For multiple product arrangement, as the number of mangoes increased, the average doses decreased. However, at both-directional irradiation, even nine mangoes were acceptably irradiated; the dose uniformity ratio was 2.26. Proper control of phytosanitary irradiation treatment is critical to ensure insect elimination while maintaining product quality.

1. Introduction

Mango is one of the most cultivated tropical fruits worldwide. Mangoes contain a significant amount of vitamins C and A, high disease resistance, and are considered as one of the healthiest foods (Mukherjee and Litz, 2009). Even though mangoes are native to Southeast Asia, they are now cultivated in most tropical and warmer subtropical climates. According to the Food and Agricultural Organization of the United Nations (FAO) database (FAOSTAT, 2012), world mango production has doubled between 1990 and 2009, and mango exports have increased almost eight-fold from 0.16 million ton to 1.20 million ton, with total export value estimated to be one billion dollars.

Phytosanitary treatments are used to disinfest exported agricultural commodities to prevent the introduction or spread of quarantine pests into new areas. The majority of fresh commodities are treated with high temperature (~46 °C), low temperature (~1 °C), or chemical fumigants. Almost 300,000 tons of mangoes imported into the United States annually are treated by immersion in hot water (46.1 °C) for 65–110 min (Hallman, 2011). However, commodity tolerance is often the principal limiting factor on the use of heat treatments of fresh produce. Moreover, chemical fumigation, the use of toxic gases to disinfest food commodities, will be phased out in the near future due to environmental problems and residues in food (UNEP, 2012). Irradiation is strongly considered as an optional treatment because it is efficacious and has high tolerance by most fresh commodities. Additionally, irradiation is residue-free process, and can be applied to the commodity after packaging or in pallet loads.

Currently, a total amount of 19,000 tons of fruits including mangoes is irradiated each year in several countries for phytosanitary purpose (Hallman, 2011). The irradiated mangoes are exported from Australia to New Zealand and from India, Philippines,

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Thailand, and Mexico to the United States (Bustos-Griffin et al., 2012). The amount of irradiated mangoes has been increasing significantly in recent years, e.g. from 261 tons in 2008 to 1095 tons in 2010 from Australia to New Zealand, and from 0 ton in 2008 to 239 tons in 2010 from Mexico to USA. Those irradiated mangoes are better in quality, compared to the ones picked for traditional market; mangoes to be irradiated could be picked at a more mature stage (75% mature, as opposed to 25% mature, which is currently used for hot water treatment). In addition, for particular mango varieties that have a soft skin, irradiation could be the only alternative.

The radiation dose used for mango to control fruit flies and other insects is 0.4 kGy, which was approved by USDA in 2007. However, the dose uniformity ratio (Dmax/Dmin) was even allowed to 3 for some low dose applications in large-scale commercial irradiators (IAEA, 2002).

Mangoes irradiated at 0.4 kGy had quality attribute profiles (pH, texture, organic acid, and carbohydrate content) similar to those of non-irradiated mangoes (Cruz et al., 2012; Uthairatanakij et al., 2006). However, the fruit receiving a dose of 1.0 kGy showed a greater loss of texture immediately after irradiation, resulting in severe changes in the structure of the cell wall after storage of 20 days (Silva et al., 2012). Sabato et al. (2009) also reported that mangoes exposed to 1.0 kGy had a reduced rate of maturation, lower firmness, and greater rate of pulp browning when compared to non-irradiated mangoes. Thus, the 1.0 kGy dose was too high for application to mangoes, creating stress on the tissue and eventually deteriorating commercial qualities significantly.

The dose uniformity ratio, which is an important factor for quality assurance of irradiation treatment, only depends on two extreme values (Dmax and Dmin). Since uneven absorption of irradiation energy is prevalent in food irradiation treatment, distribution of absorbed dose in the target is more important. The most economical application of radiation is in pallet loads, where a greater dose is being absorbed by much of the load to ensure that the minimum required dose is absorbed by the entire load; thus, the dose absorbed by the edge of a pallet could be at least twice that received in the center (Hallman, 2011). Even though dosimeters (radiochromic film or alanine pellet) are used to locate the region of the maximum and minimum doses in the pallet, they can only be placed on the surfaces or around the pallets where the products are contained.

The Monte Carlo simulation of radiation transport has been widely used for dose calculation in the field of health physics and radiation protection (Andreo, 1991; Mackie, 1990). Recently, Monte Carlo simulation with Computer Tomography (CT) scan data has been used to calculate dose distribution in various food products for microbial control purpose: apple (Kim et al., 2006), broccoli head (Kim et al., 2008), chicken (Kim et al., 2007) and other food items. Only a few studies are available for dose distribution for phytosanitary irradiation purpose: an analytical method for dose distribution in mango (George and Pradhan, 2009), and determination of dose distribution in pineapple for phytosanitary purpose (Kim et al., 2013).

Thus, the objective of this study was to provide insight on the possible differences on phytosanitary irradiation outcomes and the need to improve the irradiation process by performing a dose distribution study of mangoes in pallet loads using Monte Carlo simulation.

2. Material and methods

2.1. 3-D geometric modeling of mangoes using CT image

Geometric modeling is the process of creating a mathematical description of the shape of a real object, and is an essential step in simulation of radiation transport. Computed Tomography (CT) scan and Magnetic Resonance Imaging (MRI) are advanced methods for nondestructively evaluating a cross section of an object. Data gathered from CT or MRI can provide the basic information for the construction of more realistic computation models in which an object is represented by discrete elements of volume called voxels (Kim et al., 2007; Lee et al., 2004).

However, voxel-based Monte Carlo simulation requires huge amount of computing time to obtain statistically reliable results. In general, the computing time significantly increases as the voxel size is decreased or the number of voxel is increased (DeMarco et al., 1998). When the elemental compositions and densities at certain voxel are not much different, e.g., mango flesh above or below the seed, we can decrease the number of voxel using the simple surface card rather than a nested lattice feature which has been mostly used with CT or MRI data. Moreover, since we are more interested in the dose distribution near the mango surface area where quarantine pests could lay eggs, approximating the actual object to a simple regular geometry (e.g., ellipsoid) would be more effective.

In modeling of food engineering processes, food products such as grains, eggs, apples, and ham were considered ellipsoidal in shape to determine surface area and volume (Igathinathan et al., 2000; Sabliov et al., 2002; Du and Sun, 2006). The ellipsoidal shape, along the mutually perpendicular axes, consists of length (L), width (W), and thickness (T) (Fig. 1).

Multi-slice CT images of a mango ('Tommy Atkins') (0.4 cm slice thickness, 12 cm field of view (pixel size = 0.23 mm)) were obtained by using a Universal HD 350E X-ray scanner (Universal System, Dolon, OH). Based on the CT images, the mango was assumed a simple ellipsoidal shape for dose calculation. The physical dimensions were extracted at the CT data in the middle of the mango using ImageJ (National Institute of Health, USA). The length, width, and thickness were 10.40 cm, 9.16 cm, 7.90 cm for flesh, and 6.40 cm, 3.47 cm, and 1.48 cm for seed, respectively. The average densities were 0.89 (±0.09) g/cm^3 and 1.05 (±0.05) g/cm^3 for flesh and seed, respectively.

To calculate average doses at different depths, the mango flesh was divided into 20 segments from the surface to the seed; each segment thickness was 0.10 cm along the major axis, 0.14 cm along the minor axis, and 0.16 cm along the vertical axis. The mango was also divided by 0.05 cm vertically to calculate along the major axis (Fig. 2). The small air cavity between the seed and the flesh at both edges was not included in the simulation geometry because its radiation effect is trivial.

Nutrient values for mango flesh and seed were taken from USDA National Nutrient Database for Standard Reference and Eromosele et al. (1998), respectively. Those data were used to calculate both atomic compositions based on the elemental composition ratio in tissue (ICRP, 1975). Since the seed has high oil content

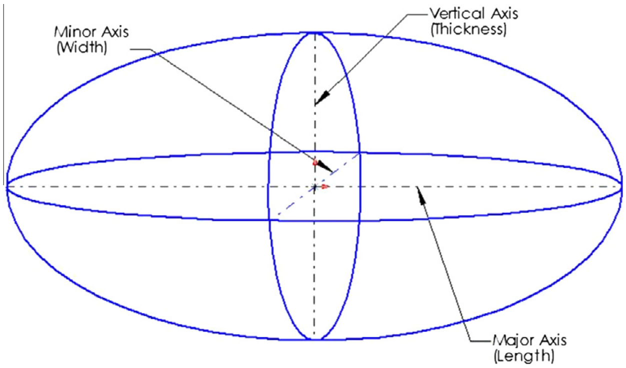

Fig. 1. Ellipsoid shape of food products.