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Quality of Mango cv. "Keitt" Treated with X-rays

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ABSTRACT: Irradiating fruits is an approved quarantine treatment to overcome biological barriers for the export of agricultural commodities, applied to prevent the introduction or spread of quarantine pests. Currently, most irradiated fruits are treated with gamma radiation, however, due to concerns mainly associated with the mobilization of radioactive materials, the international trend is to reduce the use of radioactive devices and to look for new technologies such as x-ray generators or electron accelerators. Some research has been conducted on the use of e-beam and x-ray as post-harvest treatments, but very few on fruit quality after the treatments. Here, we focused on the effect of x-ray irradiation on the physicochemical properties of mango (*Mangifera* indica L.) cv. 'Keitt'. We found that doses between 150 and 300 Gy could be applied as effective phytosanitary treatment. There were no significant differences between the irradiation treatment and the control in any of the variables measured: fruit weight, external and internal color, pH, soluble solids, firmness and on the vitamin C content. We discuss the advantages of using x-rays as an alternative to gamma radiation for phytosanitary purposes.

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KEYWORDS: Irradiation, fruit quality, fruit treatment, vitamin C, quarantine pest, physicochemical properties.

INTRODUCTION

Fruit irradiation using gamma rays is one of the newest phytosanitary treatments applied to avoid the introduction or spread of regulated pests (Hallman et al., 2016). It is a viable disinfestation technique to overcome biological barriers for the exportation of agricultural commodities (Gould and Hallman, 2004), used to eliminate insect pests before they are exported to areas free of those pests (Follet, 2009). In addition, this technology is a viable tool for many of the fresh fruits that do not tolerate any other phytosanitary treatment. International trade of fresh commodities irradiated for phytosanitary purposes has increased every year since the first routine commercial treatments in 2004 (Bustos et al., 2015). So far, 17 countries are applying this technology in more than 15 commodities. In addition, this technique has made significant improvements enhancing the microbiological safety of foods (Pillai et al., 2014). Food irradiation has the advantage to address both food quality and safety because of its ability to avoid spoilage or eliminate the pathogenic microorganisms, as well as harmful insect pests without significantly affecting the sensory and wholesome attributes of fruits (IAEA, 2013). Irradiation of fresh produce generally costs more than any other conventional technology due to the initial costs of the treatment facility. However, its increased use will lower the per-unit cost of the treatment. Although the use of irradiation is a promising technology, several obstacles should be considered before commercial use (Jeong and Jeong, 2018).

Currently, most irradiated foods including fresh fruits are treated with gamma radiation, but there is a growing interest in using e-beam and X-rays to treat foods both at the laboratory level and at large scale commercial facilities (IAEA, 2013), and although gamma rays and electron beams or X-rays are produced by different sources, they have the same mode of action (Jeong and Jeong, 2018). Before being shipped to their final destination, certain food products are collected or harvested, packaged and finally transported to a irradiation facility that usually use cobalt 60 (^{60}Co) as a source of ionizing radiation and although ^{60}Co

gamma radiation sources are easy to use, their acquisition and transportation can be complicated (IAEA, 2022). X-rays have the same penetration than gamma rays (Mehta, 2009), but X-rays are produced when electron beams are accelerated and interact into a high-density material such as gold or tantalum; although 90% of the energy of the e-beam is lost as heat, a small percentage is converted into X-rays which is enough to treat any kind of products including fresh fruit (Pillai et al., 2014).

E-beam and X-ray technologies are ionizing radiation which are not produced by nuclear processes, thus these technologies may be more accepted by the public. Additionally, X-ray technologies have the advantage that there is no radiation produced when it's switched off, there is no transportation, or management of radioactive material, and no radioactive waste (Bakri et al., 2005; Shahbaz et al., 2015). Due to rising ^{60}Co prices, limitations imposed by the regulatory institutions for the management of nuclear energy, and easier management of an irradiator using electricity instead of radioactive material, facilities using accelerators are becoming relatively more prevalent (Miller, 2005). Furthermore, the International Atomic Energy Agency is actively promoting and investing in e-beam or X-ray facilities (IAEA, 2012). Irradiation based on electron accelerators is technologically now a practical food processing option with many useful applications; however, more research is needed on key aspects of this technology and to document the effects of X-ray irradiation on different types of food (Miller, 2005).

Some studies have focused on the effect of X-ray or E-Beam on aspects such as the reproductive potential of insect pests. For example, reproduction of *Myzus persicae* (Sulzer), *Tetranychus urticae* (Koch), *Liriomyza trifolii* (Burgess), and *Frankliniella intonsa* (Trybom) was inhibited using this technology (Seung-Hwan et al., 2014); pupae of *Anastrepha suspensa* (Loew) were also sterilized using e-beam (Smitle, 1993). The inactivation of different developmental stages of various stored-product insect pests was achieved using soft electron, such as the inactivation of the red flour beetle (*Tribolium castaneum* Herbst) and the Indian meal moth (*Plutela interpunctella* Hubner) by directly irradiating eggs, larvae, pupae and adults. X rays have also been used for direct irradiation of adult adzuki bean weevil (*Callosobruchus chinensis* L.), with eggs and larvae being irradiated in bean grains; while the maize weevil (*Sitophilus zeamais* Motschulsky) was irradiated as eggs and larvae in grains of rice (Hayashi, 2004). Cho et. al. (2020), evaluated the effects of electron beam and X-ray on the development reproduction of the whitefly *Trialeurodes vaporariorum* as phytosanitary treatment for strawberry fruits, placing eggs, nymphs and adults at the top, middle and the bottom of a box filled with strawberry and irradiated at different doses. In that study, they determined that a dose of 150 Gy is adaptable as a quarantine treatment of *T. vaporariuorum* in strawberry fruit. Even a dose of 300 Gy of electron beam and X-ray irradiation did not change the quality of the strawberry fruit Cho et. al. (2020). Electron beam irradiations have also been evaluated as a phytosanitary measurement for export purposes of star apple fruits *Chrysophylumm cainito* (L.), without adversely affecting fruit quality (Nguyen et al. 2020). Also, the effect of this type of irradiation was tested on *Anastrepha fraterculus* (Wied.) larvae used as host to mass-rear the parasitoid *Diachasmimorpha longicaudata* (Ashmead), with excellent results (Bachman et al., 2015).

The use of X-rays has also been used to detect the presence of insect pest infestation in fresh fruit, including mango (Jian et al., 2008; Kim et al., 2021; Ansah et al., 2023), and as non-destructive methods for the detection of insect infestation in fruits and vegetables in combination with other technologies (Ekramirad, et al., 2016). Nevertheless, the use of X-rays as a postharvest treatment on fresh fruit has been limited at best, although it is gaining importance. There are few studies on the effects of X-ray or E-Beam on the quality of irradiated fresh fruit, and the levels of radiation dose on the fruit tolerance. Some studies have shown favorable results in mandarins, pomegranate, kiwifruits, jujube, strawberries, using x rays, and apple using electron beams (Alonso et al., 2007, Palou et al., 2007, Wall et al., 2008, Rojas-Argudo et al., 2012, Kheshti et al., 2019, Yoon et al., 2020, Sun et al., 2023, Guo et al., 2023, Ye et al., 2024). The three types of ionizing radiation, at similar doses, have similar effects on human pathogens and product quality (Fan and Wang 2020). Educating consumers about the benefits and nature of ionizing radiation will aid in the acceptance and application of the technology. X-ray and electron beam technologies that do not involve the use of radioactive isotopes, may have advantages in terms of consumer acceptance. Thus, the goal of this study was to evaluate the effect of X-rays on the quality of mangoes cv. 'Keitt', analyzing the physicochemical properties (weight loss, internal and external color, firmness, pH, total soluble solids), and vitamin C content. Mango is an ever-increasing commodity for export around the world. In Latin America, Mexico is considered as the first country in this region with APHIS-certified facilities (two) for phytosanitary treatments. Nine commodities are authorized for export from Mexico to the USA with irradiation, including mango vr. Keitt and many more fresh commodities (Bustos-Griffin et al., 2012). The availability of generic radiation treatments has stimulated the worldwide interest in use of this technology for phytosanitary purposes. Irradiation has been used to export mangoes from Australia to New Zealand, from Hawaii to the US mainland, from India to Australia and to the USA, and from Mexico and Thailand to the USA (Follet, 2009). Considering that most of the treatment has been dose by gamma radiation, we hypothesize that X-ray technology can be a good alternative to gamma radiation as phytosanitary treatment for this mango variety.

MATERIAL AND METHODS

Experimental site

Mango (*Mangifera indica* L.) cv. 'Keitt', of ¾ of commercial maturity and of export quality were obtained from the Packing Company "Orotina" located in Orotina, Costa Rica, the mangoes selected were classified as size number 8 according with the Mexican Norm NOM-188-SCFI-2012 (between 600 to 606 g that fit into an international commercial box of 4.5 kg or 10 pound of capacity (NOM-188-SCFI-2012). The fruits were taken to the fruit fly facility at Pavas, San José, Costa Rica and stored at 17 °C for 24 hours before the irradiation process. The batch of fruit was divided into 3 groups, two were irradiated a) 150 Gy; b) 300 Gy, while the third was the control c) not irradiated, each group was considered as a treatment. After treated, the fruit were stored at 25°C for 10 days; each treatment was replicated four times.

Mangoes were irradiated in an X-ray generator type Radsource® Model RD-2400 located at the Fruit Fly Program, of the Servicio Fitosanitario del Estado (SFE) of Costa Rica. A farmer type 0.18-cm^3 free air ionization chamber in conjunction with a digitizer module, model 02-0090 (RadCal Corporation, Monrovia, CA. USA), was used as a reference dosimetry system to measure the dose rate (5.49 Gy/min) and accumulated dose at a reference. The Ionization chamber was used only to characterize the x-ray generator. The maximun dose rate that the RD-2400 equipment can deliver was determined, and this data was used to calibrate the gafchromic dosimetry system (IAEA, 2004).

Mangoes were placed in five containers of three liters capacity each (7" diameter × 8" long), which moved around the X-ray generator tube. Five fruits were placed in each container. The equipment was set up at an electrical potential of 146 kV and a current of 20 mA given a Dose Energy Ratio (DER) of 0.026 Gy/kW.sec, so that to get the dose of 150 and 300 Gy, the correspondent energies were determined. The results of the dosimetry using the Gafchromic system showed average absorbed doses of 150 and 301 Gy; with a minimum dose (Dmin) of 149 and 299 Gy and a maximum dose (Dmax) of 189 and 378 Gy respectively; the Dose Uniformity Ratio (DUR) for both doses was 1.26.

After the irradiation treatment, fruit were stored at room temperature 25 °C and fruit quality was assessed every day during 10 consecutive days.

Physicochemical properties

The physicochemical properties evaluated were: weight loss, internal and external color, firmness, pH, total soluble solids (TSS); while that the vitamin C content was determined following the methodology described in the Association of Official Analytical Chemists (AOAC, 1998).

Weight loss

The weight loss rate was determined using a digital scale (Ohaus ® Brand, Model CS2000, USA). The average weight of the 10 fruits per each treatment was used to obtain one value per day during 10 consecutive days. Four replicates were carried out for each treatment and the weight loss was expressed in grams.

Internal and external color

The external color was measured in the equatorial zone for three points (apex, middle and base) of the fruit. The internal color was measured by making a longitudinal cut of the same fruit using a portable colorimeter (Brand Konica Minolta, Mod. Chroma meter CR-400, USA), recording luminosity (L), chromaticity (C) and hue angle (ºHue) (Francis, 1980).

For the determination of chromaticity value or saturation index value, the following formula was used: $Cr = (a^2 + b^2)^{½}$; the "Hue" angle was determined by (°H) = arctg b/a.

Four replicates were done daily for 10 consecutive days.

Firmness

This parameter was measured on the flesh of the fruit, a portion of the skin of the fruit was removed with a cuter and the firmness was taken using a digital penetrometer (Turoni TR® model 53205, Forli-Italy) equipped with a strut of 10 mm in diameter. Three samples were taken and averaged to obtain one value daily per treatment, the test was carried out for 10 consecutive days and the firmness was expressed in N. Four replicates per treatment were done during the whole experiment.

Total soluble solids

To obtain the concentration of total soluble solids, flesh samples were taken from three different parts of the fruit (apex, middle and base). All were mixed and macerated, a drop of pulp was taken to measure the Total Soluble Solids using a digital refractometer (Atago® model PR101, Washington, USA). Before each reading, the electrode was washed with distilled water. The average of three lectures in four fruit per day were registered for each treatment. Four replicates were done daily for 10 consecutive days.

pH

pH values were taken by direct immersion of the electrode in the samples using a digital potentiometer (Oakton®, Orion Model 5 Star, Singapur). Samples consisted of 10 g of blended pulps homogenized in 90 mL of distilled water. From each treatment, the pulp of two fruits were homogenized and two samples of 10 g were analyzed daily. Four replicates were done daily for each treatment for 10 consecutive days, so that, a total of 80 fruits per treatment were analyzed during the experiment.

Vitamin C

The concentration of vitamin C was determined at the end of the storage time when the fruit were completely ripe. At the end of the experiment, a bath of fruits from each treatment was sent to a particular laboratory for vitamin C determination, during the process the pulp of at least three fruits were mixed and a sample was taken and the vitamin C determination was done following the methodology described by the AOAC official method 967.21 Ascorbic Acid in Vitamin C Preparation and Juice (AOAC, 2006). Four replicates were done per each treatment, a total of 12 experimental units (including the control one) were evaluated.

Data analysis

Physicochemical properties such as internal and external color, firmness, total soluble solids, pH and vitamin C, were analyzed by analysis of variance (ANOVA), followed by a post-hoc Tukey test HSD (α=0.05) when significant. Weight loss data of ten days were analyzed applying an analysis of variance (ANOVA) with repeated means, followed by a post-hoc Tukey test HSD (α=0.05) in case of a significant difference. Analyses were carried out with the statistical program JMP version 5.0.1. Statistical Discovery Software (SAS Institute, 2003).

RESULTS AND DISCUSSION

In this study on mangoes cv. 'Keitt' we find that doses of 150 and 300 Gy applied by an X-ray generator did not cause detrimental effects on fruit quality compared with the quality of untreated fruit (control). This fact is important considering that postharvest handling of mangoes is the last phase (from the tree to the mouth) of an agribusiness venture (Johnson and Hofman, 2009). The effect of irradiation doses on the quality of different species of fruit has been characterized (Gould and Windeguth, 1991; Hallman and Loaharanu, 2002; McDonald et al., 2013), but all these studies have been conducted with gamma radiation, and not many using X-rays. We compare and discuss the results of this treatment against other kinds of fruits in postharvest handling subject to quarantine treatment.

Weight loss

There was no significant difference in weight loss in the different irradiation treatments (Table 1). The linear regression equations showed that mangoes irradiated with X-ray at doses of 150 and 300 Gy had similar patterns of weight loss than those observed for the control (no irradiation) (Fig. 1). There were no significant differences in weight loss at five days ($F_{2,9}$ = 1.50; p = 0.275), or ten days ($F_{2,9}$ = 3.02; p = 0.099) after the treatment.

Table 1. Linear regression equations for weight loss of mangoes cv. "Keitt" 10 days after irradiation with X-rays and stored at 25 °C.

Treatment (Gy)	Regression line (days)	r^2	f. d.
Control	703.08 – 4.49	0.9884	2.38
150	743.67 – 4.67	0.9926	2.38
300	660.67 – 5.28	0.9946	2.38

Some postharvest treatments have shown adverse effects on the tissue of the commodities, such as high hydrostatic pressure (Alvares-Virrueta et al., 2012) and heat treatments (Lurie, 1998). However, treatments such as hydrothermal process and gamma irradiation have not shown detrimental effects on the fruit weight loss after treatment (Luna-Esquivel, 2006, Gómez-Simuta et al., 2017). Similarly, in our studies X-rays did not affect weight loss.

Internal and external color

At five days after the X-ray treatment, there was no significant differences in external color for chromaticity ($F_{2,9}$ = 2.16; p = 0.171). However, there was a significant difference for Hue angle ($F_{2,9}$ = 9.03; p = 0.007), where 300 Gy had significantly lower hue angles compared to the control, and no significant differences with 150 Gy (Table 2). For internal color there was no significant differences for chromaticity ($F_{2,9}$ = 0.59; p = 0.575), nor for Hue angle ($F_{2,9}$ = 1.93; p = 0.201). At ten days after treatment, there was no significant differences in both external and internal color for chromaticity ($F_{2,9}$ = 0.52; p = 0.610), ($F_{2,9}$ = 0.28; p = 0.763), nor for Hue angle ($F_{2,9}$ = 0.27; p = 0.769), ($F_{2,9}$ = 1.54; p = 0.265), respectively.

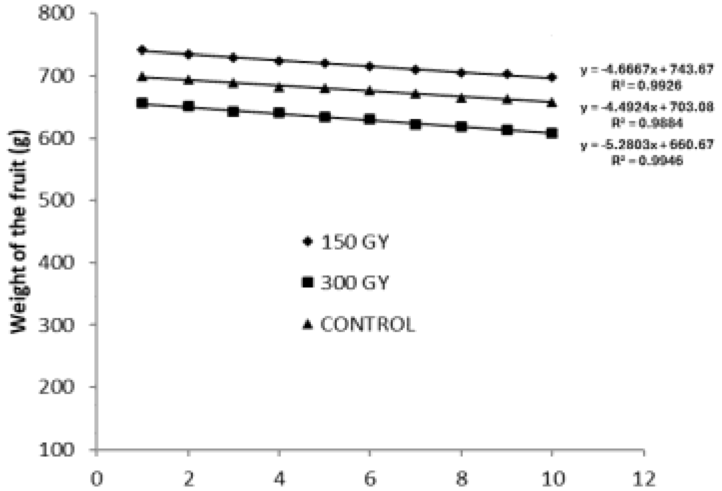

Fig. 1. Linear regression of weight loss of mango cv. 'Keitt' irradiated at different doses of X-rays and stored for 10 days at 25°C.

Table 2 Mean values of external color (Hue angle) of mango cv. "Keitt" five days after X-ray irradiation and stored at 25°C.

Treatment (Gy)	External Color (°Hue)	Standard Error
150	180.04 ab	58.98
300	71.91 a	5.41
Control	277.49 b	1.90

Different letters indicate significant differences, Tukey Test ($P \leq 0.05$).

Fruit color is a crucial parameter for consumer decisions, especially if the product is packaged and cannot be touched or smelled (Ngamchuachit et al., 2014). Studies on mango cv. "Ataulfo" have shown that gamma irradiation at doses up to 300 Gy, nor hot water treatment at 46 °C during 76 min, produced any detectable changes on the internal and external color of the fruit after 18 days of storage (Gómez-Simuta et al., 2017). Because at ten days (a standard consuming time for mango cv. 'Keitt') there are no effects of the X-ray treatment on both skin (external) and flesh (internal) color of the treated mangos; then, we assume that the electromagnetic radiation produced by an X-ray generator could have the same beneficial effects on fresh fruit than those produced by gamma radiation from ^{60}Co, and with greater advantages because its use has fewer restrictions.

Firmness

At five days after irradiation, there were no significant differences in fruit firmness ($F_{2, 9} = 3.03$; p = 0.098). However, at ten days after the treatments, mangos irradiated at 150 Gy were significantly firmer ($F_{2, 9} = 7.84$; p = 0.01) (Fig. 2). The mangoes that were treated with a dose of 300 Gy had a similar trend in firmness than the control mangoes.

Loss of fruit firmness interferes with the marketing of mangoes by increasing their susceptibility to bruising and decay during shipping and storage (Ngamchuachit et al., 2014), and most of the postharvest treatments have some effect on the quality of the commodity. For example, the conditioning treatments in cv. 'Kensington' mangoes, before the normal hot water treatment (HWT) decreased fruit firmness by 25–40% compared to untreated fruit (Jakobi et al., 2001). The HWT has a detrimental effect on cv. 'Keitt' mango firmness because the mangos softened more rapidly than the untreated control (Ngamchuachit et al., 2014). Gamma radiation (Gomez-Simuta et al., 2017) and the X-ray irradiation did not produce loss of fruit firmness after 5 days, and mangoes irradiated at 150 Gy in fact were firmer 10 days after irradiation.

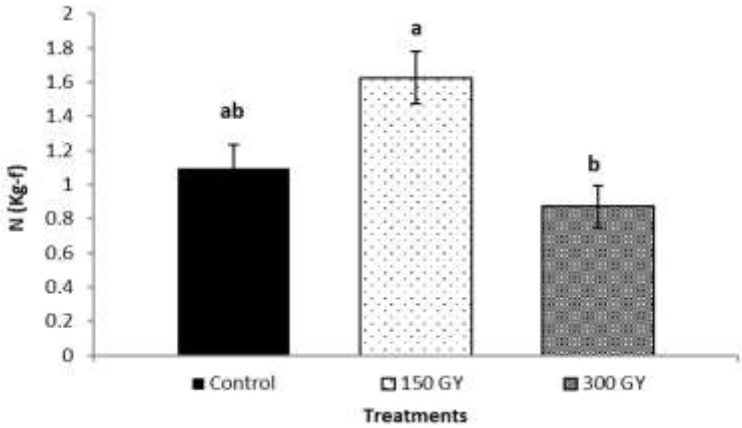

Figure 2. Firmness in N (mean ± SE) of mango cv. 'Keitt' irradiated with X-rays and stored for 10 days at 25°C. Different letters indicate significant differences.

Total soluble solids

At five days after treatment, there were no significant differences between the values of total soluble solids (TSS) ($F_{2, 9} = 0.92$; $p = 0.432$). However, at ten days, fruit irradiated at 300 Gy had more soluble solids than fruit irradiated at 150 Gy ($F_{2, 9} = 4.69$; $p = 0.040$). Although the sugar content was higher for the dose of 300 Gy at day ten compared to 150 Gy, there was no significant difference between the control and 300 Gy (Fig. 3).

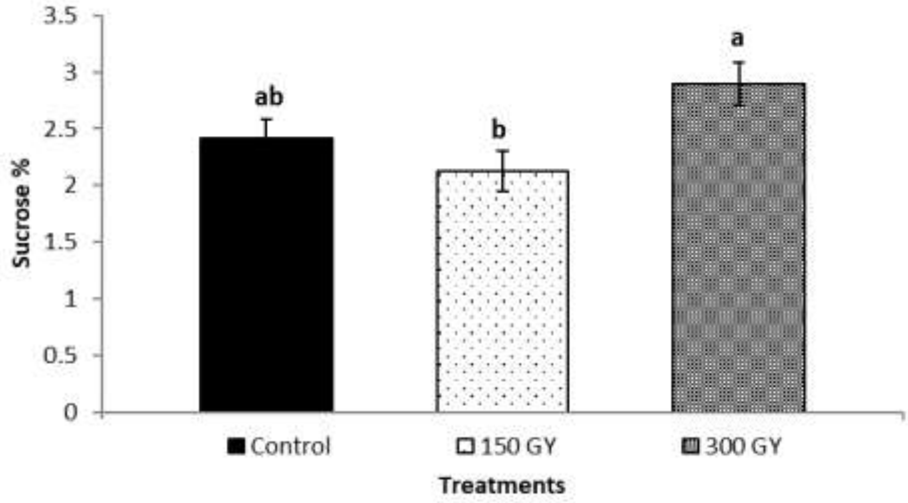

Figure 3. Total soluble solids (TSS) (mean ± SE) of mango cv. 'Keitt' irradiated with X-rays and stored for 10 days at 25 °C. Different letters indicate significant differences.

Sweetness is one of the most important factors that determine mango quality, particularly during ripening, and this parameter has been shown to be useful in determining physiological changes during the ripening stage (Delwiche et al., 2008). Although there were no differences in TSS between the control and 300 Gy, the increase of TSS at doses of 300 Gy of X-ray compared to the dose of 150 Gy, warrants further research to determine the influence of the voltage and the current used during the X-ray production at higher doses.

pH

The pH was significantly different between five days ($F_{2, 9} = 19.90$; $p = 0.001$) (Fig. 4A) and ten days later after being treated ($F_{2, 9} = 19.40$; $p = 0.001$) (Fig. 4B). For both cases, fruits irradiated at 150 Gy and the control (non-irradiated mangoes), the acidity concentration was higher than the mangoes irradiated at 300 Gy. Although the pH in fruits of all treatments increased with storage time, always the dose of 300 Gy showed a significantly higher pH compared to 150 Gy and the control.

Vitamin C

For vitamin C contents (given in g kg^{-1}) at ten days after treatment (complete ripening), there was no significant differences among treatments ($F_{2, 9} = 0.88$; $p = 0.448$). Doses of 150, 300 Gy, and the non-irradiated treatment had the following average (± SE): 0.86 ± 0.14, 1.07 ± 0.10 and 0.85 ± 0.15, respectively.

Effects of e-beam or X-rays on the quality of some foods or vegetables have been studied. For example, in green tea (*Camellia sinensis* L.) doses of 5, 10, 20 and 30 Gy delivered by an e-beam, decreased catechins, caffeine and nitrite scavenging. However, the changes of overall color and radical scavenging activity were negligible (Park et al., 2006). Many postharvest treatments negatively affect commodity quality; therefore, reducing the severity of a quarantine treatment may improve the shelf life or marketability of the commodity (Follett and Neven, 2006). Our results showed that the X-ray did not affect the vitamin C content of irradiated mangos. This technology has the potential to be applied for phytosanitary purposes, which could increase the demand for more fresh fruits treated with X-rays in the international market. The use of electricity for the treatment instead of nuclear energy could increase consumer acceptability.

The postharvest technologies must keep the nutritional and functional quality of the fruits until these arrive to consumers (Rojas-Argumedo et al., 2007). In this context, our study on tolerance of mango cv. 'Keitt' to X-ray irradiation had no detrimental effects on the quality of the fruit. Similarly, electron beam and X-ray irradiation did not change the quality of strawberry (Cho et. al. 2020), and the electron beam irradiation did not affect the quality of star apple fruits *Chrysophylumm cainito* (Nguyen et al. 2020). Irradiation of fruit and vegetables could become a cornerstone technology for countries in order to protect and secure its food supply and provide access to international markets (Pillai et al., 2014). New technologies such as X-ray and electron beam irradiation could allow consumers to access good quality fresh fruits and vegetables from around the world at a fair price, with the added benefit of ensuring safety during the handling of ionizing radiation.

CONCLUSION

We found that the quality of mangoes cv. 'Keitt' irradiated at doses of 150 and 300 Gy with X-rays did not show significant changes in physical and chemical parameters such as: weight loss, external and internal color, pH, soluble solids, firmness and vitamin C content compared to the quality of mangoes that were not treated with X-rays. The use of X-rays was as effective as gamma radiation for the treatment of fresh fruits that require quarantine process before being sent to the fruit market. Irradiators with this type of energy can be used for the treatment of mangoes to comply with the phytosanitary requirement against fruit flies imposed by the countries that purchase Mexican mangoes. However, we suggest further tests of different mango varieties to characterize their physiochemical parameters after treatment.

Figure 4A

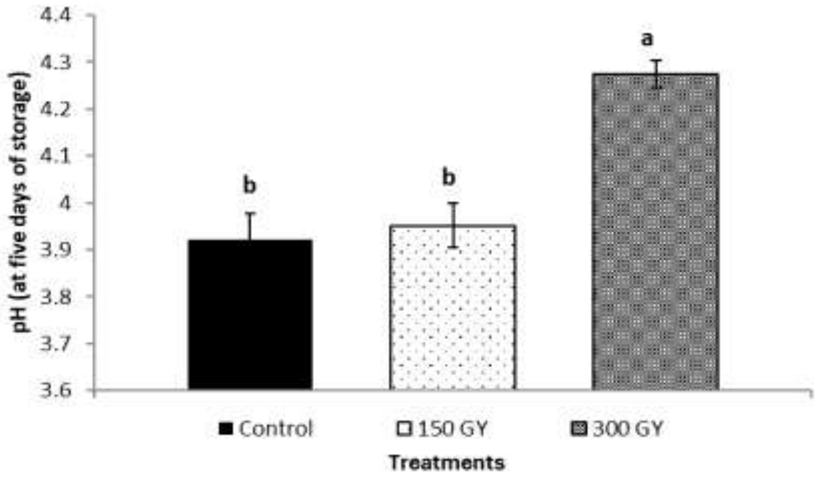

Figure 4B

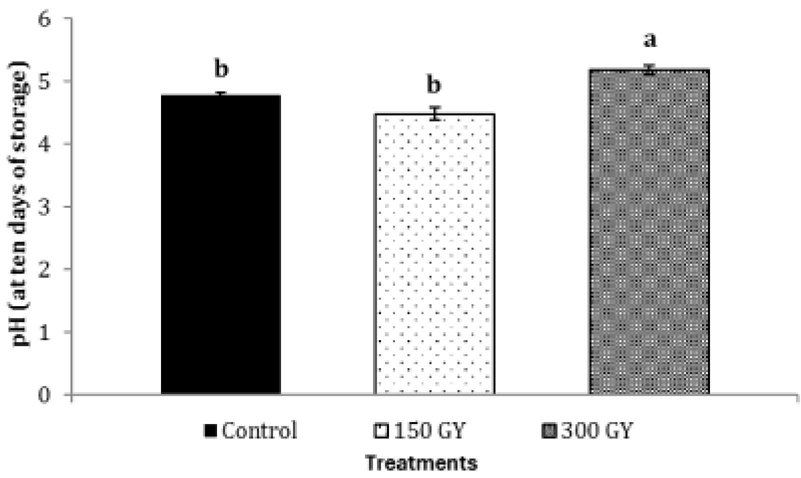

Figure 4. pH (mean ±SE) of mango cv. 'Keitt' irradiated with X-rays and stored for five days (Fig. 4 A) or for 10 days (Fig. 4 B) at 25 °C. Different letters indicate significant differences.

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