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

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Article Type: Research Paper

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27 **ABSTRACT**

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

46 non-treated fruit. The results suggest that irradiation could serve as a potential
47 phytosanitary treatment for Chandler and Sarawak pummelos, provided that the fruit
48 is subjected to minimal handling and not temperature abused.

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

51 **1 INTRODUCTION**

52 Pummelo (*Citrus maxima* (Burm.) Merr.) is one of the largest citrus fruits by size.
53 This fruit is popular throughout Asia and Europe for their desirable taste, flavor and juicy
54 texture and is gaining popularity in the U.S. In August 2014, the United States Animal and
55 Plant Health Inspection Service (APHIS) proposed the importation of five species of citrus
56 fruits, including pummelos, from China into the U.S. (USDA-APHIS, 2014) provided that
57 adequate phytosanitary measures are taken to ensure quarantine pest free fruit shipment.
58 APHIS has identified 22 pests including eight species of Bactrocera fruit flies as quarantine
59 pests that might enter U.S. through importation of citrus fruits from China (USDA-APHIS,
60 2015). Phytosanitary treatments allowed by APHIS on citrus include chemical fumigation,
61 irradiation, and cold and heat treatments (USDA-APHIS, 2015), although the commercial
62 phytosanitary treatments prevalent in the citrus industry are cold treatment and methyl
63 bromide fumigation (MeBr). Cold treatments (0.56-1.67 °C for 22-18 days) are very
64 effective in eliminating certain insect infestations (USDA-APHIS, 2015), however, the
65 optimum temperature for storage of pummelos is 12 °C, and storage at significantly lower
66 temperature can adversely affect the external appearance and color of pummelos resulting
67 in damage and loss of market quality (International Tree Fruit Network, 2011). Methyl
68 bromide (MeBr) has a depleting effect on the ozone layer and pre-plant use has been

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

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

84 The effect of irradiation depends upon the variety or cultivar of fruit, irradiation
85 dose, ripening/maturity stage of the fruit, harvest season and post-treatment storage
86 conditions of fruit such as temperature (McDonald et al., 2013; Bustos and Mindeta, 1988;
87 Patil et al., 2004; Miller et al., 2000; Nagai and Moy, 1985). Some fruits such as Valencia
88 and ‘Ambersweet’ oranges can tolerate irradiation but peel pitting is observed on irradiated
89 navel and ‘Hamlin’ oranges, and ‘Fallglo’, ‘Sunburst’ and ‘Temple’ hybrid mandarins
90 (McDonald et al., 2013; Miller et al., 2000). Irradiation also causes dose dependent
91 softening of Valencia oranges treated at 300 Gy and higher (Nagai and Moy, 1985), navel

92 oranges treated at 600 Gy and higher (McDonald et al., 2013) , and ‘Murcott’, Minneola
93 and ‘Temple’ fruit (Miller et al., 2000) whereas other varieties such as ‘Hamlin’,
94 ‘Sunburst’ and ‘Ambersweet’ are more radiotolerant (Miller et al., 2000). .

95 The effect of low-dose gamma irradiation on the post-harvest quality of pummelos
96 has not been documented. Thus, the objective of the research was to observe the effects of
97 low-dose gamma irradiation (150 Gy and 1000 Gy) on the post-harvest quality of two
98 varieties of Pummelos available in California, Chandler (red flesh) and Sarawak (white
99 flesh), after storage at 12°C for 3 weeks, the time required for sea shipment between the US
100 and Asia, followed by one week at 20°C to reflect retail conditions. The dose of 150 Gy
101 was selected since it is the specified minimum dose in the PPQ Treatment Manual (APHIS,
102 2014). 1000 Gy is the maximum dose allowed by the FDA to treat fresh fruits and
103 vegetables and was selected to exacerbate the negative effects and allow recognition of
104 symptoms of phytotoxicity.

105 2 **MATERIALS AND METHODS**

106 2.1 Fruit Procurement

107 Pummelos were harvested on January 15th, 2015 in Tulare County, CA. The fruits
108 were packed on January 17th, 2015 in Oroshi, CA following standard commercial practices.
109 The fruits were first washed using 50-150 mg/L chlorine at the point of dumping, then
110 using a mixture of 100-200 mg/L chlorine and 1-2% sodium bicarbonate in a high pressure
111 washer at 862 kPa (125 psi) followed by a fresh water rinse. After washing, the fruits were
112 treated with 200-300 mg/L heated imazalil. In addition to treatment with imazalil, the fruits
113 were waxed with carnauba-based wax that had 2000 mg/L imazalil and 3500 mg/L

114 thiabendazole mixed in it. Pummelos were bulk packed in 24 kg cartons, with
115 approximately 12 pummelos in each carton. After packaging, the cartons were stored at 5°
116 C prior to shipping to Santa Fe Springs, CA (350 km) in a refrigerated truck. The cartons of
117 pummelos were picked up from the distributor and transported in a van to Sterigenics, Inc.,
118 Tustin CA (20 km) for gamma irradiation.

119 2.2 Gamma Irradiation:

120 Upon arrival at Sterigenics, the cartons were labeled either control, 150 Gy, or 1000
121 Gy. Dose mapping was conducted using eight cartons of pummelos in the exact
122 configuration as the sample treatment with 150 Gy and 1000 Gy. Eight boxes were stacked
123 in two rows of four a fixed distance from the Co₆₀ source (~278bq). Dose mapping was
124 conducted by placing 16 alanine pellet dosimeters (FarWest Technology, In, Goleta, CA) at
125 various locations in the cases. The dose rate was determined to be 0.637 Gy s⁻¹. Eight cases
126 of pummelos were placed exactly in the same configuration as the dummy cases to receive
127 treatment at a target dose of 150 and 1000 Gy (4.6-5.5% uncertainty) and Dmax/Dmin
128 ratio of 1.33. The eight cartons used as control fruit did not receive any treatment. After
129 treatment was complete, all the cartons were transported to Chapman University, Orange,
130 CA in a van, covering a distance of approximately 24 miles. Upon arrival, all the cartons
131 were stored at 12° C for 3 weeks to simulate shipment to and from Asian countries and at
132 20° C for the 4th week to simulate one week at retail temperatures. Temperature was
133 verified using LogTags® (Auckland, New Zealand) placed in cartons of pummelos during
134 storage. Analytical and chemical tests were performed on samples taken at day 1 after
135 irradiation, then after 3 and 4 weeks of storage.

136 2.2.1 Peel pitting and external damage

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

143 2.2.2 Weight Loss

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

149 2.2.3 Texture

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

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

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

165 2.2.4 Peel and pulp color measurements

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

$$171 \quad h = \tan^{-1}(b^*/a^*)$$

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

174 2.2.5 Juice content

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

$$178 \quad \% \text{ Juice Content (whole fruit basis)} = [\text{Juice weight} \times 100] / [\text{Whole fruit weight}]$$

179 2.3 Chemical Analysis

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

185 2.3.1 Total soluble solids

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

189 2.3.2 Titratable acidity

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

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

193 2.3.3 Organic acids

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

200 x 300 mm) (Bio-Rad, Hercules, CA) at 60 °C. The mobile phase was composed of 5mM
201 H₂SO₄ and acetonitrile (90:10, v/v) at a flow rate of 0.4 mL/min. Citric, malic, oxalic,
202 tartaric, quinic, fumaric and succinic acids were monitored at λ =210 nm. The ascorbic acid
203 was monitored at λ =260 nm. Identification and quantification of organic acids was carried
204 out using reference compounds.

205 2.3.4 Sugars

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

215 2.3.5 Individual and total phenols

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

222 0 min, 93% A at 12 min, 89% A at 20 min, 86% A at 35 min, 84% A at 36 min, 82% A at
223 41 min, 79% A at 44, 0% A from min 55 to 60. The flow rate was 1 mL/min. The phenolic
224 compounds were identified and quantified by using reference compounds. The UV-Vis
225 spectrum of individual phenols was also used for identification purposes.

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

234 2.3.6 Aroma Volatiles

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

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

252 2.4 Consumer testing

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

287 This increase in fruit firmness might be a result of moisture loss from the surface of the
288 fruit (peel) due to transpiration as well as decrease in relative humidity during ambient
289 temperature storage.

290 The peel of pummelos is considered a rich source of pectin and other structural
291 polysaccharides such as cellulose (Methacanon et al., 2014). Pectin content in flavedo and
292 albedo layers of pummelos is about 15 and 19% (Chaidedgumjorn et al., 2009). Radiation-
293 induced free radical activity (Kovács and Keresztes, 2002) as well as increased
294 polygalacturonase and pectinmethylesterase activity (Ladaniya et al., 2003) can accelerate
295 degradation of cell wall pectin and other structural polysaccharides causing breakdown of
296 the middle lamella in the cell wall, ultimately resulting in reduced firmness. The high
297 pectin content in the flavedo layer of pummelos suggests that this layer will be likely
298 impacted by irradiation, and while loss of firmness of the peel was readily observed in the
299 irradiated Chandler pummelo, in the Sarawak, a significant decrease ($P<0.05$) was seen
300 only after three weeks of storage.

301 3.2 Juice Content

302 No effect of irradiation or storage was observed on the juice content of Sarawak
303 pummelos (~33%) based on total fruit weight (data not shown). An initial small but
304 significant ($P<0.05$) increase in juice content based on fruit weight was observed for the
305 1000 Gy Chandler pummelos (from 24 to 27%) but the difference was not maintained
306 during storage. Sensory testing also corroborated that consumer perception of juiciness
307 was not affected. Similarly, Ladaniya et al. (2003) and Mitchell et al. (1991) also reported
308 that treatment with gamma irradiation up to 1500 Gy and 600 Gy did not affect juice yield
309 of Mosambi oranges, Nagpur mandarins and Valencia oranges, respectively.

310 3.3 Weight Loss

311 In the first three weeks of storage, the weight loss in Chandler pummelos was ~3%
312 increasing to ~11% by the end of the fourth week (data not shown). The Sarawak
313 pummelos lost ~3% of their weight in the first three weeks, and ~8% by the end of the
314 fourth week (data not shown). In both varieties, there was no impact of treatment. As
315 previously noted, juice content was unaffected during storage, which suggests that the
316 weight loss was primarily due to loss of moisture from the peel of the fruit. Exposure to
317 warm temperature along with storage at low relative humidity (~60%) was most likely the
318 cause of weight loss. Pummelo peels are thick (0.5-1 cm) and can amount to up to 50% of
319 the weight of the whole fruit, thus moisture loss from the surface of the peel can result in
320 significant weight loss.

321 3.4 Peel and Pulp Color

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

327 3.5 Titratable Acidity and Organic Acids

328 Irradiated Chandler pummelos had a lower titratable acidity as compared to the
329 control ($P < 0.05$) after three weeks and after subsequent storage at ambient
330 temperature (Table 1). There was no consistent effect of treatment or storage on
331 Sarawak pummelos (Table 1). McDonald et al. (2013), Ladaniya et al. (2003), and

332 O'Mahony and Goldstein (1987) also reported lower titratable acidity in irradiated
333 navel oranges, Mosambi oranges, Nagpur mandarins and Kagzi limes in comparison
334 to their control counterparts.

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

354 study, loss of ascorbic acid was observed in the 1000 Gy Sarawak pummelos but not in the
355 Chandler pummelos.

356 3.6 Total Soluble Solids and Sugars

357 Chandler pummelos had higher TSS values than Sarawak pummelos (Table 1), and
358 during storage, the TSS values of the control fruit of both varieties increased ($P<0.05$) but
359 there was not a consistent effect of irradiation. Similarly, sucrose concentrations, but not
360 glucose and fructose, in the Chandler variety were higher than the Sarawak pummelos and
361 concentrations fluctuated among treatments and during storage (Table 1). Sun et al.,
362 (2012) also observed higher initial sucrose concentrations in three varieties of pomelos as
363 compared to glucose and fructose, but there were no consistent patterns in changes in the
364 sugar concentrations during storage. The only consistent pattern in our data was an increase
365 in glucose, fructose and sucrose concentrations in the control and 150 Gy Chandler
366 pummelos during storage, but no other irradiation related effect is discernible. Patil et al.
367 (2004) reported that irradiation up to 700 Gy did not affect soluble solids in early ‘Rio Red’
368 grapefruit. However, irradiation has also been shown to decrease soluble solid content in
369 ‘Ambersweet’ oranges, navel oranges and ‘Sunburst’ mandarins treated with 300, 400 and
370 450 Gy of gamma radiation respectively (McDonald et al., 2013; Miller et al., 2000). Citrus
371 fruits utilize sugars as substrates for respiration, therefore it is expected that the total
372 soluble solids and sugar content will decrease with time. Also, irradiation can cause
373 oxidative stress, which can result in a higher respiration rate and consumption of simple
374 sugars during the process of respiration, leading to a decrease in sugar content (Ladaniya et
375 al., 2003), however no such decrease was observed in our study.

376 3.7 Total and Individual Phenols

377 Total phenolics ranged between 425 mg GAE L⁻¹ and 650 mg GAE L⁻¹ in the two
378 pummelo varieties (Fig. 3). In both sets of pummelos, naringin was the most abundant
379 phenolic compound (Fig. 4), about 10 fold higher than the next most abundant compounds
380 which were hesperidin and chlorogenic acid in the Chandler pummelos. Rutin, nairutin,
381 and ferulic acid were also detected in small quantities. In Sarawak pummelos, rutin and
382 chlorogenic acid were more abundant than hesperidin. In addition to small amounts of
383 narinutin and ferulic acid, very small amounts of p-coumaric acid were also detected.

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

392 Irradiation increased total phenolics in Chandler pummelos soon after treatment. After
393 three weeks, there were no differences between the treatments, but after the fourth week at
394 ambient temperature, the irradiated fruit had higher total phenolics. In the Sarawak
395 pummelos, the 1000 Gy fruit had the highest total phenolic concentrations soon after
396 treatment. During storage, the 400 Gy samples had the highest concentrations (P<0.05),
397 but the differences between the treatments was small. Irradiation increased (P<0.05)
398 naringin concentrations in both sets of pummelos. There is no information on effect of

399 irradiation on phenolics in pummelos, however, irradiation-induced stimulation of PAL
400 activity leading to increased phenolic concentrations has been documented in citrus fruit
401 such as Clemenules and mandarins (Rojas-Argudo et al., 2012; Shen et al., 2013).

402 3.8 Aroma Volatiles

403 Sixty-four volatiles were identified in samples from both of the pumelo varieties
404 consisting of aldehydes, alcohols, esters, ketones, and various classes of terpenes
405 (data not shown). Gonzalez-Mas et al. (2011) used HS-SPME-GC-MS analysis to
406 characterize the volatile compounds in different citrus fruit (Powell Navel orange,
407 Clemenules mandarin, Fortune mandarin and Chandler pummelos). The volatile
408 profile of the pummelos was unique in that mostly terpenic compounds (β -
409 caryophyllene, (*Z*)-ocimene, (*E,E*)-2,4-nonadienal, (*Z*)- and (*E*)-linalool oxides, *p*-cymene)
410 were identified, almost exclusively in Chandler pummelos. Cheong, Liu, Zhou, Curran,
411 and Yu (2012) evaluated the flavor profile of two varieties of Malaysian pummelos, *Citrus*
412 *grandis* (L.) Osbeck PO 51 and PO 52 (red and white fleshed, respectively). They found
413 that the pink pomelo juice shared a closer resemblance to grapefruit chemically in contrast
414 to the white pumelo and that the higher terpenic content of the white pomelo juice with
415 milder acidity and lower amounts of volatiles made it unique among citrus fruit.

416 Of the 64 compounds identified in this study, 39 changed significantly ($p \leq 0.05$)
417 due to irradiation treatment in 'Chandler' (Table 3) and 48 in 'Sarawak' (Table 4). In
418 both varieties the most common trend was for irradiation to increase volatile
419 concentrations relative to the controls, with 1000 Gy often causing the greatest
420 increase. This effect of irradiation to enhance citrus volatile concentration had also
421 been seen in oranges treated at doses as high as 600 Gy, with ethanol, esters and

422 aldehydes being the primary volatiles altered in amount by irradiation in that study
423 (McDonald et al., 2013). Although the effect of irradiation on volatile components was
424 similar for both varieties there were some differences in how specific classes of
425 compounds were altered. For instance, terpenes in 'Chandler' prior to storage
426 increased as a result of irradiation while in 'Sarawak' these compounds, with the
427 exception of α -thujene, either did not significantly change or decreased in
428 concentration. Storage impacted the treatment effect in 'Chandler' as significant
429 concentration differences between the control and 150 Gy treatment became much
430 less common following storage at both 3 weeks at 5 °C and after an additional 1 week
431 at 20 °C. While the overall impact of the 1000 Gy treatment was also lessened by
432 storage, there were still elevated concentrations relative to the untreated control for
433 many of the volatile compounds, particularly in the case of ethanol and in the esters
434 and ketones. Ethyl acetate in particular was strongly increased in the irradiated fruit
435 following storage. For 'Sarawak' there was still considerable impact of the 150 Gy
436 treatment after storage, particularly in the elevated levels of aldehydes and esters
437 following 3 weeks at 5 °C. Treatment with 1000 Gy and storage led to even higher
438 concentrations in volatiles from these two classes of compounds as well as increases
439 in four of the thirteen terpenes that were quantified. As is commonly practiced
440 commercially, the pummelos used in this study had a wax coating applied to the peel
441 surface after harvest and prior to irradiation treatment and storage. Waxing citrus can
442 result in the enhancement of volatile accumulation in the fruit that can sometimes
443 alter flavor (Obenland et al., 2011). In both 'Chandler' and 'Sarawak' concentrations
444 of many of the volatiles were higher as a result of storage in the untreated fruit, this

445 being a primary reason for why there was sometimes significant differences observed
446 as a result of irradiation immediately after treatment but not following storage.

447 3.9 Consumer Testing

448 Consumer testing of Chandler and Sarawak pummelos indicates that irradiation did
449 not affect consumer liking of the two pummelo varieties (data not shown). Overall, the
450 scores for all attributes ranged between 5 (Neither Like or Dislike) and 6 (Like Slightly).
451 The reason for overall low scores might be the lack of familiarity with pummelos.
452 Although changes in aroma-active juice volatiles as a result of irradiation were noted in this
453 study, panelists were evidently unable to detect the altered aroma volatile profile of the
454 irradiated fruit. McDonalds et al. (2013) also reported that the panelists did not observe
455 any significant differences in overall liking, flavor and juiciness among control navel
456 oranges and oranges irradiated at 200, 400 and 600 Gy. In contrast, some studies have
457 reported development of off-flavor in irradiated citrus treated with doses ranging from 60
458 Gy to 1000 Gy (Nagai and Moy, 1985; O'Mahony et al., 1985; Mitchell et al., 1991; Miller
459 et al., 2000).

460 3.10 Peel Damage

461 Both varieties had small but noticeable amount of dents and scars upon receipt,
462 presumably due to postharvest handling of the fruit. During storage, fruit developed
463 significant brown colored stippling (small brown spots), loss of gloss, bruising and areas of
464 softening. In irradiated fruit, we also observed larger, sunken brown areas (Fig. 5) that have
465 been reported in the literature as peel pitting, generally associated with areas of peel that
466 collapse and discolor and not limited to oil glands (Ritenour et al., 2003). In general, peel

467 damage was greater and developed more quickly in irradiated pummelos and became even
468 more severe when the fruit was stored at ambient temperature for a week. In Chandler
469 pummelos, eight out of ten of the 150 Gy and nine out of ten of the 1000 Gy Chandler
470 pummelos showed evidence of pitting, bruising and spot development covering more than
471 5% of the total surface area of each pummelo as compared to only two out of ten control
472 pummelos after the first week of storage (Fig. 6). No pitting, bruising or spotting was
473 evident in Sarawak pummelos during the first week. The extent of damage increased
474 gradually in both varieties of pummelos during the three week storage at 12 °C, however,
475 storage at ambient temperature (20 °C) for one week severely exacerbated peel damage in
476 irradiated pummelos. By the end of the fourth week, 70 and 80% of the irradiated Chandler
477 and Sarawak fruit, respectively, showed 16% or more damaged surface area, as compared
478 to only 10% of the control Chandler and none of the control Sarawak. Pummelos with
479 pitting covering greater than 16% of the peel surface were considered unmarketable. Thus,
480 the combination of irradiation, physical manipulation and high temperature storage was
481 highly detrimental to the quality of the pummelos. Mold growth was observed in both
482 varieties of irradiated pummelos, mainly because cell injury caused by irradiation provided
483 a suitable environment for mold growth.

484 Peel pitting is a disorder that generally occurs during postharvest storage of citrus
485 fruits under environmental conditions, such as low relative humidity, that can cause
486 damage to cells in the flavedo and albedo, ultimately affecting nearby oil glands present in
487 the fruit peel (Alferez et al., 2008). Low internal oxygen concentrations within the fruit
488 might be another possible explanation for non-chilling peel pitting observed in citrus fruits
489 (Ritenour, 2013). Peel pitting as a result of irradiation has been observed in several citrus

490 fruits (McDonald et al., 2013; Ladaniya et al., 2003; Miller et al., 2000; Dennison et al.,
491 1966). One of the causes of peel pitting in irradiated citrus fruit may be irradiation-induced
492 accumulation of phenolic compounds in the flavedo cells of the peel which oxidize
493 resulting in cell death (Riov, 1975). Irradiation can also elevate respiration rate of fresh
494 fruit resulting in increased ethylene production (Riov et al., 1972), and subsequent increase
495 in PAL activity (Benoit et al., 2000). Enhanced PAL activity leads to accumulation of
496 phenolic compounds in irradiated fruits (Mahrouz et al., 2002). In this study, an immediate
497 irradiation-induced increase in naringin was seen in both varieties of pummelos. While
498 respiration rate was not measured in this study, the TA was lower in the 1000 Gy Chandler
499 pummelos suggesting that respiration rate of these fruit may be affected. Additionally,
500 the high ethanol levels measured in this study, particularly in the Sarawak pummelos
501 after 20 C storage, are indicative of low internal oxygen concentrations which can also
502 lead to peel pitting (Ritenour, 2013). Using a wax that allows adequate oxygen diffusion
503 rate may help in reducing peel pitting (Ritenour, 2013). Heat conditioning treatment at 38
504 and 42° C for 2 hours reduced PAL activity, which further resulted in reduced peel pitting
505 by 8 and 10% respectively, in grapefruit irradiated at 1000 Gy and stored at 10 °C for 4
506 weeks (McDonald et al., 2000). Thus, heat conditioning might prove helpful in case of
507 pummelos as well.

508 **4 CONCLUSION**

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

513 In general, 1000 Gy had a greater impact on pummelo quality than 150 Gy. One
514 impact of irradiation was manifested as softening of the fruit, an effect observed in most
515 irradiated pummelos, although irradiation-induced peel damage was the most significant
516 effect of irradiation. Peel damage in the irradiated fruit increased gradually during the three
517 weeks of storage under ideal conditions. However, when the conditions were less than ideal
518 in terms of ambient temperatures and excessive handling, the fruit showed signs of
519 phytotoxicity. Our results show that 150 Gy could be a feasible dose for Chandler and
520 Sarawak pummelos but they would need to be handled minimally and stored under ideal
521 temperatures.

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ACKNOWLEDGMENT

525 This work was supported by USDA-APHIS Cooperative Agreement 15-8130-0468-
526 CA. The authors are grateful to David Karp, Fruition Sales, Inc. Orange Cove and
527 Sterigenics, Tustin in California for their assistance. J. J. Ornelas-Paz thanks CONACYT
528 (Mexico) for providing support to perform his sabbatical leave at Chapman University.

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Treatment	TA	TSS (%)	Sugars (g/L)
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		(% citric acid)		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

652 Table 1. Titratable acidity, total soluble solids and sugars in irradiated Chandler and Sarawak
653 pummelos stored for three weeks at 12°C and for an additional week at 20°C. Statistically
654 significant differences ($P < 0.05$) among treatments within the same time point are denoted by
655 letters A-C; and across time points for the same treatment by letters x-z.

656 Table 2. Organic acids in irradiated Chandler and Sarawak pummelos stored for 3 weeks at 12 °C and after an additional week at 20 °C. Statistically
657 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
658 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,
659 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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Table 3 Aroma volatile concentrations ($\mu\text{g L}^{-1}$) in irradiated Chandler pummelos during storage for 3 weeks at 12 °C and after an additional week at 20 °C. Values followed by different letters within a storage regime represent significant differences ($P \leq 0.05$). Shading indicates that there is at least a two-fold difference from the control (0 Gy) dose. nd = not detectable.

Treatment	Day 1			After 3 weeks			After 4 weeks		
	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									668
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	28.65a69
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	3.38a670
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	4.23a671
Terpenes									
α-pinene	0.15c	0.27b	0.35a	0.40a	0.41a	0.43a	0.48a	0.33b	0.37b672
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	0.72a673
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	0.18a674
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	36.45a675
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	0.84a676
Terpene alcohols									
linalool	1.41c	2.16b	4.10a	3.02a	2.97a	2.45b	5.53a	4.20ab	4.06b677

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

Treatment	Day 1			After 3 weeks			After 4 weeks		
	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
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	3.33b	3.33687	^a =mg L ⁻¹
Ketones											
1-penten-3-one	45.97c	75.02b	94.98a	100.47a	83.92a	96.07a	184.47b	201.02a	114.66b	114.668	
gamma-butyrolactone	11.86b	17.72ab	21.782a	15.52a	15.21a	14.58a	12.43a	15.49a	16.65a	16.65a	
methyl-heptanone	24.06a	29.12a	30.79a	32.10b	36.35ab	40.28a	31.51b	43.88a	36.81ab	36.81ab	
dihydrocarvone	2.77a	3.30a	2.63a	3.37b	5.01a	5.33a	3.31a	3.59a	4.58a	4.58a	
carvone	5.01b	9.17a	7.09ab	11.24b	20.13a	26.97a	13.81b	10.73b	21.17a	21.17a	
piperitone	3.24b	6.35a	4.58ab	7.54a	9.26a	9.79a	8.34a	9.89a	9.59a	9.59a	
Terpenes											
α-thujene	0.85b	0.88b	1.42a	1.09c	1.60b	1.88a	1.35b	0.99c	1.97a	1.97a	
α-pinene	4.98ab	4.09b	5.76a	5.27b	8.33a	9.31a	7.29b	4.25ab	9.31a	9.31a	
camphene	0.19a	0.17a	0.20a	0.20b	0.27a	0.29a	0.23ab	0.19b	0.30a	0.30a	
β-pinene	2.94a	2.32a	3.22a	2.80b	4.62a	5.18a	4.39b	2.55c	5.73a	5.73a	
β-myrcene	2.69a	1.57b	2.11ab	2.27a	2.78a	2.94a	2.34a	2.10a	2.82a	2.82a	
α-terpinene	1.42a	0.63b	0.91b	0.79b	1.64a	1.65a	1.36ab	0.79b	1.63a	1.63a	
1-menthene	0.86a	0.34b	0.57b	0.43a	0.88b	0.80b	0.79a	0.41b	0.85a	0.85a	
p-cymene	38.78a	35.76a	51.77a	42.01b	79.21a	94.39a	59.87b	40.34c	84.05a	84.05a	
limonene	106.23a	80.03a	100.60a	104.85a	190.84a	235.15a	173.44a	100.76b	229.32a	229.32a	
γ-terpinene	14.45a	4.45b	7.99b	5.77b	13.60a	12.85a	11.11ab	5.67b	12.75a	12.75a	
β-elemene	1.23a	0.70b	1.06a	0.87a	0.95a	0.95a	0.97a	0.87a	0.90a	0.90a	
trans-caryophyllene	4.05a	2.16b	2.86b	2.93a	3.27a	3.11a	3.02a	2.63a	2.97a	2.97a	
α-humulene	0.72a	0.36b	0.49b	0.50a	0.58a	0.55a	0.55a	0.46a	0.50a	0.50a	
Terpene alcohols											
linalool	9.39a	8.22b	10.11a	10.99c	14.88a	12.40b	17.82a	10.53c	13.42b	13.42b	
4-terpineol	12.65a	11.78ab	10.21b	13.27b	22.20a	19.98a	19.24a	11.74b	18.49a	18.49a	
β-fenchyl alcohol	12.94a	13.28a	11.92a	16.36b	23.15a	21.88a	22.66a	16.88b	20.98ab	20.98ab	

689 List of Figures:

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

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

701

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

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706 Figure 4. Content of several phenolic compounds (NG, naringin; H, hesperidin; CA,
707 chlorogenic acid; R, rutin; NR, narirutin; FA, ferulic acid) in (a) Chandler and (b)
708 Sarawak pummelos. A-immediately after irradiation; B-after 3 weeks of storage at 12
709 °C and C-after additional week at 20 °C.

710

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

713
714 Figure 6. Peel damage in (a) Chandler and (b) Sarawak, control and irradiated (150 Gy
715 and 1000 Gy) pummelos stored for 3 weeks at 12 °C and for an additional week at 20
716 °C. 0=0%, 1=1-4%, 2=5-9%, 3=10-12%, 4=13-15% and 5=16% or more external
717 damage, M=Moldy pummelos.

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728 Fig. 1

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(b)

756 Fig. 2

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(a)

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(b)

764 Fig. 3

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771 (b)

772 Fig. 4

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776 Fig. 5

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Fig. 6