1-methylcyclopropene and Harvest Maturity Impact ‘Ma’afala’ Breadfruit Postharvest Storage

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Keywords. 1-methylcyclopropene, Artocarpus altilis, climacteric, discoloration, ethylene, ripening, softening

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Breadfruit [Artocarpus altilis (Parks) Fosberg] is consumed at various stages of maturity, but it is most often consumed as a mature unripe fruit (Ragone 1997; Roberts-Nkrumah 2007; Worrell et al. 1998). Ripening of breadfruit follows a pattern typical of a climacteric fruit: show a dramatic respiratory increase, marked increase in ethylene production, and continued ripening after detachment from the tree (Biale and Barcus 1970; Thompson et al. 1974; Williams and Golden 2002). The breadfruit climacteric peak coincides with complete softening of the fruit (Worrell et al. 1998). Breadfruit marketers face the challenge of transporting mature breadfruit to the consumer before it ripens and softens. As breadfruit softens, it becomes susceptible to compression damage and difficult to handle. The climacteric peak and associated softening signal the end of the marketable period of stored breadfruit.

The ethylene response inhibitor 1-methylcyclopropene is used to delay ripening of other climacteric fruit, but it has not been studied in breadfruit (Watkins 2015). 1-MCP inhibits ethylene binding and the progression of ethylene-facilitated ripening processes (Sisler and Blakenship 1994; Watkins 2015). Fruit responses to 1-MCP are highly variable between fruit types. The most common responses include reduced autocatalytic ethylene production, reduced respiration rates, delayed softening, delayed loss of greenness, and delayed breakdown of organic acids (Watkins 2006, 2015). The effects of 1-MCP depend on many factors, including cultivar, dosing, treatment temperature, fruit maturity, stage of fruit ripening, and interactions with fruit disorders (Zhang et al. 2020). Therefore, the effect of 1-MCP on breadfruit quality maintenance may be limited to very specific conditions.

The maturity of a fruit at harvest influences the texture, flavor, nutritional quality, storage duration, and response of the fruit to 1-MCP (Toivonen and Beveridge 2005). 1-MCP is typically less effective for delaying ripening as fruit progress toward ripening, which is likely related to more mature fruit having already initiated the ripening process and associated ethylene production (Cocci et al. 2014; Mir et al. 2001; Sabir and Agar 2011; Wang and Sugar 2015; Zhang et al. 2011). However, the application of 1-MCP before ripening is initiated often compromises ripening and reduces the final quality of the fruit (Huber 2008). Regarding a Caribbean breadfruit cultivar, less mature breadfruit were shown to have higher and delayed postharvest climacteric peaks compared with more mature breadfruit, suggesting that the maturity of breadfruit may interact with ethylene-mediated postharvest ripening (Worrell et al. 1998).

This study examined the effect of harvest maturity and 1-MCP on the postharvest quality of ‘Ma’afala’ breadfruit. An improved understanding of the relationship between harvest maturity and storage is important for commercial growers to determine when to pick breadfruit for the best marketing potential. 1-MCP was included in the study because it is a powerful and accessible postharvest technology that has not been considered for breadfruit.

Materials and Methods

Plant material. ‘Ma’afala’ breadfruit were selected from a 75-tree block of a commercial orchard in Mililani, Oahu, HI (21.43, −158.02; elevation 160 m). The clonally propagated trees were 8 years old and spaced 15 feet (4.5 m), with 30 feet (9.1 m) between rows. The trees were pruned every year or every other year to a height of ~9 feet (2.7 m); they were most recently pruned 3 months before the study.

Fruit sample collection. Breadfruit trees flower continuously over the course of a few months; therefore, inflorescences were tagged at flowering to count the elapsed time before harvest. During the first flowering season (May to June), 75 female inflorescences from randomly selected trees were tagged during flowering (inflorescence equatorial diameter <35 mm). Tagging was repeated after 12 and 24 d, creating three sets of tagged fruit, each with a different flowering date. Depending on the flowering date, 25% to 60% of tagged fruit were aborted during fruit development, leaving a small subset of fruit available at harvest.

Fruit from each of the three flowering dates were randomly selected for harvest at 13, 15, or 17 weeks after flowering. Four fruit were harvested from each flowering date for each harvest period; however, six fruit were harvested during the 13-week harvest period for the first two flowering dates. A total of 40 fruit were harvested: 16 at 13 weeks, 12 at 15 weeks, and 12 at 17 weeks after flowering (Table 1). The fruit were harvested during the morning using pruning shears, and the latex was allowed to drain from the peduncle. After harvest, the fruit were immediately transported to the laboratory, where they were gently washed and allowed to air-dry. After washing, the breadfruit were dipped in a fludioxonil suspension (0.58 g active ingredient/L; Scholar SC; Syngenta, Greensboro, NC, USA) to inhibit surface mold.

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Table 1. Storage traits of ‘Ma’afala’ breadfruit from three flowering dates harvested at three different maturity periods with half of each harvest treated with 1-methylcyclopropene (1-MCP) before storage.

<table>
<thead>
<tr>
<th>Flower date (m/dd)</th>
<th>Harvest period</th>
<th>1-MCP treatment</th>
<th>Days until</th>
<th>Respiratory peak (mg CO₂·kg⁻¹·h⁻¹)</th>
<th>Ethylene peak (mL·kg⁻¹·h⁻¹)</th>
<th>Compressible</th>
<th>Completely soft</th>
<th>Green fraction &lt;25%</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/26</td>
<td>13 wk</td>
<td>1-MCP</td>
<td>2.5 days</td>
<td>611</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>11</td>
</tr>
<tr>
<td>5/26</td>
<td>13 wk</td>
<td>Control</td>
<td>2.5 days</td>
<td>447</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>11</td>
</tr>
<tr>
<td>5/26</td>
<td>13 wk</td>
<td>1-MCP</td>
<td>3 days</td>
<td>431</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>11</td>
</tr>
<tr>
<td>5/26</td>
<td>13 wk</td>
<td>Control</td>
<td>3 days</td>
<td>457</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>11</td>
</tr>
<tr>
<td>5/26</td>
<td>15 wk</td>
<td>1-MCP</td>
<td>2.5 days</td>
<td>694</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>11</td>
</tr>
<tr>
<td>5/26</td>
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<td>15</td>
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<td>15</td>
<td>11</td>
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</tbody>
</table>

Respiration and ethylene measurements.
The initial respiration rate, ethylene production rate, firmness, weight, and color of the breadfruit were measured. To measure the respiration and ethylene production rates, individual breadfruit with weights between 0.4 and 1.2 kg were enclosed in separate, sealed 2.5-L jars and incubated at 22°C (72°F). Duplicate air samples (0.5 or 1 mL) were removed from the jars through rubber septa using a needle and syringe. Carbon dioxide was measured after 30 min of incubation using a flow-through, nondispersive infrared gas analyzer (LH-820 CO₂ Analyzer; LI-COR, Inc. Lincoln, NE, USA) calibrated with 1 mL of a 1% or 0.08% carbon dioxide standard. Ethylene was measured after 120 to 180 min of incubation under the same conditions using a gas chromatograph (Model GC-SA; Shimadzu Scientific Instruments, Columbia, MD, USA) with a photo ionization detector using helium carrier at 27 mL min⁻¹ and calibrated with 0.2 or 1 mL of 10 μL·L⁻¹ ethylene calibration standard. The chromatograph had a 5-8 (1.5 m) × one-eighth-inch (3 mm) diameter, 60/80 alumina column held at 60°C (140°F) with a 120°C (248°F) injection temperature.

Color measurement. Skin color was measured three ways. First, point color was measured using a point colorimeter (Nix ProColor; Nix Sensor Ltd., Hamilton, Ontario, Canada), averaging values from five points around the equator of the fruit. Second, mean color was calculated using ImageJ software to extract the CIELAB values from a photo of the fruit (Schneider et al. 2012; Strock 2021). Third, fractional green space was measured using the Cano-peo iOS smartphone application with a noise reduction value set to 1.10 (Patrignani and Ochsner 2015). The fractional green space was the percent green of the total picture when a single breadfruit was positioned in the photo frame so that its edges were touching the lateral photo edges.

Fruit weight and firmness. Fresh weight was measured using a digital scale (AC-8K; Denver Instrument Company, Arvada, CO, USA). The firmness of the breadfruit was judged by the hand-feel using a 5-point scale as follows: 1, firm; 2, firm with slight compressibility; 3, less firm with visible compressibility; 4, soft and deforms with pressure; and 5, does not hold shape.

1-MCP treatment. After the initial measurements, half of the fruit were treated with 1 μL·L⁻¹ of 1-MCP for 20 h at 25°C (77°F) in a 330-L chamber with a fruit load between 1.2 and 2.2 kg, and the other half were held under similar conditions without 1-MCP. Of a total of 40 fruit, 20 fruit were treated with 1-MCP, including equal amounts from each flowering date and harvest period (Table 1). After 20 h in the enclosed chambers, the breadfruit were stored in the laboratory at 22°C (72°F). Every 2 d, the weight, hand-feel, skin color, respiration rate, and ethylene production of the fruit were evaluated. A fruit was removed from the study when it was completely soft and misshapen or had abundant surface mold.

Statistical analysis. Breadfruit storage was compared using a time-to-event (survival) analysis for various storage events, including...
the climacteric respiratory peak, softening to the point of compressibility (hand-feel rating of 3), complete softening (hand-feel rating of 5), and skin discoloration from green to yellow or brown. Discoloration was defined as less than 25% photo green fraction for the fractional green space measurement and a positive $a^*$ CIELAB value for the point and mean color measurements. For each endpoint type, the Kaplan-Meir survival curve was plotted, and the logarithmic rank (log-rank) test determined the statistical difference between the survival curves of different treatments (Therneau 2021). Harvest period treatments were combined for the 1-MCP treatment survival analysis and vice versa; in both cases, all three flowering dates were pooled. The restricted mean survival time (RMST), which is a representation of the area under the Kaplan-Meir survival curve, was used to quantify differences between survival curves and perform between-group contrasts (Uno et al. 2020). Statistics were performed using R 4.1.2 with survival, survRM2, and survminer (Kassambara et al. 2021; R Core Team 2021; Therneau 2021; Uno et al. 2020).

The peak respiration rate was compared between harvest period treatment groups and 1-MCP treatment groups using a general linear model analysis of variance (ANOVA). There were no interactions of the peak respiration rate with the flowering date, harvest period, or 1-MCP treatment; therefore, fruit were aggregated based on the factor under consideration. One fruit with an outlying respiration rate was removed before the ANOVA (respiration rate, 2025 mg·kg$^{-1}·$h$^{-1}$) (Table 1). For the harvest period, a one-way ANOVA compared the respiration of fruit from three treatment groups (13-, 15- and 17-week harvest periods) with 12, seven, and eight fruit in the respective groups. For 1-MCP, a one-way ANOVA compared the respiration rate of two treatment groups (1-MCP and control) with 19 and 20 fruit in the respective groups.

**Results**

**Effect of harvest period on breadfruit storage.** Fruit from later harvest periods discolor more rapidly than those from early harvest periods (log-rank $P < 0.0001$) (Fig. 1), and there was no difference based on the harvest period in the magnitude of the climacteric respiratory peak (ANOVA $P = 0.34$), timing of the climacteric respiratory peak (log-rank $P = 0.21$), time to becoming compressible (log-rank $P = 0.76$), and time to being completely soft (log-rank $P = 0.13$) (Table 1, Fig. 1). When the discoloration time was determined by the fractional green space, the log-rank test of the survival analysis showed significant differences in the time to discoloration between groups ($P < 0.0001$). The RMSTs of discoloration for fruit harvested at 13, 15, and 17 weeks were 10.4, 7.5, and 5.0 d, respectively (Table 2). A similar pattern was observed when discoloration was measured with a point colorimeter or mean analysis of image pixels.

**Fig. 1.** Relationship between the harvest period and duration of ‘Ma’a’afala’ breadfruit storage considering various endpoints of storage. Graphs show the portion of the total quantity of breadfruit remaining from each harvest period for each day during storage. The breadfruit were pooled from three flowering dates and both 1-methylcyclopropene (1-MCP) treatments. Inflection points (log-rank $P = 0.01$) indicate fruit reaching the storage endpoint and being removed from the study. Plus signs (+) indicate fruit that were removed from the study before reaching the indicated storage endpoint. The $P$ value is the logarithmic rank test coefficient, where $P < 0.05$ is considered a significant difference in storage duration between treatments. Storage duration varied significantly when the endpoint was based on skin discoloration (A), but not when the endpoint was based on the climacteric respiratory peak or firmness (B-D). Skin discoloration was determined as the point when the green fraction of a photo of the breadfruit decreased to less than 25% (A).

**Effect of 1-MCP on breadfruit storage.** Breadfruit treated with 1-MCP required longer to reach the climacteric respiratory peak and soften compared with untreated fruit (Fig. 2). Fruit treated with 1-MCP showed a delayed climacteric respiratory peak (log-rank $P = 0.01$) and increased time to becoming compressible (log-rank $P = 0.02$) and completely soft (log-rank $P < 0.0001$). The RMSTs to the climacteric respiratory peak were 16.0 d for treated fruit and 9.7 d for untreated fruit, with respective ranges of 9 to 19 d (10 d) and 3 to 17 d (14 d). The RMSTs to complete softening were 19.2 d for treated fruit and 11.3 d for untreated fruit, with respective ranges of 13 to 23 d (10 d) and 3 to 21 d (18 d). The RMSTs to becoming compressible were 7.8 d for treated fruit and 5.9 d for untreated fruit, with respective ranges of 5 to 11 d (6 d) and 3 to 9 d (6 d) (Table 2).

There was no difference in the magnitude of the climacteric respiratory peak based on 1-MCP flowering and harvest. Point color refers to the skin color measurement obtained with a colorimeter from five points around the equator of the fruit. Mean color refers to the skin color measurement obtained from the average of all pixels in a photo of the fruit.

**Table 2.** Time to various storage endpoints for ‘Ma’a’afala’ breadfruit separated by harvest period and 1-methylcyclopropene (1-MCP) treatment.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>CO2 peak</th>
<th>Soft</th>
<th>Compressible</th>
<th>Green fraction</th>
<th>Event color</th>
<th>Mean color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvest period</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 wk</td>
<td>12.0</td>
<td>14.9</td>
<td>7.0</td>
<td>10.4* a</td>
<td>11.6* a</td>
<td>11.8* a</td>
</tr>
<tr>
<td>15 wk</td>
<td>14.7</td>
<td>17.1</td>
<td>6.7</td>
<td>7.5* b</td>
<td>10.5* ab</td>
<td>9.3* b</td>
</tr>
<tr>
<td>17 wk</td>
<td>12.0</td>
<td>13.4</td>
<td>6.8</td>
<td>5.0* c</td>
<td>7.8* b</td>
<td>6.8* c</td>
</tr>
<tr>
<td>1-MCP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>9.7* a</td>
<td>11.3* a</td>
<td>5.9* a</td>
<td>7.6</td>
<td>9.1</td>
<td>9.0</td>
</tr>
<tr>
<td>With 1-MCP</td>
<td>16.0* b</td>
<td>19.2* b</td>
<td>7.8* b</td>
<td>8.2</td>
<td>11.2</td>
<td>10.1</td>
</tr>
</tbody>
</table>

The harvest period is the number of weeks between flowering and harvest. Point color refers to the skin color measurement obtained with a colorimeter from five points around the equator of the fruit. Mean color refers to the skin color measurement obtained from the average of all pixels in a photo of the fruit.

* Logarithmic rank test shows a significant treatment effect.

Letters signify significant differences based on the restricted mean survival time between-group contrast.
The delays in the climacteric respiratory peak and softening of breadfruit treated with 1-MCP were also observed for other climacteric fruit treated with 1-MCP (Watkins 2006). However, the delay was smaller than what can be seen with apple which has a much longer untreated storage time. For example, for ‘Delicious’ apple, treatment with 1-MCP was observed to delay the peak ethylene production during storage from 20 to 50 d, which is a 150% delay, whereas for breadfruit, the climacteric respiratory peak was delayed from 9.7 to 16.0 d, which is a 65% delay (Fan et al. 1999). For ‘Hass’ avocado, a fruit with an untreated storage time more similar to that of breadfruit, treatment with 1-MCP was observed to delay the climacteric ethylene peak from 3.8 to 18.7 d, which is a 390% delay, and caused similar delays in softening and color loss (Feng et al. 2000).

The effect of 1-MCP on delaying the climacteric respiratory peak and softening of breadfruit confirmed that these are ethylene-mediated processes in breadfruit. Ethylene was previously shown to be involved in breadfruit ripening by the observation of a temporary increase in the ethylene-forming 1-aminocyclopropane-1-carboxylic acid oxidase as breadfruit flesh softens and yellows (Williams and Golden 2002).

Peak respiration rates did not decrease in breadfruit treated with 1-MCP, as is common for other fruit such as tomato, apple, and avocados (Watkins 2006). The peak CO₂ respiration rates observed were similar to previously reported peak respiration rates for breadfruit of 280 to 660 mg·kg⁻¹·h⁻¹ (Worrell et al. 1998). However, no relationship was observed between the harvest period and magnitude or timing of the climacteric respiratory peak, which contrasts with a report of a Caribbean white-flesh breadfruit cultivar indicating that the climacteric peak of mature breadfruit is delayed and of lesser magnitude compared with slightly immature breadfruit (Worrell et al. 1998).

In addition to delaying the climacteric respiratory peak and softening, 1-MCP delays the change in skin color associated with ripening of fruits such as tomatoes, apples, and avocados (Watkins 2006). However, the rate of breadfruit skin discoloration from green to yellow or brown was unaffected by 1-MCP. This aligns with previous reports that indicated that discoloration of breadfruit is associated with water loss rather than being an ethylene-mediated ripening response (Maharaj and Sankat 1990; Worrell and Carrington 1997). Discoloration is believed to be associated with loss of water from the epidermis, bringing polyphenol oxidase into contact with phenols, resulting in their oxidation to polyphenols (Maharaj and Sankat 1990; Worrell and Carrington 1997).

The duration of time to discoloration decreased during later harvest periods, but this trend was complicated by the initial color of the fruit. Breadfruit harvested at later harvest periods tended to be less green at the time of harvest. Therefore, more rapid discoloration at later harvest periods may be the combined effect of being less green at harvest and being more physiologically prone to discoloration. Regardless of the initial fruit color, fruit from the 13-week harvest period maintained their greenness for the longest period of time.

Discoloration tended to precede softening, especially for fruit treated with 1-MCP. In markets where fruit quality is judged by appearance, the storage duration may be limited by the loss of greenness instead of fruit softening. However, the discolored but firm fruit remain valuable for processing, and a previous survey of fresh-market breadfruit consumers suggested that some discoloration may be acceptable (Molimau-Samasoni et al. 2020).

Conclusions

The delays in the climacteric respiratory peak and softening of breadfruit treated with 1-MCP were observed for other climacteric fruit treated with 1-MCP (Watkins 2006). However, the delay was smaller than what can be seen with apple which has a much longer untreated storage time. For example, for ‘Delicious’ apple, treatment with 1-MCP was observed to delay the peak ethylene production during storage from 20 to 50 d, which is a 150% delay, whereas for breadfruit, the climacteric respiratory peak was delayed from 9.7 to 16.0 d, which is a 65% delay (Fan et al. 1999). For ‘Hass’ avocado, a fruit with an untreated storage time more similar to that of breadfruit, treatment with 1-MCP was observed to delay the climacteric ethylene peak from 3.8 to 18.7 d, which is a 390% delay, and caused similar delays in softening and color loss (Feng et al. 2000).

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