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Short Communication

Up-Regulation of plant defense genes in harvested mango using electron beam irradiation

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Abstract

Postharvest disease is a major problem in harvested mango fruit, affecting both quantity and quality during storage. Electron beam (E-beam) irradiation is a new approach that enhances plant disease resistance and controls postharvest disease development. This study investigated the effect of pre-treatment with E-beam irradiation on disease development and defense genes expression in mango fruit during cold storage. Mango fruit samples cv. 'Nam Dok Mai Si Thong' were pre-treated with an E-beam at a dose of 0 (control) or 0.5 kGy and then stored at 13°C for 16 d. The results at 16 d showed significant reductions in the postharvest disease (anthracnose) incidence of the E-beam treated fruit by 2.0-fold relative to the control (100% and 50% in the control and the E-beam treated group, respectively). Disease severity was also reduced by 3.7-fold (score 2.05 for the control and 0.56 for the treated group). The E-beam treatment up-regulated the expression of plant defense genes, such as *MiPOD, MiGLU, MiPAL* and *MiCHI*, in both the peel and the pulp. This suggested that pre-treatment with E-beam irradiation is promising to enhance postharvest disease resistance, which would help to extend the shelf life of mango fruit during cold storage.

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Introduction

Mango (*Mangifera indica* L.) is an important fruit in South and Southeast Asia including Thailand. In Thailand, more than 85 thousand tons was annually produced (Office of Agricultural Economics, 2020) for both domestic consumption and export. The main problem in the fruit of various mango cultivars, such as cv. Nam Dok Mai and Nam Dok Mai Si Thong, is infection by postharvest diseases, especially anthracnose that is caused by *Colletotrichum gloeosporioides* Penz (Dinh et al., 2003; Vivekananthan et al., 2004). Sardsud et al. (2003) reported that the percentages of mango loss by anthracnose disease during harvesting and displaying in markets in Thailand were 62.8% and 63.2%, respectively. Therefore, postharvest treatments for disease control are needed to maintain the quality and to extend the shelf life of mango fruit. Application of fungicides often works well to control postharvest diseases, but chemical residues may be harmful to the consumers and environment (Martínez-Romero et al., 2008; Bautista-Rosales et al., 2014). Postharvest disease control by antagonistic microorganisms still has some limitations, as the antagonistic microorganisms may be potential allergenic agents to humans or act as saprophytes utilizing nutrients from the wounds, which leads to enhanced fruit decay (Bautista-Rosales et al., 2013; Droby et al., 2016).

Thus, physical treatments are commonly considered as alternatives to fungicides and antagonistic microorganisms. Much evidence has demonstrated that physical treatments not only eliminate the pathogens but also kill insect pests and improve the postharvest quality of fresh produce, such as mango (Alvindia and Acda, 2015; Sripong et al., 2015), peach (Liu et al., 2012), stone fruit (Sisquella et al., 2013), nectarine and peach (Casals et al., 2010), pear (Zhang et al., 2006) and peach (Karabulut and Baykal, 2002).

Ionizing irradiation, such as gamma ray, X-ray, and E-beam, is approved as clean technology for food treatment as well as offering promising technology for maintaining the quality of fresh produce by inhibiting sprouting, delaying fruit ripening and controlling insect infestation and postharvest diseases (Farkas and Mohácsi-Farkas, 2011; Shayanfar et al., 2017; Jeong and Jeong, 2018). Amidst the types of ionizing irradiation, E-beam and gamma rays are commercially used for food treatments (Kilcast, 1995; Food and Drug Administration, 2001). However, the use of E-beam is strongly recommended in the near future, as its operating system is easier to control and it is safer than gamma irradiation (Kilcast, 1995).

Other research reported that irradiation could induce plant defense enzyme activity, leading to suppression of postharvest disease development in several types of fresh produce, such as strawberry (Pombo et al., 2011), tomato (Charles et al., 2009) and mangosteen (Sripong et al., 2019). Nguyen et al. (2021) showed that E-beam irradiation at a dose of 0.5 kGy could enhance the activities of plant defense enzymes in mango fruit, such as peroxidase (POD), chitinase (CHI) and β-1,3 glucanase (GLU). However, there is still a lack of knowledge regarding the defense response of mango fruit at a transcriptional level after exposure to E-beam irradiation. Therefore, this work was the first to show that E-beam irradiation induced the expression of plant defense genes in harvested mangoes during cold storage.

Materials and Methods

Mango sample preparation

Naturally infected mature green mango fruit (cv. Nam Dok Mai Sithong) at 90–100 d after fruit set were harvested from a commercial farm in Ratchaburi province, Thailand that had a severe epidemic history of anthracnose disease. The fruit samples were transported to the postharvest pathology laboratory at King Mongkut's University of Technology Thonburi (KMUTT), Bangkok, within 2 hr. The fruit sample was selected for uniformity in size (diameter 6.5–7.0 cm, length 14–15 cm), weight (350–370 g per fruit), color, shape, and were free of any blemish or disease symptoms. The fruits were surface disinfested with a solution of 0.1 g/L sodium hypochlorite before irradiation. Based on Nguyen et al. (2021), E-beam treatment at a dose of 0.5 kGy could reduce anthracnose disease development and so this dose was selected to be used in this study. Two hundred fruit samples were placed in a corrugated paper box (40 cm × 20 cm × 10 cm, with 14–16 fruits per box) and stored in a cold room at 13°C for one night (12 hr) in the laboratory before being transported to the irradiation plant at the Thailand Institute of Nuclear Technology (TINT), Nakhon Nayok province, Thailand the next day in a van with the temperature at 24–28°C for 90 min.

E-beam treatment

The boxes of fruit samples mentioned above were divided into two groups. The first group (100 fruits) was subjected to E-beam irradiation, while the second group (100 fruit) was the non-irradiation control. For E-beam treatment, four fruits per box were randomly attached with alanine pellet dosimeters (Bruker BioSpin; Rheinstetten, Germany), to

determining the desired dose of fruit using an Escan™ alanine dosimeter reader (Bruker BioSpin; Rheinstetten, Germany) with eight dosimeters per box. One dosimeter was placed on the top surface of each of the four fruits per box and another was placed under each of these fruits. Then, the boxes were sealed with plastic tape, before being treated using the E-beam at a dose of 0.5 kGy at ambient temperature (28 ± 2°C). An E-beam linear accelerator (AECL accelerators; Kanata On, Canada) of 10 MeV with a pulse repetition frequency of 60 Hz, was used to irradiate the fruit samples, and the under beam conveyor speed was controlled at 0.024 m/s. In this research, the uniformity of dosage values (D) of irradiated mango fruit in the process (D_{max}/D_{min}) was satisfactory at 1.81, which was in the acceptable range of uniformity ratio values for an E-beam (the required dose uniformity value is between 1.5–2.0), according to International Atomic Energy Agency (1998). After irradiation, both the irradiated fruits and non-irradiated fruits were transported to the laboratory and kept at 13°C for 16 d. On the initial day of storage, 18 fruits of each treatment were randomly collected to evaluate diseases incidence and severity and plant defense genes expression on the initial day, and then at an interval of 4 d during the period of storage. Each treatment had three replications and each replication consisted of six fruits.

Evaluation of disease incidence and severity

The incidence of fruit rot disease was determined and presented as a percentage of the total number of infected fruits subjected to each treatment. The disease severity was evaluated by estimating the total area of disease symptom on each fruit according to the method of Hofman et al. (1997) with some modifications. Disease severity scales consisted of five-point scales, where 0 = no disease symptoms, 1 = <5% of disease spots, 2 = 5.1–15% of disease spots, 3 = 15.1–30% of disease spots, 4 = 30.1–50% of disease spots and 5 = >50% of disease spots on the affected fruit surface.

Extraction of total RNA and reverse transcription real-time polymerase reaction assay

Equal amounts of peel or pulp tissue from 6 fruits were collected, mixed well, and used for replication for RNA extraction. Each collected tissue sample was freeze-dried and kept in the freezer at -40°C for further use throughout this experiment. Total RNA was extracted from the mango peel and pulp using the method described by Ikoma et al. (1996). Freeze-dried peel and pulp tissue (0.25 g peel, 0.8 g pulp) were grounded in liquid nitrogen, and then in 10 mL of phenol, chloroform, 3-methyl-butanol (25:24:1) and 10 mL of lysis buffer (containing 2 % sodium dodecyl sulfate in diethyl pyrocarbonate (DEPC)-treated water and 0.5 M of 2-mercaptoethanol) were added. The samples were mixed using a vortex mixture and centrifuged at 3,000×*g* for 30 min. The upper phase was collected and used to repeat three times the process described above. The aqueous part of the supernatant was transferred to a new tube; then, 0.11 volume of 5 M potassium acetate, 0.25 volume of 99.5% ethanol and 1.36 volume of chloroform and 3-methyl-butanol mixture (49:1) were added and well mixed. Afterward, the upper aqueous phase was added with 3M of lithium chloride (LiCl) and kept at -20°C overnight for RNA precipitation. The RNA pellets were collected using centrifugation and re-suspended in the DEPC-treated water. The total RNA was purified using an RNeasy Mini Kit (Qiagen; Hilden, Germany) in a column of DNase digestion. A 400 ng sample of purified RNA with a random hexamer was used for synthesizing cDNA, using TaqMan Reverse Transcription Reagents (Applied Biosystems; Foster City, CA, USA).

The TaqMan probe and a set of primers for *MiPOD*, *MiPAL*, *MiCHI* and *MiGLU* used in this experiment were as reported by Sripong et al. (2015). TaqMan real-time polymerase chain reaction was carried out with a StepOnePlus™ Real-Time PCR System (Applied Biosystems; Foster City, CA, USA). Each reaction mixture consisted of 1.25 µL of cDNA template, 900 nM primers and a 250 nM TaqMan MGB probe. The thermal cycling conditions were 95°C for 10 min, followed by 40 cycles of 95°C for 15 s and 60°C for 60 s. The levels of gene expression were carried out based on the StepOnePlus™ Real-Time PCR System Software (Applied Biosystems; Foster City, CA, USA) and normalized with the results of 18S ribosomal RNA. Real-Time PCR was operated with three replications of each treatment.

Statistical analysis

All data were analyzed using the statistical analysis software (SAS), version 9.0 (SAS Institute; Cary, NC, USA), for completely randomized design experiments. The means were compared using an independent sample Student's t test. The values of $p < 0.05$, $p < 0.01$ and $p < 0.001$ expressed statistical significance. Each treatment consisted of three replications and each replication consisted of six fruits. The data were expressed as mean ± SD.

Results

Effect of E-beam on postharvest disease incidence and severity

Only the symptoms of anthracnose disease were detected in the current study. The incidence and severity of anthracnose disease in mango fruit after treating it with E-beam at a dose of 0.5 kGy are shown in Figs. 1A and 1B, respectively. E-beam treatment significantly reduced both the disease incidence and severity in the mango fruit during storage (Fig. 2). At day 12 of storage, disease incidence in the E-beam treated fruit (33.33%) was approximately 2.7-fold lower than that of the control fruit (88.89%). By the end of storage (day 16), the control fruit exhibited 100% disease incidence, whereas the E-beam treated fruit had 50%. Similarly, the disease severity of the E-beam treated fruit developed slowly compared to the control fruit. Disease severity in the E-beam treated fruit was significantly lower than that of the control fruit from days 8–16. At the end of storage, disease severity in the E-beam treated fruit (0.56 score) was approximately 3.7-fold lower than for the control (2.05 score).

Effect of E-beam on plant defense genes expression

It has been reported that ionizing radiation induces the host resistance responses of a fruit through the expression of defense-related genes, leading to an increase in pathogenesis-related (PR) proteins such as phenylalanine ammonia-lyase (PAL), chitinase (CHI), peroxidase (POD), β-1 and 3-glucanase (GLU) (Jeong and Jeong, 2018). In the present study, the expressions of *MiCHI*, *MiGLU*, *MiPOD* and *MiPAL* were analyzed in the peel and pulp of mangoes (Fig. 2). Mango fruit treated with E-beam irradiation immediately showed a decrease in the expression levels of *MiPOD*, *MiCHI* and *MiGLU* in the peel, while the expression levels of *MiPAL*, *MiGLU* and *MiPOD* increased in the pulp. The transcriptional level of the *MiPAL* gene in the E-beam treated fruit increased sharply in the early stage of storage (day 0 to day 8) in the peel and then rapidly decreased until the end of storage. In contrast, the transcriptional level of *MiPAL* in the pulp increased immediately on day 0 and rapidly declined from day 4 to day 16 (Figs. 3A and 3B). In the peel, the expression of the *MiPOD* gene was lower after the E-beam treatment compared to the control on the initial day; afterwards, it rapidly increased and reached a peak at day 8, before falling at the end of storage. For the pulp, the E-beam treatment significantly induced the expression of *MiPOD* from day 0 to 12, with no significant difference at the end of storage (Figs. 3C and 3D). The mRNA level of *MiGLU* in the peel was low at day 0 of storage, followed by a sharp increase until the end of storage period (day 16) in both the E-beam treated and non-treated fruit. The transcriptional level of *MiGLU* in the E-beam treated fruit was significantly higher than for the untreated fruit from day 4 to day 16. In contrast, in the pulp, the E-beam treatment significantly induced the mRNA level of *MiGLU* compared to the untreated fruit from day 0 to day 4. Afterward, the E-beam treated fruit had significantly lower mRNA levels than the untreated fruit from day 8 to the end of storage (Figs. 3E and 3F). The E-beam treatment immediately down-regulated the expression of *MiCHI* in the peel on day 0, followed by a progressive increase from day 4 to day 8 and then its expression decreased and was lower than untreated fruit from day 12 until the end of storage. On the other hand, the E-beam treatment significantly decreased the transcript level of *MiCHI* in the pulp, especially from day 12 to day 16, except on day 4 of storage (Figs. 3G and 3H). These results implied that E-beam irradiation could suppress anthracnose disease development in harvested mangoes due to the up-regulation effect of the E-beam treatment on plant defense genes.

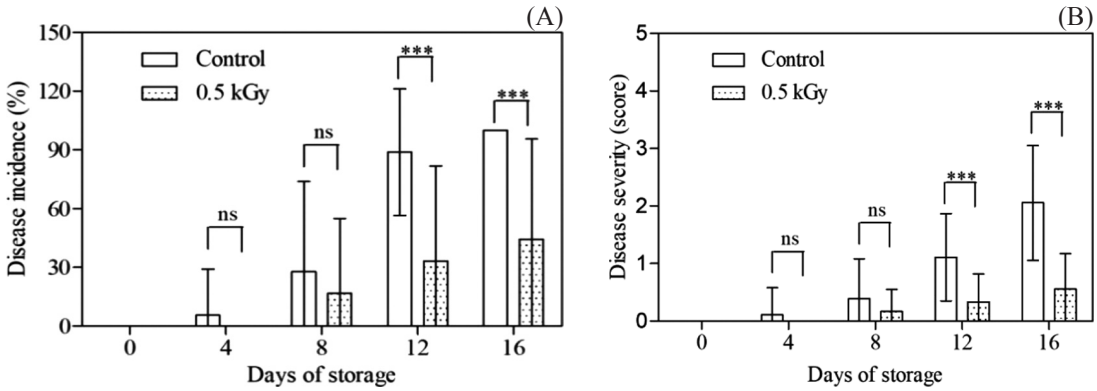

Fig. 1 Mean of disease incidence (A) and severity (B) in mango fruit after treatment with E-beam irradiation at a dose of 0.5 or 0 kGy (control) and stored at 13°C for 16 d; error bars represent ±SD; *** = highly significant ($p < 0.001$) difference; ns = non-significant difference ($p > 0.05$)

Fig. 2 Appearance of mangoes after treatment with E-beam at doses of 0 (A) and 0.5 kGy (B) and then stored at 13°C for 16 d

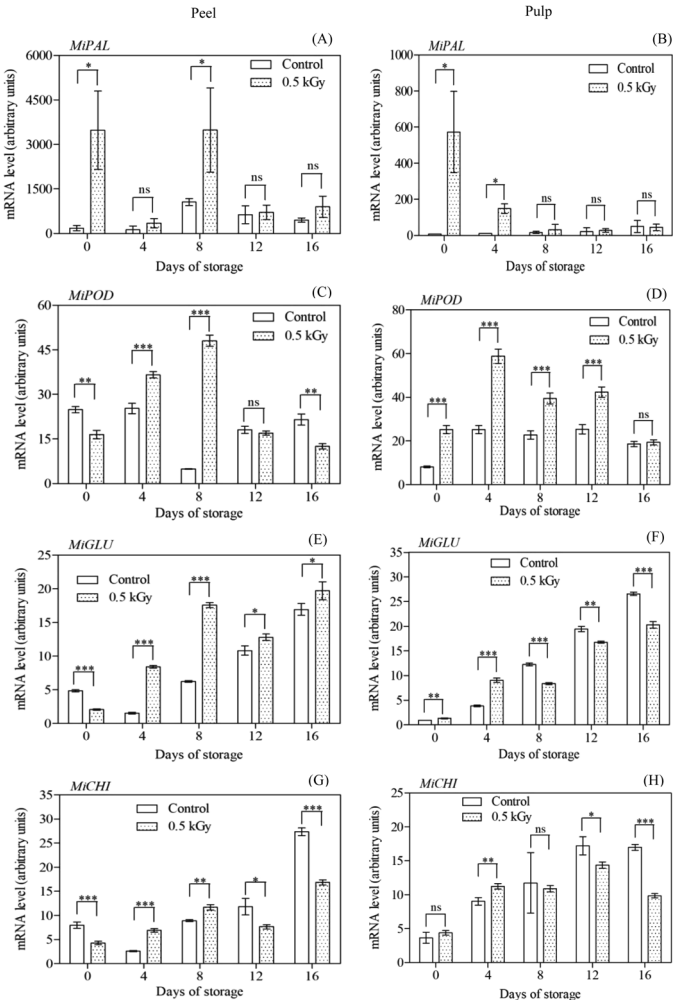

Fig. 3 Plant defense genes expression in peel and pulp of mango fruit treated with 0 or 0.5 kGy E-beam and stored at 13°C for 16 d: (A) *MiPAL* in peel; (B) *MiPAL* in pulp; (C) *MiPOD* in peel; (D), *MiPOD* in pulp; (E) *MiGLU* in peel; (F) *MiGLU* in pulp; (G) *MiCHI* in peel and (H) *MiCHI* in pulp; data are expressed as mean + SD; *, **, *** indicate significant differences between the two treatment at $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively; ns = non-significant difference ($p > 0.05$).

Discussion

Postharvest disease, especially anthracnose is one of the adverse factors that affects the consumer sensory preference, quality and shelf life of harvested mangoes. Ionizing irradiation can be applied to control postharvest diseases, which could, in turn, help to maintain the fruit quality and extend fruit shelf life. The present results indicated that the E-beam treated mangoes had lower disease incidence and severity than the untreated mangoes. Other studies showed that there were several factors involved with the responses of plants against pathogens such as the synthesis of pathogenesis related (PR) proteins, for example, CHI, GLU and POD, phytoalexins, phenolic compounds, and lignin (Lin et al., 2005; Ebrahim et al., 2011). The present study showed that E-beam irradiation elicited the expression of plant defense genes by enhancing the mRNA levels of the *MiPAL*, *MiPOD*, *MiCHI* and *MiGLU* genes as they are associated with PR protein synthesis in both the peel and pulp of mango fruit during storage. The PR protein was induced by the E-beam treatment was correlated with the disease symptoms. The increase in the PR protein level caused a decrease in disease incidence and severity in mangoes (Nguyen et al., 2021). The function of PR proteins, such as GLU and CHI, has been known to degrade the fungal cell wall, lyse the mycelial tip and lead to fungal death (Simmons, 1994). Another PR-9 protein family that may participate in the lignification pathway in plant cells is POD. Lignin can enhance the structural strength of the plant cell wall against the pathogen invasion (Ferreira et al., 2007). There is a close relationship between plant disease resistance and PR proteins in harvested fruit. Other research proved that high activities of GLU, CHI and POD caused a decrease in disease incidence and severity in various fruits, such as mango (Zeng et al., 2006; Zhang et al., 2013; Hu et al., 2014; Sripong et al., 2015), apple (Ippolito et al., 2000), avocado (Glowacz et al., 2017) and peach (Liu et al., 2012). In addition, PAL is a key enzyme in the phenylpropanoids metabolism pathway that is involved with antifungal compounds biosynthesis, such as phenolics. The increase in phenolic compounds and PAL activity has been associated with disease resistance in harvested fruit (Oufedjikh et al., 2000; Hu et al., 2014; Wu et al., 2017). Therefore, E-beam irradiation could enhance the defense mechanism in mango fruit, as it up-regulates the expression of plant defense genes, such as *MiPOD*, *MiPAL*, *MiGLU* and *MiCHI*, in both the peel and pulp during storage.

The present research showed the response of harvested mangoes to E-beam irradiation in terms of disease incidence, disease severity and the expression of plant defense genes during storage. These results demonstrated that E-beam irradiation could reduce anthracnose disease development in harvested mangoes during the storage period because of simultaneously increasing the mRNA level of plant defense genes, such as *MiPAL*, *MiPOD MiGLU* and *MiCHI*. This study suggested that an E-beam can be applied as a physical treatment to enhance plant defense against postharvest diseases in harvested mangoes.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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References

Alvindia, D.G., Acda, M.A. 2015. Revisiting the efficacy of hot water treatment in managing anthracnose and stem-end rot diseases of mango cv. "Carabao". Crop Prot. 67: 96–101. doi.org/10.1016/j.cropro.2014.09.016

Bautista-Rosales, P.U., Calderon-Santoyo, M., Servín-Villegas, R., Ochoa-Álvarez, N.A., Ragazzo-Sánchez, J.A. 2013. Action mechanisms of the yeast *Meyerozyma caribbica* for the control of the phytopathogen *Colletotrichum gloeosporioides* in mangoes. Biol. Control 65: 293–301. doi.org/10.1016/j.biocontrol.2013.03.010

Bautista-Rosales, P.U., Calderon-Santoyo, M., Servín-Villegas, R., Ochoa-Álvarez, N.A., Vázquez-Juárez, R., Ragazzo-Sánchez, J.A. 2014. Biocontrol action mechanisms of *Cryptococcus laurentii* on *Colletotrichum gloeosporioides* of mango. Crop Prot. 65: 194–201. doi.org/10.1016/j.cropro.2014.07.019

Casals, C., Viñas, I., Landl, A., Picouet, P., Torres, R., Usall, J. 2010. Application of radio frequency heating to control brown rot on peaches and nectarines. Postharvest Biol. Technol. 58: 218–224. doi.org/10.1016/j.postharvbio.2010.07.003

Charles, M.T., Tano, K., Asselin, A., Arul, J. 2009. Physiological basis of UV-C induced resistance to *Botrytis cinerea* in tomato fruit. V. constitutive defence enzymes and inducible pathogenesis-related proteins. Postharvest Biol. Technol. 51: 414–424. doi.org/10.1016/j.postharvbio.2008.08.016

Dinh, S.Q., Chongwungse, J., Pongam, P., Sangchote, S. 2003. Fruit infection by *Colletotrichum gloeosporioides* and anthracnose resistance of some mango cultivars in Thailand. Australas. Plant Pathol. 32: 533–538. doi.org/10.1071/AP03053

Droby, S., Wisniewski, M., Teixidó, N., Spadaro, D., Jijakli, M.H. 2016. The science, development, and commercialization of postharvest biocontrol products. Postharvest Biol. Technol. 122: 22–29. doi.org/10.1016/j.postharvbio.2016.04.006

Ebrahim, S., Usha, K., Singh, B. 2011. Pathogenesis-related (PR)-proteins: Chitinase and β-1,3-glucanase in defense mechanism against malformation in mango (*Mangifera indica* L.). Sci. Hortic. 130: 847–852. doi.org/10.1016/j.scienta.2011.09.014

Farkas, J., Mohácsi-Farkas, C. 2011. History and future of food irradiation. Trends Food Sci. Technol. 22: 121–126. doi.org/10.1016/j.tifs.2010.04.002

Ferreira, R.B., Monteiro, S., Freitas, R., et al. 2007. The role of plant defence proteins in fungal pathogenesis. Mol. Plant Pathol. 8: 677–700. doi.org/10.1111/j.1364-3703.2007.00419.x

Food and Drug Administration. 2001. Evaluation and definition of potentially hazardous foods: A report of the Institute of Food Technologists for the Food and Drug Administration of the United States Department of Health and Human Services. Silver Spring, MD, USA. https://www.fda.gov/files/food/published/Evaluation-and-Definition-of-Potentially-Hazardous-Foods.pdf, 12 September 2019.

Glowacz, M., Roets, N., Sivakumar, D. 2017. Control of anthracnose disease via increased activity of defence related enzymes in 'Hass' avocado fruit treated with methyl jasmonate and methyl salicylate. Food Chem. 234: 163–167. doi.org/10.1016/j.foodchem.2017.04.063

Hofman, P.J., Smith, L.G., Joyce, D.C., Johnson, G.I., Meiburg, G.F. 1997. Bagging of mango (*Mangifera indica* cv. 'Keitt') fruit influences fruit quality and mineral composition. Postharvest Biol. Technol. 12: 83–91. doi.org/10.1016/S0925-5214(97)00039-2

Hu, M., Yang, D., Huber, D.J., Jiang, Y., Li, M., Gao, Z., Zhang, Z. 2014. Reduction of postharvest anthracnose and enhancement of disease resistance in ripening mango fruit by nitric oxide treatment. Postharvest Biol. Technol. 97: 115–122. doi.org/10.1016/j.postharvbio.2014.06.013

Ikoma, Y., Yano, M., Ogawa, K., Yoshioka, T., Xu, Z.C., Hisada, S., Omura, M., Moriguchi, T. 1996. Isolation and evaluation of RNA from polysaccharide-rich tissues in fruit for quality by cDNA library construction and RT-PCR. J. Jpn. Soc. Hortic. Sci. 64: 809–814. doi.org/10.2503/jjshs.64.809

International Atomic Energy Agency. 1998. Techniques for high dose dosimetry in industry, agriculture and medicine, in session 6: Process validation. In: Proceedings of the International Symposium on High Dose Dosimetry for Radiation Processing, Vienna, Austria, pp. 229–271.

Ippolito, A., El, A., Wilson, C.L. 2000. Control of postharvest decay of apple fruit by *Aureobasidium pullulans* and induction of defense responses. Postharvest Biol. Technol. 19: 265–272. doi.org/10.1016/S0925-5214(00)00104-6

Jeong, M.A., Jeong, R.D. 2018. Applications of ionizing radiation for the control of postharvest diseases in fresh produce: Recent advances. Plant Pathol. 67: 18–29. doi.org/10.1111/ppa.12739

Karabulut, O.A., Baykal, N. 2002. Evaluation of the use of microwave power for the control of postharvest diseases of peaches. Postharvest Biol. Technol. 26: 237–240. doi.org/10.1016/S0925-5214(02)00026-1

Kilcast, D. 1995. Food irradiation: Current problems and future potential. Int. Biodeterior. Biodegrad. 36: 279–296. doi.org/10.1016/0964-8305(95)00071-2

Lin, W., Hu, X., Zhang, W., Rogers, W.J., Cai, W. 2005. Hydrogen peroxide mediates defence responses induced by chitosans of different molecular weights in rice. J. Plant Physiol. 162: 937–944. doi.org/10.1016/j.jplph.2004.10.003

Liu, J., Sui, Y., Wisniewski, M., Droby, S., Tian, S., Norelli, J., Hershkovitz, V. 2012. Effect of heat treatment on inhibition of *Monilinia fructicola* and induction of disease resistance in peach fruit. Postharvest Biol. Technol. 65: 61–68. doi.org/10.1016/j.postharvbio.2011.11.002

Martínez-Romero, D., Serrano, M., Bailén, G., et al. 2008. The use of a natural fungicide as an alternative to preharvest synthetic fungicide treatments to control lettuce deterioration during postharvest storage. Postharvest Biol. Technol. 47: 54–60. doi.org/10.1016/j.postharvbio.2007.05.020

Nguyen, T.T., Uthairatanakij, U., Srilaong. V., Laohakunjit. N., Jitareerat. P. 2021. Effect of electron beam irradiation on disease resistance and quality of harvested mangoes. Radiat. Phys. Chem. 180: 109289. doi.org/10.1016/j.radphyschem.2020.109289

Office of Agricultural Economics. 2020. Ministry of Agriculture and Cooperatives: Agricultural Import Export News, 2020. Export of mango. Bangkok, Thailand. http://impexp.oae.go.th/service/report_product01.php?S_YEAR=2563&i_type=2&PRODUCT_ID=1273&wf_search=&WF_SEARCH=Y#4453, 7 April 2020. [in Thai].

Oufedjikh, H., Mahrouz, M., Amiot, M.J., Lacroix, M. 2000. Effect of γ-irradiation on phenolic compounds and phenylalanine ammonia-lyase activity during storage in relation to peel injury from peel of *Citrus clementina* Hort. ex. Tanaka. J. Agric. Food Chem. 48: 559–565. doi.org/10.1021/jf9902402

Pombo, M.A., Rosli, H.G., Martínez, G.A., Civello, P.M. 2011. UV-C treatment affects the expression and activity of defense genes in strawberry fruit *(Fragaria×ananassa*, Duch.). Postharvest Biol. Technol. 59: 94–102. doi.org/10.1016/j.postharvbio.2010.08.003

Sardsud, U., Sardsud, V., Singkaew, S. 2003. Postharvest loss assessment of mango cv. Nam Dok Mai. Thai J. Agric. Sci. 34(Suppl. 3–4): 37–40. https://agris.fao.org/agris-search/search.do?recordID=TH2005000687 [in Thai].

Shayanfar, S., Mena, K.D., Pillai, S.D. 2017. Quantifying the reduction in potential infection risks from non-O157 Shiga toxin producing Escherichia coli in strawberries by low dose electron beam processing. Food Control 72: 324–327. doi.org/10.1016/j.foodcont.2016.04.057

Simmons, C.R. 1994. The physiology and molecular biology of plant 1,3-β-D-glucanases and 1,3; 1,4- β-D-glucanases. Crit. Rev. Plant Sci. 13: 325–387. doi.org/10.1080/07352689409701919

Sisquella, M., Casals, C., Picouet, P., Viñas, I., Torres, R., Usall, J. 2013. Immersion of fruit in water to improve radio frequency treatment to control brown rot in stone fruit. Postharvest Biol. Technol. 80: 31–36. doi.org/10.1016/j.postharvbio.2013.01.010

Sripong, K., Jitareerat, P., Tsuyumu, S., et al. 2015. Combined treatment with hot water and UV-C elicits disease resistance against anthracnose and improves the quality of harvested mangoes. Crop Prot. 77: 1–8. doi.org/10.1016/j.cropro.2015.07.004

Sripong, K., Jitareerat, P., Uthairatanakij, A. 2019. UV irradiation induces resistance against fruit rot disease and improves the quality of harvested mangosteen. Postharvest Biol. Technol. 149: 187–194. doi.org/10.1016/j.postharvbio.2018.12.001

Vivekananthan, R., Ravi, M., Saravanakumar, D., Kumar, N., Prakasam, V., Samiyappan, R. 2004. Microbially induced defense related proteins against postharvest anthracnose infection in mango. Crop Prot. 23: 1061–1067. doi.org/10.1016/j.cropro.2004.03.014

Wu, Y., Duan, X., Jing, G., Ouyang, Q., Tao, N. 2017. Cinnamaldehyde inhibits the mycelial growth of *Geotrichum citri-aurantii* and induces defense responses against sour rot in citrus fruit. Postharvest Biol. Technol. 129: 23–28. doi.org/10.1016/j.postharvbio.2017.03.004

Zeng, K., Cao, J., Jiang, W. 2006. Enhancing disease resistance in harvested mango (*Mangifera indica* L. cv. Matisu) fruit by salicylic acid. J. Sci. Food Agric. 86: 694–698. doi.org/10.1002/jsfa.2397

Zhang, Z., Yang, D., Yang, B., Gao, Z., Li, M., Jiang, Y., Hu, M. 2013. β-Aminobutyric acid induces resistance of mango fruit to postharvest anthracnose caused by *Colletotrichum gloeosporioides* and enhances activity of fruit defense mechanisms. Sci. Hortic. 160: 78–84. doi.org/10.1016/j.scienta.2013.05.023

Zhang, H., Zheng, X., Su, D. 2006. Postharvest control of blue mold rot of pear by microwave treatment and *Cryptococcus laurentii*. J. Food Eng. 77: 539–544. doi.org/10.1016/j.jfoodeng.2005.06.066