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Effect of phytosanitary irradiation on the quality of two varieties of pummelos (*Citrus maxima* (Burm.) Merr.)

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ABSTRACT

Phytosanitary treatments prevent the introduction of pests such as fruit flies into pest free zones, and are often required for international trade. Irradiation is increasingly being considered as an alternative to cold and chemical phytosanitary treatments, such as methyl bromide. . In this study, the effect of low dose gamma irradiation on the post-harvest quality of two varieties of pummelos (*Citrus maxima* (Burm.) Merr.), an emerging crop of interest in the US was evaluated. Two varieties of pummelos grown in California were irradiated at the phytosanitary target dose of 150 Gy and a higher dose of 1000 Gy to exaggerate and hence confirm the effects of treatment. The fruit was stored at 12 °C for 3 weeks and at 20 °C for the 4th week to reflect three weeks of sea shipment at the ideal temperature for storage of pummelos and an additional week of retail under ambient conditions. Neither irradiation nor storage affected juice content, organic acids, sugars, peel or pulp color and consumer sensory preference, although numerous volatiles increased in concentration as a result of irradiation treatment. Irradiation caused an immediate reduction in whole fruit and pulp firmness in 'Chandler' but not 'Sarawak' pummelos at both 150 Gy and 1000Gy. The quality of irradiated pummelos stored at refrigerated temperature for 3 weeks was similar to untreated pummelos, however, physical handling and exposure to higher temperature

resulted in increased peel pitting of irradiated fruit compared to non-treated fruit. The results suggest that irradiation could serve as a potential phytosanitary treatment for Chandler and Sarawak pummelos, provided that the fruit is subjected to minimal handling and not temperature abused.

Keywords: Citrus, Postharvest quality, Ionizing irradiation, Chemical composition, Peel damage

1 INTRODUCTION

Pummelo (*Citrus maxima* (Burm.) Merr.) is one of the largest citrus fruits by size. This fruit is popular throughout Asia and Europe for their desirable taste, flavor and juicy texture and is gaining popularity in the U.S. In August 2014, the United States Animal and Plant Health Inspection Service (APHIS) proposed the importation of five species of citrus fruits, including pummelos, from China into the U.S. (USDA-APHIS, 2014) provided that adequate phytosanitary measures are taken to ensure quarantine pest free fruit shipment. APHIS has identified 22 pests including eight species of Bactrocera fruit flies as quarantine pests that might enter U.S. through importation of citrus fruits from China (USDA-APHIS, 2015). Phytosanitary treatments allowed by APHIS on citrus include chemical fumigation, irradiation, and cold and heat treatments (USDA-APHIS, 2015), although the commercial phytosanitary treatments prevalent in the citrus industry are cold treatment and methyl bromide fumigation (MeBr). Cold treatments (0.56-1.67 °C for 22-18 days) are very effective in eliminating certain insect infestations (USDA-APHIS, 2015), however, the optimum temperature for storage of pummelos is 12 °C, and storage at significantly lower temperature can adversely affect the external appearance and color of pummelos resulting in damage and loss of market quality (International Tree Fruit Network, 2011). Methyl bromide

(MeBr) has a depleting effect on the ozone layer and pre-plant use has been mostly phased out as required by the 1987 Montreal Protocol (Kuijpers et al., 2014). Due to lack of viable alternatives, MeBr is currently exempted from the ban under the Montreal Protocol for post-harvest phytosanitary purposes (Hallman and Thomas, 2011), although continuous efforts are being made to phase out MeBr completely (USDA-EPA, 2013). The Methyl Bromide Technical Options Committee under the United Nations Environmental Programme has recognized irradiation as a potential phytosanitary alternative to MeBr fumigation (Kuijpers et al., 2014).

Irradiation is a highly efficacious phytosanitary treatment which utilizes ionizing radiation from radioisotopes (gamma rays), electron beam or x-rays to disrupt the genetic material of the pest or microorganism infesting food, causing either sterilization or death of the target organisms. Irradiation is used commercially to treat several fruit including mangos, guavas, litchi, dragon fruit and rambutan in various countries, although it is not currently utilized for citrus products. USDA-APHIS (2015) is considering allowing citrus from China to be treated at 150 Gy, a dose effective against all fruit flies from the family Tephritidae, and in particular the Oriental fruit fly (*Bactrocera dorsalis*).

The effect of irradiation depends upon the variety or cultivar of fruit, irradiation dose, ripening/maturity stage of the fruit, harvest season and post-treatment storage conditions of fruit such as temperature (McDonald et al., 2013; Bustos and Mindeta, 1988; Patil et al., 2004; Miller et al., 2000; Nagai and Moy, 1985). Some fruits such as Valencia and ‘Ambersweet’ oranges can tolerate irradiation but peel pitting is observed on irradiated navel and ‘Hamlin’ oranges, and ‘Fallglo’, ‘Sunburst’ and ‘Temple’ hybrid mandarins (McDonald et al., 2013; Miller et al., 2000). Irradiation also causes dose dependent softening of Valencia

oranges treated at 300 Gy and higher (Nagai and Moy, 1985), navel oranges treated at 600 Gy and higher (McDonald et al., 2013) , and 'Murcott', Minneola and 'Temple' fruit (Miller et al., 2000) whereas other varieties such as 'Hamlin', 'Sunburst' and 'Ambersweet' are more radiotolerant (Miller et al., 2000). .

The effect of low-dose gamma irradiation on the post-harvest quality of pummelos has not been documented. Thus, the objective of the research was to observe the effects of low-dose gamma irradiation (150 Gy and 1000 Gy) on the post-harvest quality of two varieties of Pummelos available in California, Chandler (red flesh) and Sarawak (white flesh), after storage at 12°C for 3 weeks, the time required for sea shipment between the US and Asia, followed by one week at 20°C to reflect retail conditions. The dose of 150 Gy was selected since it is the specified minimum dose in the PPQ Treatment Manual (APHIS, 2014). 1000 Gy is the maximum dose allowed by the FDA to treat fresh fruits and vegetables and was selected to exacerbate the negative effects and allow recognition of symptoms of phytotoxicity.

2 MATERIALS AND METHODS

2.1 Fruit Procurement

Pummelos were harvested on January 15th, 2015 in Tulare County, CA. The fruits were packed on January 17th, 2015 in Orosi, CA following standard commercial practices. The fruits were first washed using 50-150 mg/L chlorine at the point of dumping, then using a mixture of 100-200 mg/L chlorine and 1-2% sodium bicarbonate in a high pressure washer at 862 kPa (125 psi) followed by a fresh water rinse. After washing, the fruits ware treated with 200-300 mg/L heated imazalil. In addition to treatment with imazalil, the fruits were

waxed with carnauba-based wax that had 2000 mg/L imazalil and 3500 mg/L thiabendazole mixed in it. Pummelos were bulk packed in 24 kg cartons, with approximately 12 pummelos in each carton. After packaging, the cartons were stored at 5° C prior to shipping to Santa Fe Springs, CA (350 km) in a refrigerated truck. The cartons of pummelos were picked up from the distributor and transported in a van to Sterigenics, Inc., Tustin CA (20 km) for gamma irradiation.

2.2 Gamma Irradiation:

Upon arrival at Sterigenics, the cartons were labeled either control, 150 Gy, or 1000 Gy. Dose mapping was conducted using eight cartons of pummelos in the exact configuration as the sample treatment with 150 Gy and 1000 Gy. Eight boxes were stacked in two rows of four a fixed distance from the Co_{60} source (~278bq). Dose mapping was conducted by placing 16 alanine pellet dosimeters (FarWest Technology, In, Goleta, CA) at various locations in the cases. The dose rate was determined to be 0.637 Gy s^{-1}. Eight cases of pummelos were placed exactly in the same configuration as the dummy cases to receive treatment at a target dose of 150 and 1000 Gy (4.6-5.5% uncertainity) and Dmax/Dmin ratio of 1.33. The eight cartons used as control fruit did not receive any treatment. After treatment was complete, all the cartons were transported to Chapman University, Orange, CA in a van, covering a distance of approximately 24 miles. Upon arrival, all the cartons were stored at 12° C for 3 weeks to simulate shipment to and from Asian countries and at 20° C for the 4^{th} week to simulate one week at retail temperatures. Temperature was verified using LogTags® (Auckland, New Zealand) placed in cartons of pummelos during storage. Analytical and chemical tests were performed on samples taken at day 1 after irradiation, then after 3 and 4 weeks of storage.

2.2.1 Peel pitting and external damage

Ten pummelos per treatment were labeled (control, 150 Gy and 1000 Gy) and used for determining external damage during storage. The fruit was evaluated during storage for surface damage such as peel pitting, scarring bruising and discoloration by three panelists using a five-point scale reflecting the percentage of surface area impacted by damage. The scale was as follows: 0=0% damage, 1=1-4%, 2=5-9%, 3=10-12%, 4=13-15% and 5=16% or more external damage.

2.2.2 Weight Loss

The same ten pummelos used for determining peel pitting and external damage were also used for measuring change in weight. To measure weight loss, ten whole fruits per treatment were weighed together on each evaluation day. The fruits were weighed using a Mettler Toledo SD32000 scale (Columbus, OH) and percentage weight loss was calculated.

2.2.3 Texture

Pulp firmness was measured using a Kramer Shear probe attachment on a TA-XT2 Stable Micro Texture Analyzer equipped with Exponent software (Stable Microsystems, Godalming, Surrey, U.K and Texture Technology Corp. Scarsdale, N.Y.). Six pummelos per treatment were first scored with a knife and then hand peeled. Pummelo segments were separated carefully by hand to ensure fruit firmness was not compromised then cut into halves. Aliquots weighing approximately 150 g were placed in the holding cell of the Kramer shear press. Blades were positioned 80 mm above the bottom of the holding unit platform; the test speed was 1 mm/s with a pre and post-test speed of 5 mm/s. The maximum force (N)

159 required to pierce through the pulp and the area (N.mm) under the curve was recorded. Eight
160 measurements were made for each treatment and averaged.

161 Whole fruit firmness was measured using a puncture probe. Six pummelos per
162 treatment were each punctured six times along the equatorial region to a depth of 35 mm
163 using a 3 mm puncture probe at a speed of 3 mm/sec with a pre and post speed of 5 mm/sec.
164 The maximum force (N) required to penetrate and the area (N.mm) under the curve were
165 recorded.

166 2.2.4 Peel and pulp color measurements

167 Hunter Lab values of the external peel of six pummelos from each dose was measured
168 at four equidistant points along the equatorial axis using a Konica Minolta
169 Spectrophotometer CM-2500d (Ramsey, NJ). The same fruits were cut into half at the
170 equatorial axis, and two measurements for internal color were made on each half; a total of
171 four measurements per fruit. Hue values were calculated using the following formula:

172 $$h = \tan^{-1}(b^*/a^*)$$

173 where h is hue value, a* represents the red/green opponent colors and b* represents
174 the yellow/blue opponent colors on the L*a*b* color space.

175 2.2.5 Juice content

176 Six whole pummelos per treatment were weighed and peeled. The juice was
177 extracted from each pummelo using a TS-738 Elite Gourmet Maxi-Matic Juice Extractor
178 (City of industry, CA) and % juice was calculated using the following formula:

179 % Juice Content (whole fruit basis) = [Juice weight x100]/ [Whole fruit weight]

2.3 Chemical Analysis

Fifteen pummelos per treatment were juiced as described above. The juice was centrifuged (20000 g/ 20 °C/10 min) and the supernatant divided into five samples which were individually evaluated for total soluble solids content (TSS), titratable acidity (TA), individual sugars, individual organic acids, individual and total phenolic compounds, and volatile compounds.

2.3.1 Total soluble solids

A few drops of the centrifuged juice were placed on the prism of a Digital "Pocket" Refractometer PAL (Atago Co., Ltd, Tokyo, Japan). Five readings per treatment were recorded and average total soluble solids were determined.

2.3.2 Titratable acidity

Five mL of the centrifuged juice was combined with 50 mL of di-ionized water and titrated to an end point of 8.2 (pH) using 0.1 N NaOH. Five readings per treatment were recorded. Percentage citric acid was calculated using:

$$\%\ \text{Acid} = [(\text{ml NaOH}) \times (0.1\ \text{N NaOH}) \times (0.064) \times (100)] / \text{ml of sample}$$

2.3.3 Organic acids

Organic acids were analyzed according to Ornelas-Paz et al. (2013) with some modifications. One mL of centrifuged juice was diluted with three mL of HPLC grade water. The diluted juice was filtered using a 45 μm pore size polyethylene membrane (Sigma-Aldrich, St. Louis, MO, USA) and injected (20 μL) into an Agilent 1100 series HPLC system equipped with a diode array detector (Agilent Technologies, Santa Clara, CA). The organic acids were separated in an Aminex HPX-87H ion exchange column (7.8 x 300 mm) (Bio-

202 Rad, Hercules, CA) at 60 °C. The mobile phase was composed of 5mM H_2SO_4 and
203 acetonitrile (90:10, v/v) at a flow rate of 0.4 mL/min. Citric, malic, oxalic, tartaric, quinic,
204 fumaric and succinic acids were monitored at λ=210 nm. The ascorbic acid was monitored
205 at λ=260 nm. Identification and quantification of organic acids was carried out using
206 reference compounds.

207 2.3.4 Sugars

208 Glucose, fructose and sucrose were analyzed according to Ornelas-Paz et al. (2013)
209 with some modifications, using the HPLC system described above but using refractive index
210 detection. One hundred µL of filtered juice was mixed with 2 mL of HPLC grade water and
211 filtered using a 0.45 µm pore size polyethylene membrane. Five µL of the mixture were
212 injected into the HPLC system. The separation was carried out at 80 °C in a Sugar SC 1821
213 (8.0 x 300 mm, 6 µm) ion exclusion column fitted to a Sugar SC-LG precolumn (6.0 x 50
214 mm, 10 µm) (Shodex, Tokyo, Japan). Water was used as mobile phase at a flow rate of 0.8
215 mL/min. The identification and quantification of sugars was performed using standard
216 compounds.

217 2.3.5 Individual and total phenols

218 The analysis of individual and total phenols was simultaneously performed. The juice
219 was filtered with a 0.45 µm membrane and directly injected (100 µL) into the HPLC
220 described previously. The separation of phenolic compounds was performed in a Kinetex
221 C18 (4.6 x 100 mm) (Phenomenex, Torrance, CA, USA) at 30 °C. The phenolic compounds
222 were monitored at λ= 280, 320, 350 and 520 nm. The mobile phase consisted of 2% acetic
223 acid (A), and acetonitrile (B), according to the following gradient: 100% A at 0 min, 93% A

224 at 12 min, 89% A at 20 min, 86%A at 35 min, 84% A at 36 min, 82% A at 41 min, 79% A
225 at 44, 0% A from min 55 to 60. The flow rate was 1 mL/min. The phenolic compounds were
226 identified and quantified by using reference compounds. The UV-Vis spectrum of individual
227 phenols was also used for identification purposes.

228 For total phenols content, 100 µL of filtered juice were mixed with 100 µL of Folin-
229 Ciocalteu, 3 mL of deionized water and 100 µL of 20% Na_2CO_3. The mixture was vigorously
230 shaken for 1 min and incubated for 1h in the darkness. The absorbance was evaluated five
231 times at 765 nm using a FLUOstar Omega microplate reader (BMG LABTECH Inc.; Cary,
232 NC, USA). The absorbance values were corrected with those generated with blank
233 reactions. Quantification was performed using a calibration curve constructed with several
234 sets of dilutions of gallic acid. The results were expressed as mg GAE per liter of juice.

235 2.3.6 Aroma Volatiles

236 Five samples of juice (5 mL each) were placed into headspace vials (12 x 32 mm)
237 and then 5 mL of saturated sodium chloride and 1-pentanol at a final concentration of 490
238 µg L^{-1} as an internal standard were added. The vials were sealed with a cap with a Teflon-
239 coated septum. Immediately prior to being run the samples were held at 4 °C in a water-
240 cooled rack. Analysis of volatile headspace components was conducted using solid phase
241 microextraction (SPME) with a 75-µm carboxen/polydimethylsiloxane fiber (Supelco, St.
242 Louis, MO, USA). The equipment utilized and analytical run conditions were exactly as
243 detailed in Ummarat et al. (2015) again using a FID detector for quantification.
244 Identification of compounds utilized mass spectrometry with comparison to Wiley/NBS
245 library spectra, retention times of standards when available and retention indices using *n*-
246 alkanes. Volatile concentrations were semi-quantified from the FID detector data by

247 utilizing calibration curves produced from standards purchased from Sigma-Aldrich (St.
248 Louis, MO, USA) placed into deodorized citrus juice. The standard used to quantify each
249 compound class is as follows: ethanol (ethanol), ethyl acetate (esters), 3-methyl butanol
250 (alcohols), E-2-hexenal (aldehydes), α-pinene (terpenes), 4-terpineol (terpene alcohols),
251 and carvone (ketones). Differences in SPME or GC detector response were adjusted for by
252 using the internal standard (1-pentanol).

253 2.4 Consumer testing

254 Consumer testing of pummelos was conducted at Chapman University on day 26
255 (during the fourth week of storage at 20 °C). Forty panelists including faculty, staff and
256 students from Chapman University participated in the testing. Six randomly selected
257 pummelos per treatment were peeled and segmented. The membrane surrounding the
258 segments was removed and the segments were further cut into halves. Each panelist was
259 provided with 2-3 half segments of pummelos per treatment in soufflé cups, labeled with a
260 3-digit code. Panelists were also provided with water cup and unsalted cracker to cleanse
261 their palates between samples. Consumers rated the degree of liking for overall liking,
262 overall flavor, sweetness, bitterness and juiciness on a 9-point hedonic scale (Peryam and
263 Pilgrim, 1957). Tests were administered in individual booths with samples and their
264 corresponding question sets presented in random order using SIMS 2000 Sensory
265 Evaluation software (Berkley Heights, N.J., U.S.A.) to prevent positional bias.

266 2.5 Statistical analysis using JMP statistical software

267 Two-way analysis of variance with replication was used to determine effects of irradiation
268 dose and storage time in a randomized complete block design. When F-values were

significant, least significant differences (LSD) at a significance level of 0.05 were calculated using a Tukey-Kramer test. Statistical analysis was performed using JMP statistical software ver. 8.0 (SAS Institute, Inc., NC, USA).

3 RESULTS AND DISCUSSION

3.1 Firmness of pummelo fruit and segments

The pulp of the Chandler pummelos was twice as firm as compared to the Sarawak pummelos, which could be a difference in variety or stage of maturity. Irradiation caused an immediate softening of pulp in Chandler but not in Sarawak pummelos (Fig. 1). During storage, the pulp of Chandler pummelos from the control fruit continued to soften, but Sarawak pummelos did not show consistent pulp softening due to irradiation or storage.

The puncture test profile indicated that the peak force was recorded as the probe punctured through the peel of the pummelos, which is the outer 5-10 mm of the fruit. The peak force measured using the puncture probe were similar for the Chandler and Sarawak pummelos indicating that the peels of the two varieties had similar firmness. Similar to pulp texture measured using a Kramer Shear, irradiated Chandler pummelos, but not Sarawak, had significantly lower peel firmness on day one after irradiation (Fig. 2). During the fourth week of storage, however, the peel of the 1000 Gy samples of both varieties were softer than the control and 150 Gy treated fruit, although it is important to note that peel firmness increased for all Chandler and control Sarawak pummelos during that time. This increase in fruit firmness might be a result of moisture loss from the surface of the fruit (peel) due to transpiration as well as decrease in relative humidity during ambient temperature storage.

The peel of pummelos is considered a rich source of pectin and other structural polysaccharides such as cellulose (Methacanon et al., 2014). Pectin content in flavedo and

albedo layers of pummelos is about 15 and 19% (Chaidedgumjorn et al., 2009). Radiation-induced free radical activity (Kovács and Keresztes, 2002) as well as increased polygalacturonase and pectinmethylesterase activity (Ladaniya et al., 2003) can accelerate degradation of cell wall pectin and other structural polysaccharides causing breakdown of the middle lamella in the cell wall, ultimately resulting in reduced firmness. The high pectin content in the flavedo layer of pummelos suggests that this layer will be likely impacted by irradiation, and while loss of firmness of the peel was readily observed in the irradiated Chandler pummelo, in the Sarawak, a significant decrease ($P<0.05$) was seen only after three weeks of storage.

3.2 Juice Content

No effect of irradiation or storage was observed on the juice content of Sarawak pummelos (~33%) based on total fruit weight (data not shown). An initial small but significant ($P<0.05$) increase in juice content based on fruit weight was observed for the 1000 Gy Chandler pummelos (from 24 to 27%) but the difference was not maintained during storage. Sensory testing also corroborated that consumer perception of juiciness was not affected. Similarly, Ladaniya et al. (2003) and Mitchell et al. (1991) also reported that treatment with gamma irradiation up to 1500 Gy and 600 Gy did not affect juice yield of Mosambi oranges, Nagpur mandarins and Valencia oranges, respectively.

3.3 Weight Loss

In the first three weeks of storage, the weight loss in Chandler pummelos was ~3% increasing to ~11% by the end of the fourth week (data not shown). The Sarawak pummelos lost ~3% of their weight in the first three weeks, and ~8% by the end of the fourth week

(data not shown). In both varieties, there was no impact of treatment. As previously noted, juice content was unaffected during storage, which suggests that the weight loss was primarily due to loss of moisture from the peel of the fruit. Exposure to warm temperature along with storage at low relative humidity (~60%) was most likely the cause of weight loss. Pummelo peels are thick (0.5-1 cm) and can amount to up to 50% of the weight of the whole fruit, thus moisture loss from the surface of the peel can result in significant weight loss.

3.4 Peel and Pulp Color

Neither irradiation nor storage affected the color of peel or pulp in the pummelos (data not shown). Previous studies have also observed minimal effects on citrus fruit and pulp color at low dose levels. McDonald et al. (2013) and Ladaniya et al. (2003) reported that storage or irradiation up to 600 Gy and 1500 Gy did not affect the color of the pulp in navel oranges, Nagpur mandarins or Mosambi oranges.

3.5 Titratable Acidity and Organic Acids

Irradiated Chandler pummelos had a lower titratable acidity as compared to the control ($P<0.05$) after three weeks and after subsequent storage at ambient temperature (Table 1). There was no consistent effect of treatment or storage on Sarawak pummelos (Table 1). McDonald et al. (2013), Ladaniya et al. (2003), and O'Mahony and Goldstein (1987) also reported lower titratable acidity in irradiated navel oranges, Mosambi oranges, Nagpur mandarins and Kagzi limes in comparison to their control counterparts.

Citric acid followed by quinic then succinic and tartaric acids were the predominant acids in Chandler and in the Sarawak pummelos, citric was followed by succinic then

quinic acids (Table 2). Citric acid in the 1000 Gy Chandler pummelos decreased after four weeks of storage, consistent with the change in TA, but not in the Sarawak, also consistent with TA results. However, in general, acid concentrations remained fairly stable during the four weeks of storage and there was no consistent effect of irradiation or storage. Small differences in concentrations can be attributed to fruit variability rather than an effect of irradiation or storage. In a study of three cultivars of pummelos, Sun et al. (2012) found citric acid to be the predominant acid followed by malic, fumaric and aconitic acids. During storage for 100 days, the changes in acid content were small and inconsistent, similar to the pattern observed in our study. Previous studies suggest that effect of irradiation on the organic acid content of citrus fruit varies depends upon the dose, storage time and temperature and mainly on the species and cultivar of fruit. Macfarlane and Roberts (1968) and Rouse et al. (1966) reported a dose dependent decrease in citric acid content of Valencia oranges treated with 250 Gy-2000 Gy; a possible explanation could be the excessive utilization of citric acid as substrate during accelerated respiration in irradiated fruits (Ladaniya, 2008) and resultant lowered TA. Irradiation-induced loss of ascorbic has been observed in grapefruit, Mosambi oranges, Nagpur mandarins, Kagzi acid limes and lemons (Vanamala et al., 2005; Ladaniya et al., 2003; Maxie et al., 1964). In our study, loss of ascorbic acid was observed in the 1000 Gy Sarawak pummelos but not in the Chandler pummelos.

3.6 Total Soluble Solids and Sugars

Chandler pummelos had higher TSS values than Sarawak pummelos (Table 1), and during storage, the TSS values of the control fruit of both varieties increased ($P<0.05$) but there was not a consistent effect of irradiation. Similarly, sucrose concentrations, but not

359 glucose and fructose, in the Chandler variety were higher than the Sarawak pummelos and
360 concentrations fluctuated among treatments and during storage (Table 1). Sun et al., (2012)
361 also observed higher initial sucrose concentrations in three varieties of pomelos as compared
362 to glucose and fructose, but there were no consistent patterns in changes in the sugar
363 concentrations during storage. The only consistent pattern in our data was an increase in
364 glucose, fructose and sucrose concentrations in the control and 150 Gy Chandler pummelos
365 during storage, but no other irradiation related effect is discernible. Patil et al. (2004)
366 reported that irradiation up to 700 Gy did not affect soluble solids in early 'Rio Red'
367 grapefruit. However, irradiation has also been shown to decrease soluble solid content in
368 'Ambersweet' oranges, navel oranges and 'Sunburst' mandarins treated with 300, 400 and
369 450 Gy of gamma radiation respectively (McDonald et al., 2013; Miller et al., 2000). Citrus
370 fruits utilize sugars as substrates for respiration, therefore it is expected that the total soluble
371 solids and sugar content will decrease with time. Also, irradiation can cause oxidative stress,
372 which can result in a higher respiration rate and consumption of simple sugars during the
373 process of respiration, leading to a decrease in sugar content (Ladaniya et al., 2003), however
374 no such decrease was observed in our study.

375 3.7 Total and Individual Phenols

376 Total phenolics ranged between 425 mg GAE L^{-1} and 650 mg GAE L^{-1} in the two
377 pummelo varieties (Fig. 3). In both sets of pummelos, naringin was the most abundant
378 phenolic compound (Fig. 4), about 10 fold higher than the next most abundant compounds
379 which were hesperidin and chlorogenic acid in the Chandler pummelos. Rutin, nairutin,
380 and ferulic acid were also detected in small quantities. In Sarawak pummelos, rutin and

chlorogenc acid were more abundant than hesperidin. In addition to small amounts of narirutin and ferulic acid, very small amounts of p-coumaric acid were also detected.

Literature on phenolic compounds in pummelos is limited. Li et al. (2012) reported that the phenolic content of honey pomelos was 55 mg/100 g fruit which decreased during storage. Mäkynen et al. (2013) evaluated the phenolic compounds in six varieties of pummelos found in Thailand and found that total phenols ranged between 101.32 to 113.73 mg gallic acid equivalent/g extract and the predominant phenolic compounds were naringin, hesperidin, neohesperidin, neohesperidin dihydrochalcone, naringenin, and hesperitin. The relative amounts of these phenolic compounds varied between the six varieties.

Irradiation increased total phenolics in Chandler pummelos soon after treatment. After three weeks, there were no differences between the treatments, but after the fourth week at ambient temperature, the irradiated fruit had higher total phenolics. In the Sarawak pummelos, the 1000 Gy fruit had the highest total phenolic concentrations soon after treatment. During storage, the 400 Gy samples had the highest concentrations ($P<0.05$), but the differences between the treatments was small. Irradiation increased ($P<0.05$) naringin concentrations in both sets of pummelos. There is no information on effect of irradiation on phenolics in pummelos, however, irradiation-induced stimulation of PAL activity leading to increased phenolic concentrations has been documented in citrus fruit such as Clemenules and mandarins (Rojas-Argudo et al., 2012; Shen et al., 2013).

3.8 Aroma Volatiles

Sixty-four volatiles were identified in samples from both of the pumelo varieties consisting of aldehydes, alcohols, esters, ketones, and various classes of terpenes

(data not shown). Gonzalez-Mas et al. (2011) used HS-SPME-GC-MS analysis to characterize the volatile compounds in different citrus fruit (Powell Navel orange, Clemenules mandarin, Fortune mandarin and Chandler pummelos). The volatile profile of the pummelos was unique in that mostly terpenic compounds (β-caryophyllene, *(Z)*-ocimene, *(E,E)*-2,4-nonadienal, *(Z)*- and *(E)*-linalool oxides, *p*-cymene) were identified, almost exclusively in Chandler pummelos. Cheong, Liu, Zhou, Curran, and Yu (2012) evaluated the flavor profile of two varieties of Malasian pummelos, Citrus grandis (L.) Osbeck PO 51 and PO 52 (red and white fleshed, respectively). They found that the pink pomelo juice shared a closer resemblance to grapefruit chemically in contrast to the white pummelo and that the higher terpenic content of the white pomelo juice with milder acidity and lower amounts of volatiles made it unique among citrus fruit.

Of the 64 compounds identified in this study, 39 changed significantly ($p \leq 0.05$) due to irradiation treatment in 'Chandler' (Table 3) and 48 in 'Sarawak' (Table 4). In both varieties the most common trend was for irradiation to increase volatile concentrations relative to the controls, with 1000 Gy often causing the greatest increase. This effect of irradiation to enhance citrus volatile concentration had also been seen in oranges treated at doses as high as 600 Gy, with ethanol, esters and aldehydes being the primary volatiles altered in amount by irradiation in that study (McDonald et al., 2013). Although the effect of irradiation on volatile components was similar for both varieties there were some differences in how specific classes of compounds were altered. For instance, terpenes in 'Chandler' prior to storage increased as a result of irradiation while in 'Sarawak' these compounds, with the exception of α-thujene, either did not significantly change or decreased in

concentration. Storage impacted the treatment effect in 'Chandler' as significant concentration differences between the control and 150 Gy treatment became much less common following storage at both 3 weeks at 5 °C and after an additional 1 week at 20 °C. While the overall impact of the 1000 Gy treatment was also lessened by storage, there were still elevated concentrations relative to the untreated control for many of the volatile compounds, particularly in the case of ethanol and in the esters and ketones. Ethyl acetate in particular was strongly increased in the irradiated fruit following storage. For 'Sarawak' there was still considerable impact of the 150 Gy treatment after storage, particularly in the elevated levels of aldehydes and esters following 3 weeks at 5 °C. Treatment with 1000 Gy and storage led to even higher concentrations in volatiles from these two classes of compounds as well as increases in four of the thirteen terpenes that were quantified. As is commonly practiced commercially, the pummelos used in this study had a wax coating applied to the peel surface after harvest and prior to irradiation treatment and storage. Waxing citrus can result in the enhancement of volatile accumulation in the fruit that can sometimes alter flavor (Obenland et al., 2011). In both 'Chandler' and 'Sarawak' concentrations of many of the volatiles were higher as a result of storage in the untreated fruit, this being a primary reason for why there was sometimes significant differences observed as a result of irradiation immediately after treatment but not following storage.

3.9 Consumer Testing

Consumer testing of Chandler and Sarawak pummelos indicates that irradiation did not affect consumer liking of the two pummelo varieties (data not shown). Overall, the scores for all attributes ranged between 5 (Neither Like or Dislike) and 6 (Like Slightly). The reason

for overall low scores might be the lack of familiarity with pummelos. Although changes in aroma-active juice volatiles as a result of irradiation were noted in this study, panelists were evidently unable to detect the altered aroma volatile profile of the irradiated fruit. McDonalds et al. (2013) also reported that the panelists did not observe any significant differences in overall liking, flavor and juiciness among control navel oranges and oranges irradiated at 200, 400 and 600 Gy. In contrast, some studies have reported development of off-flavor in irradiated citrus treated with doses ranging from 60 Gy to 1000 Gy (Nagai and Moy, 1985; O'Mahony et al., 1985; Mitchell et al., 1991; Miller et al., 2000).

3.10 Peel Damage

Both varieties had small but noticeable amount of dents and scars upon receipt, presumably due to postharvest handling of the fruit. During storage, fruit developed significant brown colored stippling (small brown spots), loss of gloss, bruising and areas of softening. In irradiated fruit, we also observed larger, sunken brown areas (Fig. 5) that have been reported in the literature as peel pitting, generally associated with areas of peel that collapse and discolor and not limited to oil glands (Ritenour et al., 2003). In general, peel damage was greater and developed more quickly in irradiated pummelos and became even more severe when the fruit was stored at ambient temperature for a week. In Chandler pummelos, eight out of ten of the 150 Gy and nine out of ten of the 1000 Gy Chandler pummelos showed evidence of pitting, bruising and spot development covering more than 5% of the total surface area of each pummelo as compared to only two out of ten control pummelos after the first week of storage (Fig. 6). No pitting, bruising or spotting was evident in Sarawak pummelos during the first week. The extent of damage increased gradually in both varieties of pummelos during the three week storage at 12 °C, however, storage at

473 ambient temperature (20 °C) for one week severely exacerbated peel damage in irradiated
474 pummelos. By the end of the fourth week, 70 and 80% of the irradiated Chandler and
475 Sarawak fruit, respectively, showed 16% or more damaged surface area, as compared to only
476 10% of the control Chandler and none of the control Sarawak. Pummelos with pitting
477 covering greater than 16% of the peel surface were considered unmarketable. Thus, the
478 combination of irradiation, physical manipulation and high temperature storage was highly
479 detrimental to the quality of the pummelos. Mold growth was observed in both varieties of
480 irradiated pummelos, mainly because cell injury caused by irradiation provided a suitable
481 environment for mold growth.

482 Peel pitting is a disorder that generally occurs during postharvest storage of citrus
483 fruits under environmental conditions, such as low relative humidity, that can cause damage
484 to cells in the flavedo and albedo, ultimately affecting nearby oil glands present in the fruit
485 peel (Alferez et al., 2008). Low internal oxygen concentrations within the fruit might be
486 another possible explanation for non-chilling peel pitting observed in citrus fruits (Ritenour,
487 2013). Peel pitting as a result of irradiation has been observed in several citrus fruits
488 (McDonald et al., 2013; Ladaniya et al., 2003; Miller et al., 2000; Dennison et al., 1966).
489 One of the causes of peel pitting in irradiated citrus fruit may be irradiation-induced
490 accumulation of phenolic compounds in the flavedo cells of the peel which oxidize resulting
491 in cell death (Riov, 1975). Irradiation can also elevate respiration rate of fresh fruit resulting
492 in increased ethylene production (Riov et al., 1972), and subsequent increase in PAL activity
493 (Benoit et al., 2000). Enhanced PAL activity leads to accumulation of phenolic compounds
494 in irradiated fruits (Mahrouz et al., 2002). In this study, an immediate irradiation-induced
495 increase in naringin was seen in both varieties of pummelos. While respiration rate was not

measured in this study, the TA was lower in the 1000 Gy Chandler pummelos suggesting that respiration rate of these fruit may be affected. Additionally, the high ethanol levels measured in this study, particularly in the Sarawak pummelos after 20 C storage, are indicative of low internal oxygen concentrations which can also lead to peel pitting (Ritenour, 2013). Using a wax that allows adequate oxygen diffusion rate may help in reducing peel pitting (Ritenour, 2013). Heat conditioning treatment at 38 and 42° C for 2 hours reduced PAL activity, which further resulted in reduced peel pitting by 8 and 10% respectively, in grapefruit irradiated at 1000 Gy and stored at 10 °C for 4 weeks (McDonald et al., 2000). Thus, heat conditioning might prove helpful in case of pummelos as well.

4 CONCLUSION

Radiation impacted the quality of the two varieties differently with a greater impact observed on Chandler pummelos, which could reflect varietal differences. The differences could also be attributed to maturity level at harvest, however that can only be confirmed if the same variety was studied at different maturity levels.

In general, 1000 Gy had a greater impact on pummelo quality than 150 Gy. One impact of irradiation was manifested as softening of the fruit, an effect observed in most irradiated pummelos, although irradiation-induced peel damage was the most significant effect of irradiation. Peel damage in the irradiated fruit increased gradually during the three weeks of storage under ideal conditions. However, when the conditions were less than ideal in terms of ambient temperatures and excessive handling, the fruit showed signs of phytotoxicity. Our results show that 150 Gy could be a feasible dose for Chandler and

Sarawak pummelos but they would need to be handled minimally and stored under ideal temperatures.

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649 Table 1. Titratable acidity, total soluble solids and sugars in irradiated Chandler and Sarawak

Treatment		TA (% citric acid)	TSS (%)	Sugars (g/L)		
				Glucose	Fructose	Sucrose
Chandler						
Day 1	Control	0.76 Bxy	11.58 Cz	10.73 By	14.17 y	69.85 Cy
	150 Gy	0.84 Ax	13.10 Ax	12.20 Ay	14.74 y	78.18 Ax
	1000 Gy	0.79 Bx	12.44 Bx	12.27 A	14.92 y	72.57 B
After 3 weeks	Control	0.78 Ax	12.40 Ay	12.79 x	15.51 Ax	76.28 x
	150 Gy	0.57 Bz	12.06 Cz	12.34 y	14.92 By	74.78 y
	1000 Gy	0.58 Bz	12.30 By	12.58	15.14 ABx	73.69
After 4 weeks	Control	0.73 Ay	12.72 Ax	12.78 x	15.66 x	77.36 Ax
	150 Gy	0.66 By	12.40 By	13.20 x	16.30 x	74.90 Ay
	1000 Gy	0.66 By	11.72 Cz	12.99	15.95 x	72.03 B
Sarawak						
Day 1	Control	0.740 A	10.50 Bz	16.71 Ax	16.92 Ax	48.62 By
	150 Gy	0.75 Ax	10.62 A	15.86 B	16.04 B	51.08 Ax
	1000 Gy	0.71 B	10.52 By	16.34 ABy	16.69 Ax	50.89 A
After 3 weeks	Control	0.72 AB	10.58 Ay	16.05 Ay	16.45 Ay	51.33 Cx
	150 Gy	0.75 Ax	10.60 A	15.90 A	16.27 A	50.81 Bxy
	1000 Gy	0.70 B	10.44 By	15.18 Bz	15.75 By	50.41 B
After 4 weeks	Control	0.69	10.70 Bx	15.97 By	16.33 By	50.68 x
	150 Gy	0.68 y	10.62 C	15.61 B	15.99 B	49.81 y
	1000 Gy	0.68	10.86 Ax	16.96 Ax	17.16 Ax	50.81

650 pummelos stored for three weeks at 12°C and for an additional week at 20°C. Statistically
651 significant differences ($P<0.05$) among treatments within the same time point are denoted by
652 letters A-C; and across time points for the same treatment by letters x-z.

653 Table 2. Organic acids in irradiated Chandler and Sarawak pummelos stored for 3 weeks at 12 ºC and after an additional week at 20 ºC. Statistically
654 significant differences (P<0.05) among treatments within the same time point are denoted by letters A-C; and across time points for the same
655 treatment by letters x-z. OA-Oxalic acid, CA-Citric acid, TA-Tartaric acid, MA-Malic acid, AA-Ascorbic acid, QA-Quinic acid, SA-Succinic acid,
656 FA-Fumaric acid

		Organic acids							
Time	Treatment	OA	CA	TA	MA	AA	QA	SA	FA
Chandler									
Day 1	Control	109.84 Bx	12143.97 Cy	1683.17 Ax	815.18 Axy	494.74 Ax	2514.41 By	1734.33 Ay	12.19 Ay
	150 Gy	119.78 Ax	13558.84 Ax	1710.36 Ax	682.76 Cy	477.98 By	2909.36 Az	1487.87 Bz	10.64 Bz
	1000 Gy	101.95 Cy	12394.95 By	1620.00 Bx	753.31 Bz	506.50 Ax	2807.91 By	1469.76 By	11.80 By
After 3 weeks	Control	100.66 By	12516.30 Ax	1582.55 Bz	842.48 Bx	475.99 Ax	3314.61 x	1994.52 x	13.33 x
	150 Gy	103.95 Aby	12259.55 By	1631.56 Az	931.11 Ax	471.60 Ay	3271.30 y	2104.62 y	14.27 y
	1000 Gy	104.96 Ax	12594.32 Ax	1577.73 By	787.71 Bx	473.33 Ay	3356.93 x	2160.43 x	13.36 x
After 4 weeks	Control	110.89 Ax	12625.31 Ax	1629.80 By	775.55 Cy	433.10 By	3436.22 Bx	2119.94 Bx	13.70 Bx
	150 Gy	105.39 By	12051.15 Bz	1677.13 Ay	885.38 Ax	504.39 Ax	3719.23 Ax	2323.57 Ax	15.373 Ax
	1000 Gy	104.42 Bx	12074.80 Bz	1607.40 Bx	806.70 Bx	498.81 Ax	3285.17 Cx	2271.21 Ax	13.53 Bx
Sarawak									
Day 1	Control	151.20 Ay	11757.35 y	1403.31 Bx	842.07 Cz	316.64 Ax	3801.45 Ay	6012.78 Ay	13.83 Abx
	150 Gy	138.26 By	11723.57 y	1365.78 Cx	914.17 Bz	290.68 Bx	3562.29 Bz	5159.71 Cz	12.87 Bx
	1000 Gy	136.49 Bz	11710.07 z	1444.21 Ax	952.98 Ay	271.46 Cx	3828.69 Ax	5365.34 Bz	14.179 Ax
After 3 weeks	Control	142.36 Bz	12073.39 Bx	1320.87 y	997.40 Cx	245.06 Ay	4723.92 Cx	6127.47 By	9.75 By
	150 Gy	149.11 Ax	12415.31 Ax	1335.24 y	1079.11 Ax	237.65 Bz	4898.32 Bx	6377.26 Ax	10.674 Ay
	1000 Gy	142.43 By	12256.39 Ax	1321.35 y	1017.71 Bx	232.63 By	5053.08 Ax	5923.80 Cy	10.20 By
After 4 weeks	Control	159.99 Ax	11749.47 By	1291.39 By	945.85 By	245.27 By	4732.49 Bx	6610.734 Ax	10.27 y
	150 Gy	151.94 Bx	11525.89 Cz	1380.50 Ax	960.94 By	259.12 Ay	4765.30 By	5961.60 By	10.72 y
	1000 Gy	154.50 Bx	11956.54 Ay	1314.27 By	1009.67 Ax	226.76 Cx	5203.20 Ax	6574.14 Ax	10.40 y

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661 Table 3 Aroma volatile concentrations (μg L-1) in irradiated Chandler pummelos during storage for 3 weeks at 12 ºC and after an additional
662 week at 20 ºC. Values followed by different letters within a storage regime represent significant differences (P≤0.05). Shading indicates that
663 there is at least a two-fold difference from the control (0 Gy) dose. nd = not detectable.

	Day 1			After 3 weeks			After 4 weeks		
Treatment	Control	150 Gy	1000 Gy	Control	150 Gy	1000 Gy	Control	150 Gy	1000 Gy
Alcohols									
ethanol[a]	145.90c	279.66b	317.04a	321.76b	434.87b	863.19a	522.58b	462.04b	894.44a
2-butanol	1.75b	1.81b	2.48a	19.09a	9.82b	10.53b	8.67a	3.58b	3.75b
1-penten-3-ol	2.44c	4.13a	3.56b	8.89a	7.24ab	6.48b	9.45a	9.33a	7.17b
3-methylbutanol	0.95a	0.51b	0.81ab	3.02c	4.64b	8.00a	4.11b	3.78b	7.17a
cis-3-hexenol	12.44c	24.78a	16.84b	49.05a	38.86a	24.15b	52.81a	40.75b	16.37c
hexanol	17.32c	25.66a	20.79b	35.89a	28.87b	29.17b	46.20a	34.50a	15.40b
Aldehydes									
acetaldehyde	47.23b	50.81ab	51.78a	50.96a	57.73a	55.64a	56.17a	52.41a	58.47a
2-methylpropanal	1.52b	1.542b	2.15a	6.07a	3.57b	4.17b	3.58a	2.93b	3.53a
3-methylbutanal	1.84b	1.84b	2.17a	3.25b	3.66b	7.21a	4.03b	3.67b	5.99a
2-methylbutanal	1.78b	1.97b	2.33a	2.59b	3.69ab	5.16a	2.75a	2.22b	2.73a
pentenal	4.34b	5.10a	4.64b	15.29b	20.25a	22.33a	15.46a	15.38a	15.20a
E-2-pentenal	0.95a	0.71b	0.92b	2.00a	2.12a	2.05a	1.78a	1.77a	1.89a
hexanal	22.84c	28.00a	25.65b	95.78a	103.85a	117.72a	84.96a	71.06a	65.42b
heptanal	1.83a	1.94a	1.86a	4.92b	6.74a	7.87a	4.73a	4.52a	4.80a
2,4-hexadienal	1.10a	1.11a	1.20a	4.31a	2.54b	2.05b	2.88a	2.85a	2.18b
E-2-heptanal	1.20a	1.33a	1.39a	3.14b	3.38b	3.82a	2.91a	2.88a	3.25a
octanal	0.81a	0.83a	0.91a	1.86a	1.51a	1.51a	1.41a	1.41a	1.40a

nonanal	1.64a	1.58a	1.72a	2.79b	3.26ab	3.82a	3.08a	3.14a	3.57a
Esters									
ethyl acetate	1.35c	2.89b	3.53a	22.89b	36.09b	428.25a	42.97c	93.69b	853.27a
ethyl propanoate	0.55a	0.64a	0.76a	2.68a	4.51a	8.31a	4.22b	5.50b	12.78a
ethyl-2-methylpropanoate	nd	nd	nd	0.35b	0.50b	2.02a	0.60b	0.61b	2.32a
ethyl-2-methylbutanoate	0.24a	0.20a	0.24a	0.46b	0.70b	3.36a	0.79b	1.03b	4.93a
ethyl hexanoate	0.69c	1.19b	1.62a	1.40b	1.32b	1.93a	1.54b	1.64b	2.42a
Ketones									
1-penten-3-one	40.33a	32.83b	33.73b	76.05b	80.34b	96.89a	74.23b	80.15b	104.01a
4-methyl-2-heptanone	11.42a	11.63a	9.97a	15.24b	14.24b	18.27a	21.86b	19.95b	28.65a
methyl-heptanone	19.07b	17.37c	21.32a	33.56b	36.61ab	42.82a	34.30b	40.07ab	45.49a
dihydrocarvone	0.99a	1.32a	1.40a	1.71a	1.88a	2.22a	2.54b	2.49b	3.38a
carvone	1.30b	1.88a	2.24a	3.90ab	3.67b	5.28a	4.15a	4.81a	4.72a
piperitone	0.91a	0.98a	1.07a	2.45b	2.97ab	4.13a	2.65a	3.14a	4.23a
Terpenes									
α-pinene	0.15c	0.27b	0.35a	0.40a	0.41a	0.43a	0.48a	0.33b	0.37b
camphene	0.04b	0.06ab	0.08a	0.10a	0.08a	0.09a	0.09a	0.08a	0.08a
β-pinene	0.28b	0.31b	0.44a	0.67a	0.70a	0.69a	0.66a	0.54b	0.72a
β-myrcene	0.46c	0.76b	1.02a	1.17a	1.14a	1.43a	1.21a	1.04a	1.16a
α-terpinene	0.13b	0.17a	0.19a	0.22a	0.21a	0.24a	0.18a	0.17a	0.18a
p-cymene	1.05a	1.40b	1.81a	3.64a	2.34a	3.90a	4.16a	3.90a	2.38a
limonene	12.93c	32.02b	48.50a	40.03a	39.86a	46.56a	47.68a	32.04b	36.45ab
β-elemene	0.06c	0.10b	0.14a	0.13b	0.12b	0.22a	0.17b	0.19b	0.23a
trans-caryophyllene	0.19c	0.25b	0.32a	0.46a	0.47a	0.54a	0.58b	0.64ab	0.84a
Terpene alcohols									
linalool	1.41c	2.16b	4.10a	3.02a	2.97a	2.45b	5.53a	4.20ab	4.06b

Table 4. Aroma volatile concentrations (μg L-1) in irradiated Sarawak pummelos during storage for 3 weeks at 12 ºC and after an additional week at 20 ºC. Values followed by different letters within a storage regime represent significant differences (P≤0.05). Shading indicates that there is at least a two-fold difference from the control (0 Gy) dose. nd = not detectable.

	Day 1			After 3 weeks			After 4 weeks		
Treatment	Control	150 Gy	1000 Gy	Control	150 Gy	1000 Gy	Control	150 Gy	1000 Gy
Alcohols									
ethanol[a]	380.98a	322.50a	428.91a	410.95b	500.67b	813.69a	1053.10a	1019.55a	1020.96a
2-butanol	9.72b	15.05a	13.77a	18.62a	14.51b	17.27a	12.54a	10.60a	10.90a
2-methyl-3-buten-2-ol	107.68a	84.01b	82.31b	112.57a	95.42a	70.77b	120.66a	100.83a	94.41a
1-penten-3-ol	7.55b	8.27b	9.59a	6.22a	6.41a	6.14a	4.53b	5.01ab	5.60a
3-methylbutanol	4.76b	4.64b	7.10a	6.79b	8.70b	12.68a	45.75a	48.66a	44.54a
cis-3-hexenol	63.41b	69.07a	51.95c	54.62a	59.38a	46.73b	29.47ab	27.32b	35.95a
hexanol	39.36a	39.94a	31.84b	32.51b	39.56a	38.27a	21.77b	20.31b	30.44a
Aldehydes									
butanal	1.56b	3.51a	3.66a	3.89ab	3.64b	4.35a	3.17a	3.36a	3.72a
2-methylpropanal	6.00b	21.19a	20.60a	25.02ab	19.98b	29.65a	16.26c	21.37b	24.97a
3-methylbutanal	2.49b	3.18a	3.79a	4.61a	4.08a	5.64a	7.15a	7.07a	6.92a
2-methylbutanal	1.85a	1.99a	2.10a	2.52b	3.12b	4.42a	3.67b	4.34a	4.77a
pentenal	8.63b	56.80a	50.39a	63.69b	67.24b	85.09a	41.03b	56.27a	62.25a
hexanal	139.44b	370.36a	312.37a	463.49b	487.20b	663.74a	315.88b	476.74a	509.81a
heptanal	4.17b	21.60a	16.81a	25.02b	26.67b	37.84a	17.79b	26.32a	27.13a
2,4-hexadienal	4.68a	6.45a	4.84a	5.56a	7.06a	4.73a	2.76a	5.40a	4.47a
E-2-heptenal	2.88b	4.51a	4.42a	5.50a	6.02a	5.90a	3.96b	5.33a	5.45a
benzaldehyde	1.78b	1.89ab	2.22a	2.10a	2.23a	1.95a	2.06a	2.11a	2.13a
octanal	3.14b	6.34a	5.67a	7.20b	7.63b	10.40a	6.09b	8.84a	7.69ab
nonanal	3.12b	5.68a	4.39ab	6.41b	6.98ab	9.38a	5.91a	8.29a	7.03a
decanal	0.63a	1.43a	1.26a	1.81a	1.68a	2.28a	1.45b	2.10a	1.72ab
Esters									
ethyl acetate	18.36b	13.98c	20.40a	18.69b	17.55b	39.79a	27.16c	42.95b	104.92a

ethyl propanoate	1.07b	1.85b	5.01a	1.21b	3.95a	4.45a	2.52b	4.28ab	5.95a	
ethyl-2-methylpropanoate	0.36a	0.32ab	0.27b	0.37b	0.46b	0.78a	1.16b	1.45b	2.24a	
ethyl-2-methylbutanoate	0.36a	0.43a	0.45a	0.62b	0.59b	1.64a	1.27c	2.39b	4.35a	[a]=mg L-1
E-2-hexenal	24.99a	26.58a	23.06a	35.82a	39.06a	29.26a	20.08b	31.51a	23.96b	
ethyl hexanoate	1.30b	2.13a	2.70a	2.05b	1.88b	2.87a	2.48b	3.94a	3.33a	
Ketones										
1-penten-3-one	45.97c	75.02b	94.98a	100.47a	83.92a	96.07a	184.47b	201.02a	114.86c	
gamma-butyrolactone	11.86b	17.72ab	21.782a	15.52a	15.21a	14.58a	12.43a	15.49a	16.65a	
methyl-heptanone	24.06a	29.12a	30.79a	32.10b	36.35ab	40.28a	31.51b	43.88a	36.81ab	
dihydrocarvone	2.77a	3.30a	2.63a	3.37b	5.01a	5.33a	3.31a	3.59a	4.58a	
carvone	5.01b	9.17a	7.09ab	11.24b	20.13a	26.97a	13.81b	10.73b	21.17a	
piperitone	3.24b	6.35a	4.58ab	7.54a	9.26a	9.79a	8.34a	9.89a	9.59a	
Terpenes										
α-thujene	0.85b	0.88b	1.42a	1.09c	1.60b	1.88a	1.35b	0.99c	1.97a	
α-pinene	4.98ab	4.09b	5.76a	5.27b	8.33a	9.31a	7.29b	4.25ab	9.31a	
camphene	0.19a	0.17a	0.20a	0.20b	0.27a	0.29a	0.23ab	0.19b	0.30a	
β-pinene	2.94a	2.32a	3.22a	2.80b	4.62a	5.18a	4.39b	2.55c	5.73a	
β-myrcene	2.69a	1.57b	2.11ab	2.27a	2.78a	2.94a	2.34a	2.10a	2.82a	
α-terpinene	1.42a	0.63b	0.91b	0.79b	1.64a	1.65a	1.36ab	0.79b	1.63a	
1-menthene	0.86a	0.34b	0.57b	0.43a	0.88b	0.80b	0.79a	0.41b	0.85a	
p-cymene	38.78a	35.76a	51.77a	42.01b	79.21a	94.39a	59.87b	40.34c	84.05a	
limonene	106.23a	80.03a	100.60a	104.85a	190.84a	235.15a	173.44a	100.76b	229.32a	
γ-terpinene	14.45a	4.45b	7.99b	5.77b	13.60a	12.85a	11.11ab	5.67b	12.75a	
β-elemene	1.23a	0.70b	1.06a	0.87a	0.95a	0.95a	0.97a	0.87a	0.90a	
trans-caryophyllene	4.05a	2.16b	2.86b	2.93a	3.27a	3.11a	3.02a	2.63a	2.97a	
α-humulene	0.72a	0.36b	0.49b	0.50a	0.58a	0.55a	0.55a	0.46a	0.50a	
Terpene alcohols										
linalool	9.39a	8.22b	10.11a	10.99c	14.88a	12.40b	17.82a	10.53c	13.42b	
4-terpineol	12.65a	11.78ab	10.21b	13.27b	22.20a	19.98a	19.24a	11.74b	18.49a	
β-fenchyl alcohol	12.94a	13.28a	11.92a	16.36b	23.15a	21.88a	22.66a	16.88b	20.98ab	

686 List of Figures:

687 Figure 1. Pulp firmness of (a) Chandler and (b) Sarawak pummelos stored for three
688 weeks at 12°C and for an additional week at 20°C measured using a Kramer shear
689 press. Statistically significant differences ($P<0.05$) among treatments within the same
690 time point are denoted by letters A-C; and across time points for the same treatment by
691 letters x-z.

692

693 Figure 2. Fruit firmness of (a) Chandler and (b) Sarawak pummelos stored for three
694 weeks at 12°C and for an additional week at 20°C measured using a puncture
695 probe. Statistically significant differences ($P<0.05$) among treatments within the same
696 time point are denoted by letters A-C; and across time points for the same treatment by
697 letters x-z.

698

699 Figure 3. Content total phenols in (a) Chandler and (b) Sarawak pummelos. A-
700 immediately after irradiation; B-after 3 weeks of storage at 12 °C and C-after
701 additional week at 20 °C.

702

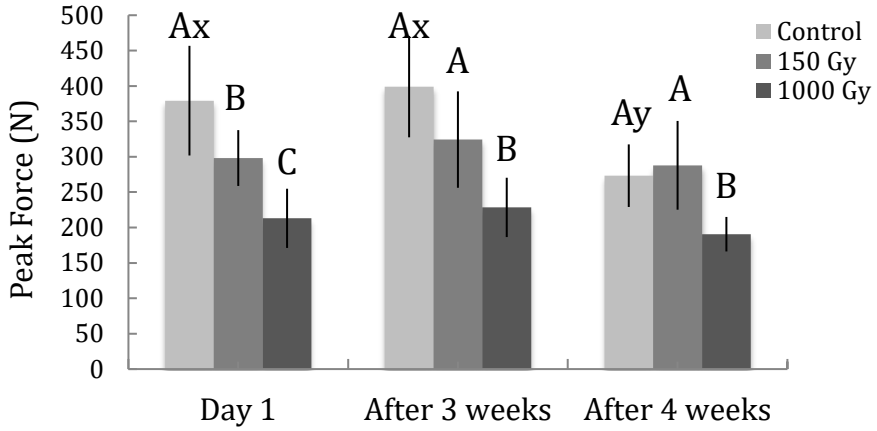
703 Figure 4. Content of several phenolic compounds (NG, naringin; H, hesperidin; CA,
704 chlorogenic acid; R, rutin; NR, narirutin; FA, ferulic acid) in (a) Chandler and (b)
705 Sarawak pummelos. A-immediately after irradiation; B-after 3 weeks of storage at 12
706 °C and C-after additional week at 20 °C.

707

708 Figure 5. Peel damage in 150 Gy Chandler pummelo after 4 weeks of storage, 3 weeks
709 at 12 °C and 4th week at 20 °C.

710
711 Figure 6. Peel damage in (a) Chandler and (b) Sarawak, control and irradiated (150 Gy
712 and 1000 Gy) pummelos stored for 3 weeks at 12 °C and for an additional week at 20
713 °C. 0=0%, 1=1-4%, 2=5-9%, 3=10-12%, 4=13-15% and 5=16% or more external
714 damage, M=Moldy pummelos.

715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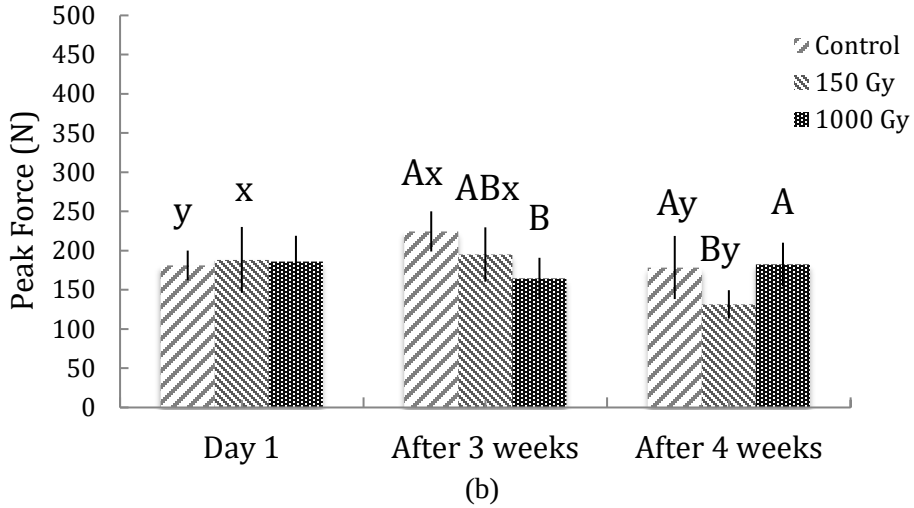
500
450
400
350
300
250
200
150
100
50
0
Ax
B
C
Ax
A
B
Ay
A
B
Control
150 Gy
1000 Gy
Day 1
After 3 weeks
After 4 weeks

(a)


Peak Force (N)
500
450
400
350
300
250
200
150
100
50
0
y
x
Ax
ABx
B
Ay
By
A
Control
150 Gy
1000 Gy
Day 1
After 3 weeks
After 4 weeks

(b)

Fig. 1

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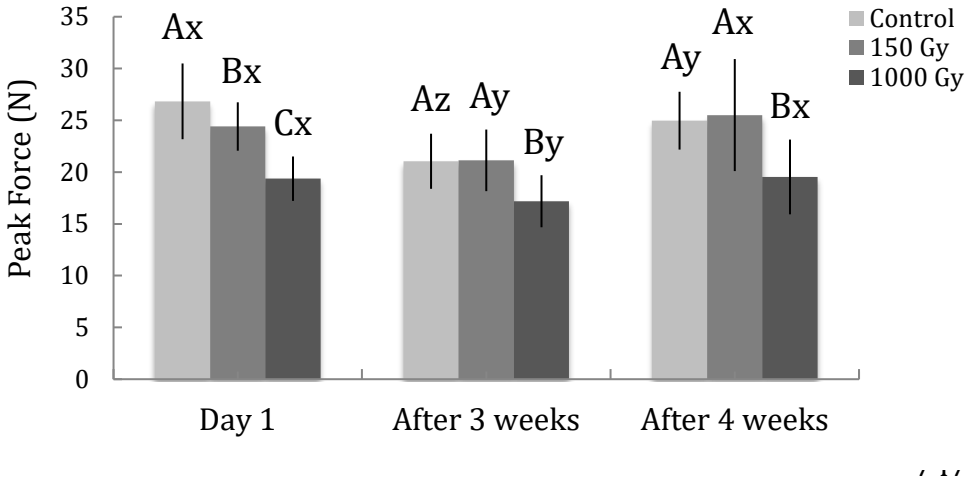

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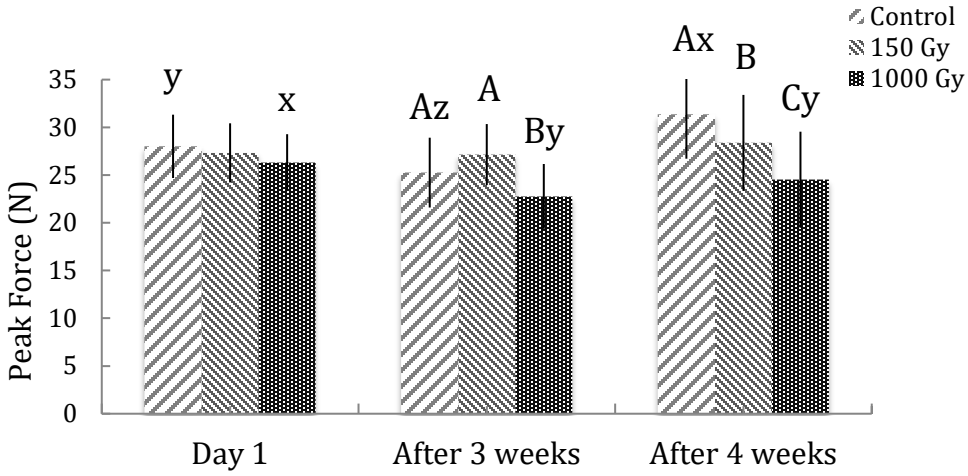
749 (a)

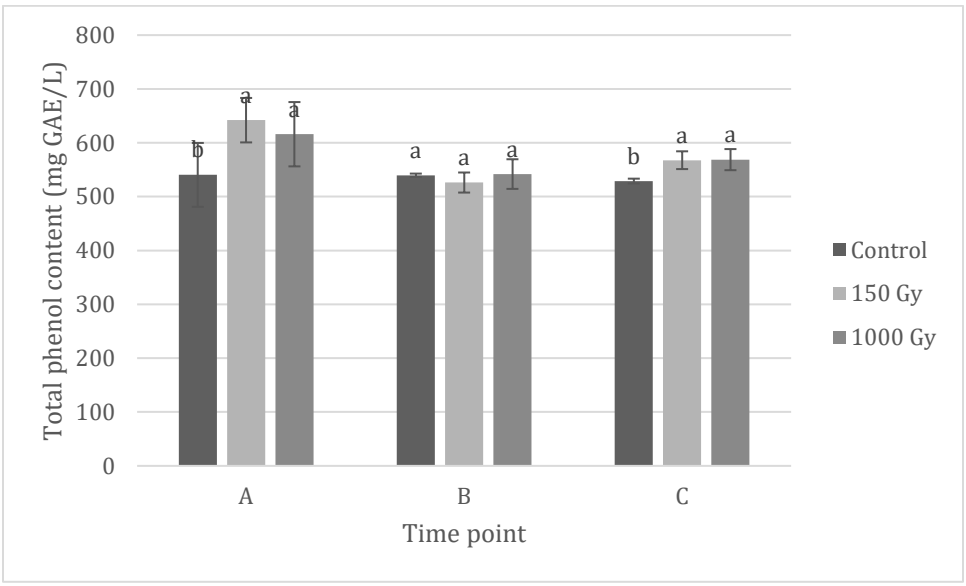


750

751

752 (b)

753 Fig. 2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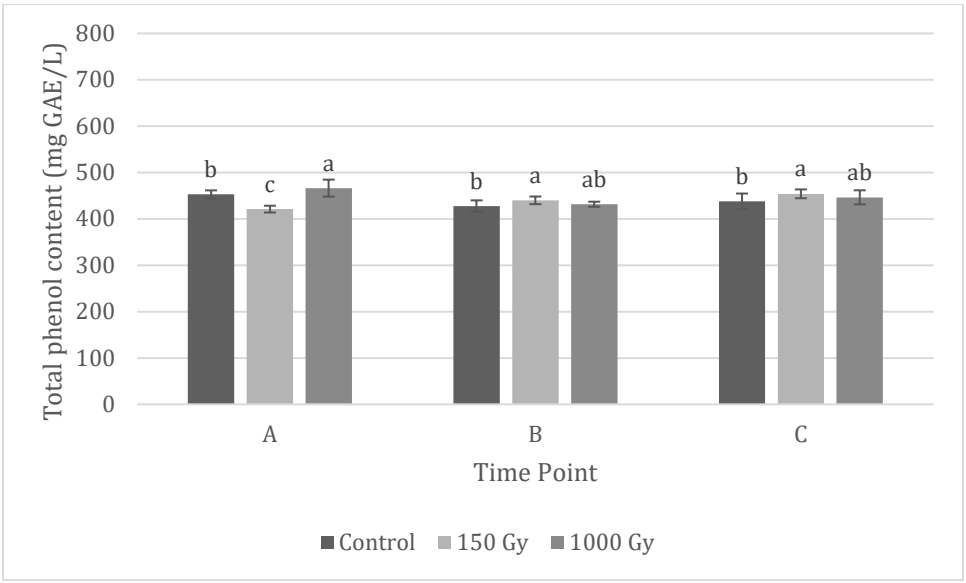
700
600
500
400
300
200
100
0
Total phenol content (mg GAE/L)
b
a
a
a
a
a
b
a
a
A
B
C
Time point
Control
150 Gy
1000 Gy

(a)


800
700
600
500
400
300
200
100
0
Total phenol content (mg GAE/L)
b
c
a
b
a
ab
b
a
ab
A
B
C
Time Point
Control
150 Gy
1000 Gy

(b)

Fig. 3

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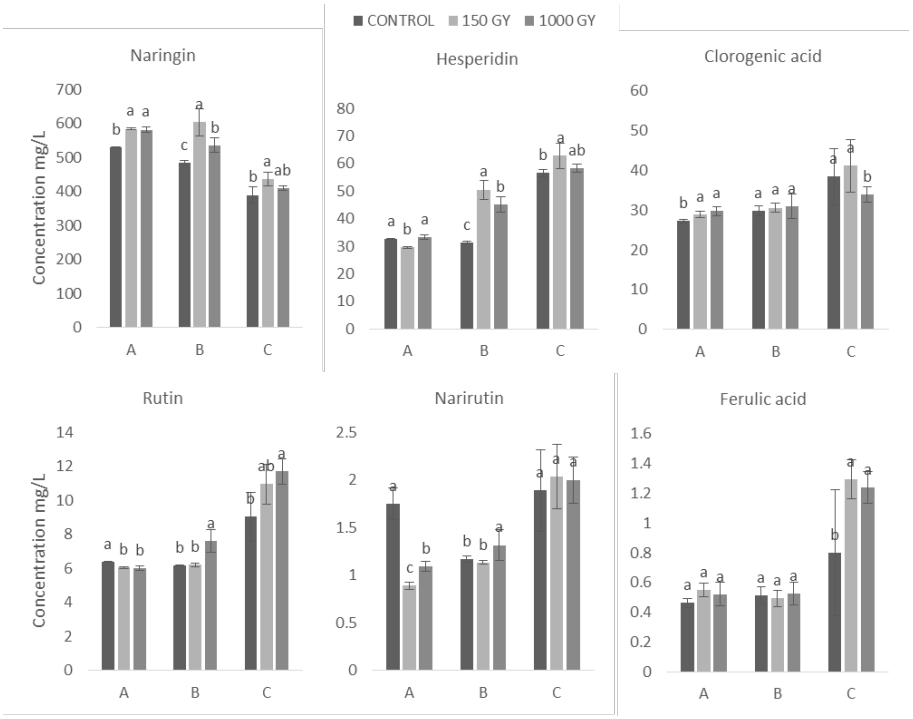

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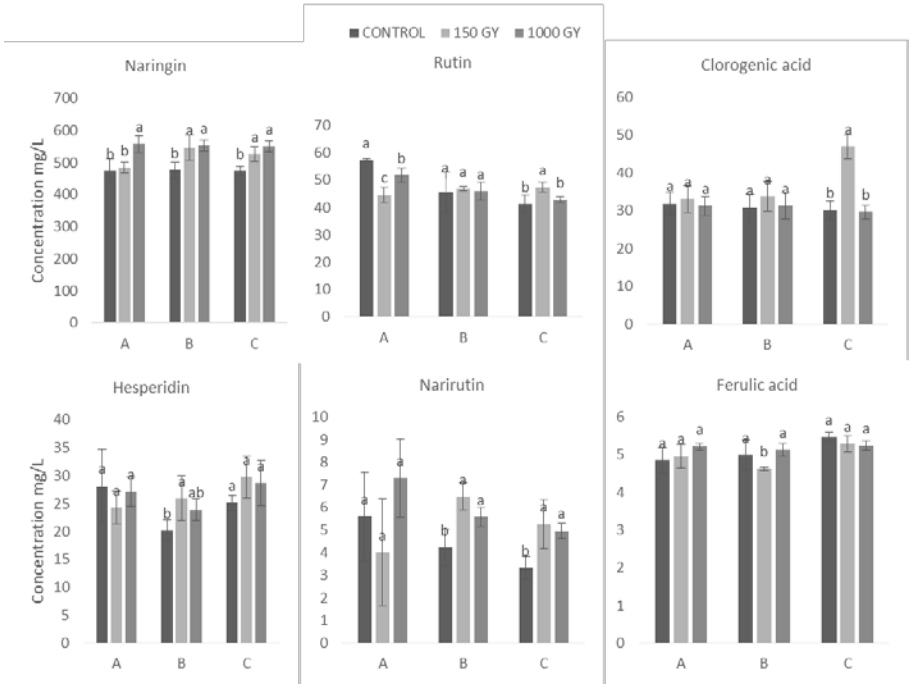
766 (a)



767

768 (b)

769 Fig. 4

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773 Fig. 5

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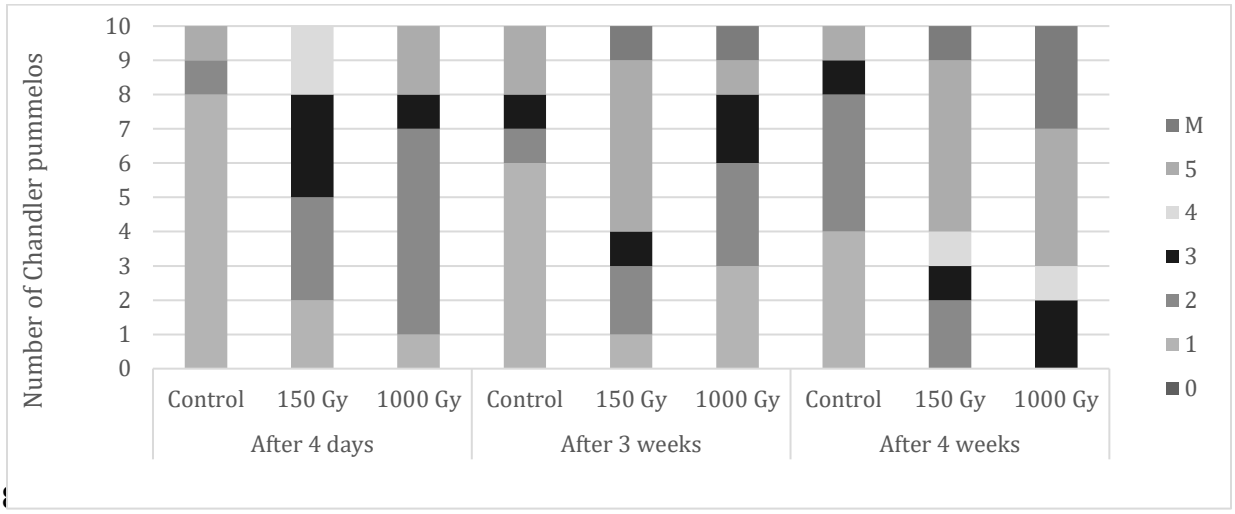

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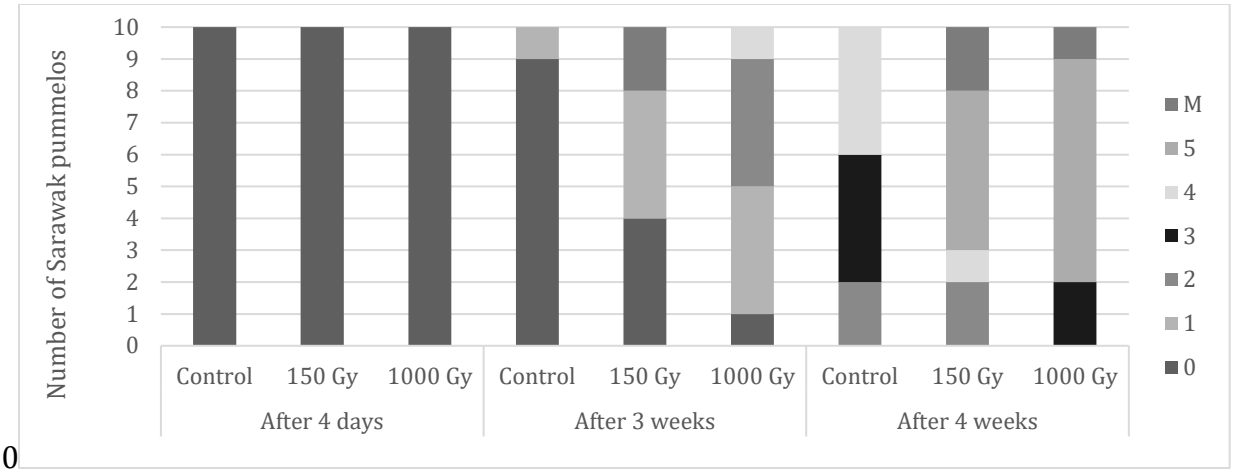
789 (a)



790

791 (b)

792 Fig. 6