Influence of Modified Atmosphere Packaging on Radiation Tolerance in the Phytosanitary Pest Melon Fly (Diptera: Tephritidae)

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Influence of Modified Atmosphere Packaging on Radiation Tolerance in the Phytosanitary Pest Melon Fly (Diptera: Tephritidae)

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ABSTRACT Modified atmosphere packaging (MAP) produces a low-oxygen (O2) environment that can increase produce shelf life by decreasing product respiration and growth of pathogens. However, low O2 is known to increase insect tolerance to irradiation, and the use of MAP with products treated by irradiation before export to control quarantine pests may inadvertently compromise treatment efficacy. Melon fly, Bactrocera cucurbitae Coquillet (Diptera: Tephritidae), is an important economic and quarantine pest of tropical fruits and vegetables, and one of the most radiation-tolerant tephritid fruit flies known. The effect of low O2 generated by MAP on the radiation tolerance of B. cucurbitae was examined. Third-instar larval B. cucurbitae were inoculated into ripe papayas and treated by 1) MAP + irradiation, 2) irradiation alone, 3) MAP alone, or (4) no MAP and no irradiation, and held for adult emergence. Three types of commercially available MAP products were tested that produced O2 concentrations between 1 and 15%, and a sublethal radiation dose (50 Gy) was used to allow comparisons between treatments. Ziploc storage bags (1–4% O2) increased survivorship to adult from 14 to 25%, whereas Xtend PP61 bags (3–8% O2) and Xtend PP53 bags (11–15% O2) did not enhance survivorship to the adult stage in B. cucurbitae irradiated at 50 Gy. Radiation doses approved by the United States Department of Agriculture and the International Plant Protection Commission for B. cucurbitae and Ceratitis capitata (Wiedemann) (Mediterranean fruit fly) are 150 and 100 Gy, respectively. In large-scale tests, 9,000 B. cucurbitae and 3,800 C. capitata larvae infesting papayas in Ziploc bags were irradiated at 150 and 100 Gy, respectively, with no survivors to the adult stage. MAP can increase insect survivorship during irradiation treatment at certain doses and O2 concentrations, but should not compromise the efficacy of the 150-Gy generic radiation treatment for tephritid fruit flies or the 100-Gy radiation treatment for C. capitata.

KEY WORDS irradiation, Mediterranean fruit fly, quarantine, generic dose, modified atmosphere

Modified atmosphere (MA) is used to prolong the shelf life of fresh produce and its use is increasing (Kader and Watkins 2000). MA can slow or retard maturation, ripening, or senescence; reduce chilling injury; and control certain pathogenic and physiological disorders (Yahia 1998). In modified atmosphere packaging (MAP), the atmosphere around the commodity is modified through the use of permeable polymeric films (Lange 2000). This normally reduces oxygen (O2) and/or elevates carbon dioxide (CO2) concentrations. MA can be created inside a package either passively through product respiration (consumption of O2 and production of CO2), or actively by replacing the atmosphere in the package with a desired mixture of gases. Recommended MA conditions during transport and storage for different fruits and vegetables vary between 1 and 10% O2 and 0 and 30% CO2 (Kader 2002).

Ionizing radiation is a postharvest treatment option for the control of quarantine pests in traded commodities (Follett and Neven 2006, Follett and Griffin 2006). Ionizing energy breaks chemical bonds within DNA and other molecules, thereby disrupting normal cellular function in the pest. Insect response to irradiation varies with the insect species and life stage, and with the absorbed dose received by the insect. Irradiation effects are partially caused by the creation of free radicals from O2 and water, which react with and damage nearby molecules. Insects are known to exhibit higher tolerance to radiation in low-O2 environments (Clark and Herr 1955, Balock et al. 1963, Earle et al. 1979). Low O2 causes the insect to slow respiration, thereby reducing O2 in the hemolymph and reducing the creation of free radicals during irradiation. Low O2 can also increase antioxidant capacity and decrease oxidative stress in insects (Lopez-Martinez and Hahn 2012). Low O2 concentrations generated with MAP may inadvertently reduce the efficacy of irradiation treatment used to control quarantine pests on exported fresh commodities.

Several recent studies with tephritid fruit flies demonstrated the effect of simulated low-O2 conditions on
Radiotolerance. A low-O<sub>2</sub> atmosphere increased the estimated dose (from 30 to 35.7 Gy) to achieve 99% prevention of the full pupal stage in irradiated third-instar apple maggots, *Rhagoletis pomonella* (Walsh), compared with ambient atmospheres (Hallman 2004b). A radiation dose of 200 Gy prevented adult emergence in 55779 treated fifth-instar oriental fruit moths, *Grapholita molesta* (Busck), in ambient atmosphere, but in an atmosphere flushed with nitrogen (presumably <1% O<sub>2</sub>), 5.3% of adults emerged from 44,050 fifth instars (Hallman 2004a). Anoxia conditioning for 1 h applied to late-stage Caribbean fruit fly, *Anastrepha suspensa* (Loew), pupae before irradiation at 70 Gy improved flight ability and male mating success (Lopez-Martinez and Hahn 2012); anoxia also significantly improved adult emergence and percentage flies when pupae received higher radiation doses of 200–400 Gy. Elevated CO<sub>2</sub> is not known to have a radioprotective effect (Tilton et al. 1965, Alpen 1998), unless it replaces O<sub>2</sub>, as in the case of a 100% CO<sub>2</sub> environment (Clark and Herr 1955, Balock et al. 1963, Earle et al. 1979).

In 2006, the United States Department of Agriculture–Animal and Plant Health Inspection Service (USDA–APHIS) approved for the first time, generic radiation treatments of 150 Gy for tephritid fruit flies and 400 Gy for other insects (USDA–APHIS 2006, Follett 2009), except Lepidoptera pupae and adults (that may require higher doses). At the same time, doses were approved for 10 specific quarantine pests for which there was sufficient information. India, Thailand, Vietnam, and Mexico are exporting fruit to the United States, and Australia is exporting fruit to New Zealand and Malaysia, by using generic radiation treatments (Follett 2009, Follett and Weinert 2012). In 2009, the International Plant Protection Commission approved the radiation dose of 150 Gy for tephritid fruit flies, which should facilitate worldwide adoption (International Plant Protection Commission 2009).

Studies showing increased survival in irradiated insects under low-O<sub>2</sub> conditions raise concerns about the efficacy of approved irradiation treatments when commodities are treated in MAP. Since the advent of generic doses, irradiation is being used for insect control without specific data on its effectiveness in some cases, and for most quarantine pests, there is no information on response to radiation treatment under low-O<sub>2</sub> conditions. USDA–APHIS recently decided to restrict use of MAP creating low O<sub>2</sub> or elevated CO<sub>2</sub> atmospheres in irradiated imported fresh commodities until further research is conducted to elucidate the relationship between O<sub>2</sub> and CO<sub>2</sub> concentrations and radiation tolerance.

Melon fly, *Bactrocera cucurbitae* Coquillet (Diptera: Tephritidae), is an important economic and quarantine pest of tropical fruits, and one of the most radiation-tolerant tephritid fruit flies known (Follett and Armstrong 2004, Follett et al. 2011). *B. cucurbitae* was used as a representative insect to investigate the effect of low-O<sub>2</sub> MAP on insect response to irradiation in fruit by using a sublethal radiation dose (50 Gy). Large-scale tests were conducted with *B. cucurbitae* to determine whether MAP may inadvertently compromise the 150-Gy generic dose for tephritid fruit flies. Large-scale studies were also performed with Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann), to determine whether MAP may compromise the 100-Gy dose specifically approved for its control.

Materials and Methods

**Sublethal Radiation Dose Tests.** *B. cucurbitae* were obtained from laboratory colonies maintained at the USDA–ARS Pacific Basin Agricultural Research Center in Hilo, HI, and reared on a standard diet (Vargas 1989). Laboratory and wild strains of *B. cucurbitae* were shown to be equally susceptible to ionizing radiation (Follett and Armstrong 2004). Mature third instars were used in all tests because this is the most radiotolerant life stage found in fruit (Follett and Armstrong 2004, Follett et al. 2011).

For each test, cohorts of 100 third instars were artificially inoculated into freshly harvested one-half to three-fourths ripe papayas (‘Kapoho Solo’ cultivar) through a hole made with a 12-mm cork borer, then sealed inside with a fruit plug and hot glue. Larvae were transferred to papayas 24 h before treatment to allow larvae to distribute themselves in the fruit. Infested fruit were randomly assigned to four experimental treatments: 1) MAP + irradiation (50 Gy), 2) irradiation alone, 3) MAP alone, or 4) no MAP and no irradiation. For MAP treatments, infested papayas were placed individually inside 2.5-liter bags and bags were then sealed by using heat (Impulse Foot Sealer, American International Electric Co., City of Industry, CA). Ripe papayas held in heat-sealed bags at 24 ± 1°C created a MA inside the packaging through respiration. Three types of commercially available MAP products were tested with different O<sub>2</sub> permeabilities: Ziploc storage bags (low-density polyethylene producing 1–4% O<sub>2</sub>, S.C. Johnson, Racine, WI), Xtend PP61 (semipermeable film producing 3–8% O<sub>2</sub>, StePac L.A. Ltd., Tefen, Israel), and Xtend PP53 (semipermeable film producing 11–15% O<sub>2</sub>, StePac L.A. Ltd.). The Xtend films are composed of a proprietary blend of polymers with microperforations to obtain the desired MA (hereafter referred to as Xtend 61 and Xtend 53). Each MAP product was tested separately by using the four experimental treatments, and treatments were replicated 10 times in each test (1000 third instars per treatment) by using a completely randomized design.

Approximately 18–24 h after placing infested fruit in heat-sealed bags, samples were transported to a nearby commercial X-ray irradiation facility (CW Hawaii Pride, Keaau, HI) and treated by using an electron linear accelerator (5 MeV, model TR-5/15, Titan Corp., San Diego, CA). A sublethal radiation dose of 50 Gy (range, 43–64 Gy) was used to allow comparisons between treatments. ROW dosimeters (Optichromic detectors, FWT-70–83M, Far West Technology, Goleta, CA) were placed inside uninfested fruit in each replicate to estimate dose variation during treatment. Dosimeters were read with an FWT-200...
reader (Far West Technology) at 600-nm absorbance. To minimize the dose uniformity ratio (the ratio of the maximum/minimum dose), wooden racks holding a single row of bagged (MAP) and unbagged (no MAP) papayas were placed perpendicular to the X-ray beam and elevated by placement on a cardboard box positioned in the center of the carrier. With X-ray radiation, product moves in front of the beam on a conveyor belt, so individual fruit pass in front of the beam sequentially and each can be considered a replicate. The dose uniformity (or maximum–minimum) ratio was ≤1.1 for all replicates.

Immediately after radiation treatment, bagged and unbagged fruit were returned to the laboratory and held at 24 ± 1°C. Bags were fitted with septa for gas sampling. Approximately 2 h after irradiation treatment, measurements of O₂ and CO₂ concentrations in bags were taken by using a headspace gas analyzer (Illinois Instruments model 6600, Johnsburg, IL). Gas measurements were made again 24 h later (42–48 h after sealing fruit in bags). In a small subset of MAP bags (n = 8 for each MAP type), gas measurements were also taken hourly for the first 6 hours after sealing the fruit inside to examine the rate of approach to equilibrium gas levels. After the 48-h gas measurements, infested papayas were removed from bags, placed in 2-liter ventilated plastic containers with 300 g sand (as a pumation medium), and held for pupal development. After 2–3 wk, fruit and sand were inspected for pupae, and pupae were transferred to 120-ml cups for adult emergence. The number of adults emerging from each fruit was counted, and percentage adult emergence was the criterion used for comparing treatment effects. For each packaging type, data on adult emergence were subjected to a one-way analysis of variance, and when significant, means separations were performed by using a Tukey’s honestly significant difference test at α = 0.05 (SAS Institute 2010).

Dose–Response Tests With Ziploc Bags. Ziploc bags were evaluated further after they appeared to cause an increase in B. cucurbitae survivorship after irradiation. A dose–response test was conducted by irradiating B. cucurbitae third instars in papayas in Ziploc bags at 0, 60, 90, 120, and 150 Gy by using the methods previously described. Eight papayas, each holding 100 third instars, were treated at each dose in a factorial design. An equal number of infested papayas were irradiated without MAP (no Ziploc bags) at each dose for comparison. Data on adult emergence were arcsine transformed and analyzed by using linear regression.

Large-Scale Tests. Large-scale tests were conducted to evaluate the integrity of the 150-Gy generic dose by treating B. cucurbitae third instars in papayas at 0 Gy (controls) with or without Ziploc packaging, or at 150 Gy (measured doses 143–147 Gy) with Ziploc packaging. As with previous tests, cohorts of 100 third instars were artificially inoculated into ripe papayas, placed in Ziploc bags and sealed with heat, and irradiated 24 h later. Identical tests using Ziploc packaging were conducted with laboratory-reared C. capitata third instars at 100 Gy (measured doses 96–104 Gy). In total, 9,000 B. cucurbitae third instars were treated in 90 fruit in MAP at 150 Gy, 1,500 third instars were treated with MAP only (no irradiation), and 1,500 third instars were not treated with irradiation or MAP. In total, 3,600 C. capitata third instars were treated in 36 fruit in MAP at 100 Gy, 500 third instars were treated with MAP only (no irradiation), and 700 third instars were not treated with irradiation or MAP. Data on adult emergence were subjected to one-way analysis of variance and means separations were performed by using a Tukey’s test (SAS Institute 2010).

Results and Discussion

Papaya respiration inside each of the three types of commercially available MAP products rapidly reduced O₂ and increased CO₂ concentrations. Equilibrium O₂ levels were reached in ~6 h after sealing infested ripe fruit in bags (Fig. 1), and O₂ levels at equilibrium were significantly different among the three MAP films (F₃,₅₃ = 9.1; P < 0.001). The 24-h mean O₂ concentrations for the MAP types at the time of irradiation were 2.5, 5.5, and 13.1% for the Ziploc, Xtend 61, and Xtend 53 bag types, respectively, which were all significantly different from each other (P < 0.001). At 48 h, the O₂ concentration had increased only slightly in the three MAP treatments. At 24 h, mean CO₂ concentrations were significantly higher in the Xtend 61 bag type (21.0%) than the Ziploc or Xtend 53 bag types (both 8.1%) (F₃,₅₃ = 5.8; P = 0.005) and levels were unchanged at 48 h (data not shown).

Sublethal Radiation Dose Tests. Irradiation and MAP treatment had a significant effect on survivorship of B. cucurbitae third instars to the adult stage in the Ziploc (F₃,₃₀ = 11.5; P < 0.001), Xtend 61 (F₃,₃₀ = 26.1; P < 0.001), and Xtend 53 (F₃,₃₀ = 25.6; P < 0.001) tests (Figs. 2–4). Placement of papayas infected with B. cucurbitae larvae in MAP bags without irradiation reduced survivorship to the adult stage by 18–24% compared with control fruit not placed in MAP bags. Survivorship was reduced from 59.0, 58.2, and 69.1% in

![Fig. 1. Reduction in oxygen concentration (mean ± SE) in three types of modified atmosphere packages (MAP) containing respiring ripe papayas. Equilibrium was reached in ~6 h. For experimental treatments, irradiation was applied ~18–24 h after placing infested fruit in sealed MAP bags.](image-url)
controls to 38.7, 34.1, and 51.9% in the Ziploc, Xtend 61, and Xtend 53 treatments, respectively. This indicates that low O₂ and/or elevated CO₂ is moderately toxic to \textit{B. cucurbitae} larvae, as is the case in other insects (Nicolas and Sillans 1989, Mitcham et al. 1997, De Carli et al. 2010).

Irradiation at 50 Gy caused a significant reduction in survivorship of \textit{B. cucurbitae} larvae to the adult stage, both with and without MAP (Figs. 2–4). Irradiation alone reduced survivorship from 58 to 69% in the untreated controls to 13.2 to 17.3% in MAP. The response of \textit{B. cucurbitae} to irradiation under the low-O₂ conditions produced by MAP depended on the package type. Placement of infested papayas in Ziploc bags (1–4% O₂) followed by irradiation increased survivorship to adult stage from 14 to 25% compared with irradiated controls (Fig. 2), suggesting that low O₂ can increase radiation tolerance in \textit{B. cucurbitae}. Survivorship in the Ziploc bags plus irradiation treatment was not significantly different from the Ziploc bags alone treatment, underscoring the radioprotective effects of the low-O₂ environment produced by respiring papayas in this low-density polyethylene film. Placement of infested papayas in Xtend 61 bags (3–8% O₂) (Fig. 3) and Xtend 53 bags (11–15% O₂) (Fig. 4) followed by irradiation did not enhance survivorship to the adult stage. In the Xtend 53 bag plus irradiation treatment, survivorship was identical to the irradiation treatment alone, and in the Xtend 61 bag plus irradiation treatment, survivorship was reduced compared with the irradiation alone treatment, possibly because of the higher levels of CO₂ produced by this film (White et al. 1995). Therefore, only the Ziploc bag treatment, which produced the lowest O₂ concentration of 1–4%, caused an increase in survivorship after irradiation. This suggests that increased radiation tolerance in MAP is dependent on O₂ concentration.

**Dose–Response Tests With Ziploc Bags.** The 50 Gy dose used in the sublethal radiation dose tests was chosen to ensure that the treatments had moderate survivorship and comparisons could be made between MAP types. The Ziploc MAP treatment increased \textit{B. cucurbitae} survival after irradiation at 50 Gy over irradiation under ambient conditions (no MAP), and therefore, dose–response tests were performed with \textit{B. cucurbitae} third instars inside papayas in Ziploc bags to determine whether any survival was possible at higher radiation doses. In dose–response tests, survivorship generally decreased with increasing dose (Fig. 5).
Table 1. Efficacy of 150-Gy radiation treatment against Bactrocera cucurbitae third instars in papaya using modified atmosphere packaging (Ziploc storage bags) to produce low oxygen conditions

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Measured doses (Gy)</th>
<th>O₂ level (mean ± SE)</th>
<th>CO₂ level (mean ± SE)</th>
<th>No. treated</th>
<th>Pupae (mean ± SE)</th>
<th>Adults emerged (mean ± SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>—</td>
<td>20.9</td>
<td>0.0</td>
<td>1,300</td>
<td>1,174</td>
<td>1,015</td>
</tr>
<tr>
<td>MAP</td>
<td>—</td>
<td>1.2 ± 0.1</td>
<td>8.5 ± 0.5</td>
<td>1,500</td>
<td>665</td>
<td>350</td>
</tr>
<tr>
<td>MAP + Irrad</td>
<td>142-146</td>
<td>1.4 ± 0.1</td>
<td>5.5 ± 0.4</td>
<td>9,000</td>
<td>1,444</td>
<td>16.0 ± 1.2c</td>
</tr>
</tbody>
</table>

*Means in columns followed by different letters were significantly different by a Tukey’s test at P < 0.05.

The equations for linear regression of survivorship against radiation dose were $y = -0.07x + 9.0$ ($R^2 = 0.43$) for Ziploc bags (MAP) plus irradiation, and $y = -0.43x + 50.4$ ($R^2 = 0.67$) for irradiation alone. The predicted dose to completely prevent adult emergence was 124.4 Gy (107.0–164.7, 95% confidence limit) for the Ziploc MAP and irradiation treatment, and 116.7 Gy (103.8–133.8, 95% confidence limit) for the irradiation alone treatment, indicating that the low O₂ created by Ziploc MAP increased radiation tolerance. The Ziploc MAP treatment caused a reduction in survivorship from 68.3 to 10.6% in the nonirradiated (0-Gy dose) B. cucurbitae in papayas. At 60 Gy (measured doses 57–58 Gy), survivorship trended higher in the Ziploc MAP treatment (3.5 ± 2.1%) compared with the irradiation alone treatment (1.0 ± 0.5%) (Fig. 5). Ten individuals survived to the adult stage in one of the replicates of the Ziploc MAP treatment at 120 Gy, suggesting a large-scale test at 150 Gy (the generic dose approved for tephritid fruit flies) was warranted. Identical large-scale tests were conducted with C. capitata at its approved dose, 100 Gy.

Large-Scale Tests. The Ziploc MAP alone treatment significantly reduced survivorship to the adult stage in B. cucurbitae (Table 1), and no C. capitata emerged as adults in the Ziploc MAP alone treatment (Table 2). A radiation dose of 150 Gy applied to B. cucurbitae third instars inside papayas in Ziploc MAP resulted in no survivors to the adult stage in 9,000 treated individuals (Table 1). Likewise, in large-scale tests conducted with C. capitata, a radiation dose of 100 Gy applied to third instars inside papayas in Ziploc MAP resulted in no survivors to the adult stage in 3,500 treated individuals (Table 2). Therefore, the Ziploc MAP producing O₂ levels of 1–4% did not compromise the 150-Gy generic dose for B. cucurbitae or the 100-Gy specific dose for C. capitata.

Phytosanitary Irradiation and MAP Films. The generic radiation dose of 150 Gy for tephritid fruit flies was recommended by using data from more than a dozen species of quarantine concern from four genera (Follett and Armstrong 2004). The relative radiation tolerance of the fruit fly genera was Rhagoletis < Anastrepha < Ceratitis < Bactrocera. Within the Bactrocera, B. cucurbitae appears to be one of the most tolerant species tested to date (Follett and Armstrong 2004, Follett et al. 2011), and therefore, B. cucurbitae is one of the most radiation tolerant of all tephritid fruit fly species. Hence, the results showing that the USDA-APHIS-approved 150-Gy generic dose is not compromised by MAP for B. cucurbitae should extend to other less radiation-tolerant tephritid fruit fly species.

This is the first study of MAP effects on the radiation tolerance of quarantine pests under realistic conditions, that is, by using commercial MAP and infested fruit. However, not all of the experimental conditions were consistent with typical product handling during export. In our experiments, infested ripe fruit were held at room temperature to enhance fruit respiration and rapidly lower O₂ levels, whereas commercially irradiated fruit in MAP would normally be placed in cold storage to slow respiration and extend shelf life until it reached the market. Whereas cold storage is used to preserve fruit quality, it can be a stressor for insect pests that reduces survivorship, particularly after irradiation treatment (Von Windeguth and Gould 1990, Palou et al. 2007). Our experimental conditions produced a worst-case scenario by providing a warm environment for fruit fly development after treatment to maximize the potential survival of B. cucurbitae and C. capitata irradiated with or without MAP. Cold temperature stress during storage may counteract any radioprotective effects of low O₂ from MAP and will add a margin of safety to any irradiation treatment to control quarantine insects.

Extremely low O₂ levels can be detrimental to fruit quality, and in practice, MAP producing 1–4% O₂ is

Table 2. Efficacy of 100-Gy radiation treatment against Ceratitis capitata third instars in papaya using modified atmosphere packaging (Ziploc storage bags) to produce low oxygen conditions

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Measured doses (Gy)</th>
<th>O₂ level (mean ± SE)</th>
<th>CO₂ level (mean ± SE)</th>
<th>No. treated</th>
<th>Pupae (mean ± SE)</th>
<th>Adults emerged (mean ± SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>—</td>
<td>20.9 ± 0.0</td>
<td>0.0</td>
<td>500</td>
<td>357</td>
<td>323</td>
</tr>
<tr>
<td>MAP</td>
<td>—</td>
<td>1.9 ± 0.7</td>
<td>6.2 ± 0.3</td>
<td>500</td>
<td>91</td>
<td>20.5 ± 6.0b</td>
</tr>
<tr>
<td>MAP + Irrad</td>
<td>96–104</td>
<td>2.3 ± 0.3</td>
<td>6.5 ± 0.1</td>
<td>3,800</td>
<td>317</td>
<td>9.8 ± 1.9b</td>
</tr>
</tbody>
</table>

*Means in columns followed by different letters were significantly different by a Tukey’s test at P < 0.05.
avoided for fresh papaya (Yahia et al. 1992) and many other fruits (Kader 2002). The recommended MAP conditions for blueberry, raspberry, and strawberry are 1–4% O₂, whereas 5–13% O₂ is recommended for papaya, mango, rambutan, and orange (Yahia 1998, Beaudry 2000, Kader 2002). Our results suggest the risk of increased radiotolerance is greater for fruit flies on fruit at lower O₂ levels. For fresh produce, MAP is commonly used for berries (strawberry, blueberry, and raspberry), persimmon, sweet cherry, and, sometimes, peach and nectarine. Other products are stored in controlled atmosphere under low O₂ such as apple, pear, and pomegranate (Fonseca and Malcata 2003). Currently, none of the irradiated fruit exported to the United States or from Australia use MAP, but this may change with recent approvals, for example, sweet cherries to the United States from South Africa, and pomegranate to the United States from India. Future research should focus on insect pests of fruits that are currently using MAP (e.g., Drosophila suzukii on small fruits), so that information on the potential for increased radiotolerance and reduced efficacy is available when exports using phytosanitary irradiation start. Additional studies are also needed with several Anastrepha spp. fruit flies, which have specific approved doses (70 Gy) that are considerably lower than the 150-Gy generic dose. Studies are also needed with economically important quarantine insects from other taxa such as Lepidoptera, which tend to be more radiation tolerant than tephritid fruit flies (Follett and Snook 2012).

MAP producing very low O₂ concentrations can increase tephritid fruit fly survivorship during irradiation treatment at certain doses, but should not compromise the efficacy of the approved 150-Gy generic radiation treatment. These results will inform USDA–APHIS, as they consider modifying restrictions on the use of MAP films producing a low O₂ atmosphere for fruit receiving irradiation treatments for tephritid fruit flies. The effect on irradiation efficacy of elevated CO₂ and its interaction with low O₂ will and require further investigation.

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