MICROWAVE-VAPOUR HEAT DISINFESTATION ON ORIENTAL FRUIT FLY EGGS IN MANGOES

J. VARITH\textsuperscript{1,4}, W. SIRIKAJORNJARU\textsuperscript{2} and T. KIATSIRIROAT\textsuperscript{3}

\textsuperscript{1}Department of Agricultural and Food Engineering
\textsuperscript{2}Department of Plant Protection
Maejo University
Chiang Mai, 50290, Thailand
\textsuperscript{3}Department of Mechanical Engineering
Chiang Mai University
Chiang Mai, Thailand

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ABSTRACT

The objective of this research was to develop a microwave-vapor heat treatment (MW-VHT) for mangoes (\textit{Mangifera indica} L.) cv. Namdokmai Si Thong to disinfest the oriental fruit fly, \textit{Bactrocera dorsalis} (Hendel). The mortality of oriental fruit fly eggs and quality acceptability characterized by thermal-death-time and thermal-quality-time overlay plots were initially obtained by hot-water immersion. Two treatments within a range of acceptable quality were selected for inoculation experiments to confirm MW-VHT process. The acceptable range was temperature ranging from 46 to 55°C with time ranging from 2 to 20 min. The MW-VHT using microwave for preheating followed by vapor for holding processes effectively disinfested oriental fruit fly eggs. Changes in physiochemical properties of mangoes, e.g., color, titratable acid (TA), total soluble solid (TSS), TSS/TA and firmness, of MW-VHT-treated mangoes were not significantly different (\(P \geq 0.05\)) from physiochemical properties of the nontreated mangoes. MW-VHT resulted in less heat damage of mangoes than conventional vapor heat treatment (VHT) and shortened process time more than 90\% during the preheating period. MW-VHT also retained equivalent or better lethality of oriental fruit fly eggs than did conventional VHT.

\textsuperscript{4} Corresponding author. TEL: +66-53-875-515; FAX: +66-53-498-902; EMAIL: jatuphon@mju.ac.th
PRACTICAL APPLICATIONS

This research provided preliminary guidance to apply microwave (MW) for mango disinfection process. Oriental fruit fly eggs was disinfested with MW preheating to disinfest temperature between 46–55°C within less than 1 minute, followed by the conventional vapor heat treatment (VHT) for holding process. The higher temperature for MW preheating, the less holding time for VHT holding process. To minimize damage on mango, treatment temperature must be less than 55°C. Future work on MW-VHT process on oriental fruit fly in other stages will provide the completed protocol necessary for pest quarantine treatment. On-line MW-VHT treatment is of high potential for the commercial application as well.

INTRODUCTION

The export of Thai mangoes (*Mangifera indica* L.) is growing due to its high selling price. In 2004, the export value per kilogram of mangoes increased about 58% compared to the export value in 2003 (Office of Agriculture Economics 2005). One of the major problems of the premium markets such as Japan and Australia with Thai mangoes is the presence of the oriental fruit fly, *Bactrocera dorsalis* (Hendel), inside mangoes. Currently, vapor heat treatment (VHT) is a common method to control oriental fruit fly. Recently, an interest in electromagnetic treatments which generate heat inside fruits, e.g., microwave and radio frequency, to control the fruit pests, is emerging (Ikediala *et al.* 1999; Mitcham *et al.* 2004; Hansen *et al.* 2006). Microwave rapidly generates heat in foods and may be used as an alternative to or in conjunction with conventional VHT to disinfect oriental fruit fly in mangoes.

According to the regulations for mangoes exported to Japan, general guidelines to disinfect oriental fruit fly in mangoes using VHT were accomplished by maintaining the core temperature of mango at 47°C for 20 min during VHT. This VHT treatment achieved the estimated thermal-death-time (TDT) higher than 5D for the first instars (16.45 min) and the egg of oriental fruit fly (<8.91 min) (Jang 1986), but slightly lower than 5D for the third instars (22.3 min) (Jang 1991). An increase in internal temperature of mango up to 47°C by VHT requires longer than 45 min, hence the mangoes may be susceptible to heat damage. With rapid microwave heating, high-temperature-short-time (HTST) treatments are possible to shorten the treatment time while retaining lethality effect greater than 5D. The HTST concept is extensively used in food processing to minimize thermal degradation of food quality (Stumbo 1973; Lund 1977; Holdsworth 1997) and
may be applicable to insect disinfestation processes. Tang et al. (2000) proposed the HTST thermal disinfestation using radio frequency on codling moth larvae in walnuts with the temperature ranging from 50 to 54°C. The third instars codling moth in cherry were also studied by Ikediala et al. (1999) where the 915-MHz microwave treatment of cherries achieved the fruit core temperatures of 45, 50 or 55°C, but the quality of the fruit was most promising at temperatures less than 50°C. The potential of using radio frequency and microwave heating for pest control in fruits was also reported elsewhere, e.g., Bing cherry (Monzon et al. 2006) or walnuts (Wang et al. 2002, 2005; Mitcham et al. 2004). However, we are unaware of any literature reporting on microwave combined with VHT to disinfest oriental fruit fly in mangoes.

With regard to mango disinfestation, HTST may provide several advantages over conventional heating in terms of shortening of preheating time, equivalent or better quality retention, energy minimization and insect mortality assurance due to the HTST treatment. Even though a drawback of microwave is nonuniform heating, knowing the microwave nature where the wave concentrates in the mango will help overcome uneven heating problem and assist with the process design. Varith and Kiatsiriroat (2004) studied the microwave heating on mangoes cv. Chokanan with 2,450-MHz/800-W microwave oven and observed an increase of internal temperature up to 46°C within 40 s. The heat distribution inside the mangoes depended on mango orientation, microwave power and treatment time. The horizontal-positioned mangoes treated with 50% microwave power yielded better heat distribution than vertical-positioned mangoes did.

Continuing with this research, our purpose is to preliminarily develop a microwave-vapor heat treatment (MW-VHT) to disinfest oriental fruit fly eggs in mangoes cv. Namdokmai Si Thong, the export cultivar. The first experiment explored the TDT and quality kinetics at temperatures higher than 48°C. The MW-VHT process was then developed based on the survival of oriental fruit fly and quality kinetics. Finally, experiments were conducted to confirm the MW-VHT disinfestation method along with minimal changes in mango quality after the MW-VHT process. Information obtained from this research may provide guidance to a full-ranged quarantine process development of oriental fruit fly using MW-VHT in the future.

MATERIALS AND METHODS

Materials

Mangoes (M. indica L.) cv. Namdokmai Si Thong (330 g/mango) freshly harvested at approximately 100 days after full bloom from two
orchards in Chiang Mai, Thailand, were used in this research. The first orchard provided domestic-graded mangoes while the second orchard offered export-graded mangoes. During the fruiting stage, intact export-graded mangoes were enfolded in horticultural envelopes while the domestic-graded mangoes were enfolded in regular white paper. The differences in fruiting stage handlings yielded a major difference in the color of the mango skin where domestic-graded mangoes were predominantly green in color while the export-graded mangoes were predominantly yellow ($\Delta E^* = 72.3$), although there was no difference in flesh color ($\Delta E^* = 2.3$). Other physical-chemical properties of mangoes between two orchards were not different (Table 1). After harvesting, each lot of mangoes was stored at $13^\circ C/90\%$ relative humidity (RH) for 48 h prior to the experiment. The experiment was accomplished within 72 h to avoid the effect of ripening. Eight hours prior to the test, the mangoes were equilibrated in the laboratory at $25^\circ C/60\%$ RH.

### TABLE 1.
BASIC THERMOPHYSICAL PROPERTIES OF TWO CROPS OF MANGOES CV.
NAMDOKMAI SI THONG AT $25^\circ C$

<table>
<thead>
<tr>
<th>Thermophysical property</th>
<th>Value</th>
<th>Unit</th>
<th>Measuring device/method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fruit whole mass (m)</td>
<td>$0.313 \pm 0.009$</td>
<td>kg</td>
<td>0.01-g precision balance</td>
</tr>
<tr>
<td>Density of flesh ($p$)</td>
<td>$973.0 \pm 29.0$</td>
<td>kg/m$^3$</td>
<td>Mass/volume of flesh cylinder*</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>$1.006 \pm 0.004$</td>
<td>–</td>
<td>Water replacement</td>
</tr>
<tr>
<td>Thermal conductivity ($k$)</td>
<td>$0.474 \pm 0.015$</td>
<td>W/m-C</td>
<td>Line-heat source†</td>
</tr>
<tr>
<td>Specific heat ($C_p$)</td>
<td>$3.795 \pm 0.211$</td>
<td>kJ/kg-C</td>
<td>Differential scanning calorimetry‡</td>
</tr>
<tr>
<td>Firmness</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Failure force</td>
<td>$3.27 \pm 0.52$</td>
<td>N</td>
<td>Texture analyzer with $\phi 6$-mm probe using ASAE standards</td>
</tr>
<tr>
<td>Apparent elastic modulus</td>
<td>$1.69 \pm 0.31$</td>
<td>MPa</td>
<td></td>
</tr>
<tr>
<td>Total soluble solid content</td>
<td>$8.05 \pm 0.74$</td>
<td>°Brix</td>
<td>Refractometer</td>
</tr>
<tr>
<td>Titratable acid</td>
<td>$0.034 \pm 0.013$</td>
<td>%</td>
<td>Indicator method</td>
</tr>
<tr>
<td>Color of peel/flesh 1 (export)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L^*$</td>
<td>$64.1 \pm 2.2/71.2 \pm 3.4$</td>
<td></td>
<td>Spectrophotometer model MiniScan XE (Hunter Associates Laboratory, Inc., Reston, VA)</td>
</tr>
<tr>
<td>$a^*$</td>
<td>$-4.1 \pm 1.9/-0.9 \pm 0.2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b^*$</td>
<td>$34.9 \pm 1.8/17.6 \pm 4.5$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Color of peel/flesh 2 (domestic)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L^*$</td>
<td>$66.6 \pm 3.6/69.2 \pm 2.4$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a^*$</td>
<td>$-9.6 \pm 3.5/-1.2 \pm 0.5$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b^*$</td>
<td>$37.2 \pm 2.8/16.5 \pm 4.3$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Mean values with SD of six mangoes from each orchard.
† Probe made by Thermal Logic, Pullman, WA; thermal power/unit length = 3.40 W/m; guideline by Sweat and Haugh (1974).
‡ Guideline by TA Instruments (1998); scan rate of 1C/min.
Mass Rearing of Oriental Fruit Fly

Oriental fruit fly eggs were obtained from the Department of Agriculture, Ministry of Agriculture and Cooperatives, Bangkok, Thailand. Pupae were reared in the Department of Plant Protection, Maejo University, in screen cages at 25–27°C/70% RH. The flies that emerged were provided with sugar, hydrolyzed yeast protein and water. Eggs were collected from mature females (10–14 days old) during a 1-h period. The eggs used in the mortality study were transferred into an agar gel box (size of 30 \( \times \) 55 \( \times \) 20 mm) while those used in inoculation experiments were transferred to the mangoes. For each treatment, the control eggs emerged more than 98%.

Study of Mortality and Quality Acceptability

The mortality of oriental fruit fly eggs was studied using hot-water immersion technique. Two hundred eggs were incubated on a thin layer of agar gel inside the plastic boxes (50 eggs each). For each treatment, four incubated boxes were immersed into a water bath (model MD16-G, Julabo Labortechnik GmbH, Seelbach, Germany) with an accuracy of \( \pm 0.5^\circ \text{C} \) under controlled temperatures of 46, 48, 51 or 55°C for 2, 5, 12 or 20 min. This resulted in total production of 3,200 eggs.

For quality acceptability, eight mangoes (domestic-graded) per treatment were immersed in hot water bath under the desired temperatures of 46, 48, 51 and 55°C for 2, 5, 12 and 20 min, equivalent to the mortality study. After the hot-water immersion, the treated mangoes were hydrocooled with 25°C sprayed water for 30 min. The treated mangoes were then stored at 13°C/90% RH for 3 days before assessing the heat damage as percentage of skin browning area.

To quantify the acceptable temperature and time for disinfestation treatment, the TDT plot of insect mortality was established, overlaying with thermal-quality-time (TQT) plot to identify the acceptable area. The TDT plot exhibited ranges of oriental fruit fly egg mortality while the TQT plot indicated the percentage of heat damage area observed on mango peels. An acceptable disinfestation process was an area in the overlay plot where the insect was 100% disinfested and there was unobservable damage on the mango. Treatments with acceptable temperature and time were selected for disinfestation process development in the next experiment.

Development of MW-VHT Thermal Disinfestation Process

Preheating during come-up period was accomplished by the MW treatment adopted from Varith and Kiatsiriroat (2004) where mangoes cv. Chokanan treated with MW power of 400 W for 40 s increased the internal
Export-graded mangoes were treated with 50% MW power using 2,450-MHz/800-W microwave oven model R-254 (Sharp Co., Ltd., Tokyo, Japan). The MW preheat treatment was divided into two steps. First, one mango was placed in a horizontal position on a polypropylene support at the center of the oven and rotated while being heated with MW power of 400 W for 40 s (Fig. 1a), denoted as MW20/20a. Second, the same mango was placed approximately 20 mm away from the exit of the waveguide without rotation (Fig. 1b). A glass container of 1,800 cm³/25°C water was placed beside the mango to absorb the microwave after penetrating through the mango to reduce the microwave reflection to the mango. This step provided a virtual one-dimensional radiation focusing at the mango cheek, the thickest part of mangoes subjected to the slowest heating during conventional VHT heating. The second treatment was denoted as MW10/10b. Figure 1 schematically demonstrates the steps of MW preheating process.

For the third process, six MW-preheated mangoes were heated in a vapor (saturated steam) chamber for the VHT holding process where the chamber temperature was controlled at 55 ± 1°C. During treatments, the mangoes were removed after five periods and cut in half. Thermography images of the halved mangoes were quickly taken to observe step-wise heat distribution during MW and VHT periods using a thermal imaging camera (model IR FlexCam Pro, Infrared Solutions, Inc., Plymouth, MN). After MW treatment, the slowest heating spot during VHT holding process was identified and used as a reference for VHT holding temperatures. After preheating and holding period of VHT, the mangoes were cooled with showering water at 25°C for 30 min. MW-VHT preliminary experiments were replicated six times with six mangoes for each treatment. The treated mangoes were stored at 13°C/90% RH for 24 h and assessed for the percentage of damage on peel and flesh.
Confirmation Experiments on MW-VHT and VHT Disinfestation Processes: Insect Mortality and Fruit Quality

Two selected time–temperature combinations in acceptable range of TDT and TQT curves were selected for disinfestation experiment. Each domestic-graded mango was inoculated with 50 eggs at the slowest heating spot and sealed with clear tape to prevent leakage of condensed vapor into inoculation area. Two MW-VHTs and one conventional VHT using 55C saturated vapor were performed for disinfestation treatments as follows:

**MW-VHT1.** The preheating process was composed of MW20/20a, followed by MW10/10b and a VHT 55C holding process for 18 min. The cooling process was carried out by showering water at 25C for 30 min.

**MW-VHT2.** The preheating process was completed with a process equivalent to MW-VHT1 but with a shorter VHT 55C holding time of 7 min. The cooling process was performed by showering water at 25C for 30 min.

**VHT.** The preheating process was performed by vapor at 55C using a temperature probe near the pit as a control point. A holding process of 18 min began when control point reached 47C in a vapor temperature of 55C. The cooling process was performed by showering water at 25C for 30 min.

Each treatment was replicated six times. The treated mangoes were stored at 25C/70% RH to observe the emergence of larvae. The mortality of oriental fruit fly eggs (reciprocal of percent of egg emergence) was reported. To examine the quality changes over a period of storage time, two MW-VHTs and one VHT were selected on export-graded mangoes with six replications of six mangoes per treatment. After treatment, the mangoes were stored at 13C/80% RH for 13 days during quality evaluation.

**Quality Change Evaluation**

Quality evaluation of color of peel and flesh, firmness, titratable acid (TA) and total soluble solids (TSS) was determined on six mangoes from each replication every third day of storage. Details of quality measurement are as follows.

A spectrophotometer (model MiniScan XE, Hunter Associates Laboratory, Inc., Reston, VA) was used to measure the color of mangoes. The measuring condition was set using 10/45° angle with D65 illuminant. The spectrophotometer was standardized with white and black plates following the factory protocol. CIE scale ($L^* - a^* - b^*$) was reported as the color indices. $L^*$ indicated lightness scaled from 0 to 100; $a^*$ indicated red ($- a^*$) to green ($+ a^*$); and $b^*$ indicated blue ($- b^*$) to yellow ($+ b^*$) scale.
The firmness of mangoes was determined using a texture analyzer (model TA-XT2i, Texture Technology, Godalming, Surrey, U.K.) with a semispherical probe diameter of 8 mm equivalent to a Magness–Taylor penetration probe. Penetration test was performed with a crosshead speed of 1 mm/s. The force–distance profiles were obtained and used to determine the firmness with two parameters, e.g., maximum force during penetration and apparent elastic modulus. The maximum force was the peak force before failure of mango tissue occurred during the penetration test. The apparent elastic modulus was determined using the data from the same force–distance profile following the guideline of ASAE S386.4 DEC00 (ASAE Standards 2003) as:

\[
E = \frac{0.338K_{u}^{2}F(1-\mu^{2})}{D^{3}}\left(\frac{4}{d}\right)^{1/2}
\]

where \(E\) = apparent modulus of elasticity (Pa); \(D\) = deformation (m); \(\mu\) = Poisson’s ratio (assumed to be 0.45); \(F\) = force (N); \(K_{u}\) = dimensionless factor (= 1.351 for a flat surface-indenter test); and \(d\) = diameter of curvature of the spherical indenter.

TA was determined by indicator method following the guideline of AOAC 942.15. (AOAC 1996). Mango juice of 5 mL was titrated with 0.2-N NaOH solution using phenolphthalein as an indicator. Titration reached the end point when the pink color of the indicator appeared. TA was expressed in terms of milliequivalent of citric acid per mL of juice extract.

TSS was determined with a hand refractometer (model N-1α, Atego Co., Ltd, Tokyo, Japan).

Heat damage assessment on treated mangoes was determined from digital image using a tool in Adobe Reader version 8.0.0 (Adobe Systems Inc., San Jose, CA). The percentage of damage was assessed from the ratio of browning area of the peel or whitening area of the flesh to the total area of mangoes captured by the digital camera.

Quality parameters were analyzed using analysis of variance using StatView version 5.0 (SAS Institute, Inc., Cary, NC) with 95% confidence interval. Quality parameters were reported significantly different when \(P \leq 0.05\).

**RESULTS AND DISCUSSION**

**Mortality of Oriental Fruit Fly Eggs and Quality of Mangoes**

Oriental fruit flies in the egg stage were susceptible to 100% disinfested at 46°C with a holding time of 20 min. Because disinfestation temperatures
greater than 48°C with holding of time at least 2 min also yielded 100% mortality, these thermal treatments were adequate to apply as the conditions for the MW-VHT disinfestation treatments. Mangoes undergoing thermal treatment at 51°C with holding time up to 12 min were not damaged due to heat. Mangoes subjected to thermal treatment at 51°C for 20 min and 55°C for 5 min were susceptible to damage less than 5%. With a temperature of 55°C for a holding time longer than 5 min, the heat damage in mango increased no more than 15%. The TDT and TQT overlay plot (Fig. 2) presents disinfection treatment as a shaded area where solid line represents the minimum threshold of 100% mortality and dashed line represents the maximum threshold of quality acceptance. To assure undamaged mangoes, the maximum threshold of quality acceptance was approximately at 55°C with a holding time for 2 min, or lower temperature at 48°C with a holding time for 20 min. Meanwhile, the mortality of oriental fruit fly eggs was 100% with the minimum threshold of 46°C for 20 min or at a higher temperature of 48°C for 2 min. The thermal treatments within the shaded area in between maximum threshold of quality acceptability and minimum threshold of oriental fruit fly egg mortality were adequate for HTST disinfestation development using an MW-VHT process.
MW-VHT Disinfestation Process

MW20/20a increases the internal temperature of mangoes initially at 25 to 54°C (Fig. 3). However, heat was concentrated near the stem and base of the mangoes. The slowest heating spot was observed at the cheek of the mango as indicated in Fig. 3. With the addition of the MW10/10b treatment, the temperature increased around the center of the mangoes as well as at the slowest heating spot. Therefore, after preheating with MW20/20a and MW10/10b treatments, the internal temperature of mangoes increased to a range of 51–57°C, while the skin temperature attained about 46°C. As the disinfestation treatment proceeded to the VHT holding treatment, the internal temperature started to decrease but remained greater than 47°C. Thermography imaging after 1 min of MW preheating and 2 min of VHT revealed that the internal temperature reached a plateau at a temperature greater than 47°C throughout the mango. Therefore, it is suggested that the holding period for disinfestation heating may require two extra minutes in VHT chamber to equalize the internal temperature for mangoes. Following MW preheating treatments, temperatures at the stem, lower cheek and base of mangoes (points 1, 3 and 4 in Fig. 3, accordingly) increased faster than the temperature at the upper cheek.

FIG. 3. TEMPERATURE HISTORY OF MICROWAVE-VAPOR HEAT TREATMENT (MW-VHT) MANGOES PREHEATED WITH MW20/20a AND MW10/10b (DASHED LINE), FOLLOWED BY VHT OF 55°C (SOLID LINE)

Note: Locations of temperature taken inside mango corresponding to numbers indicated in thermography image. Gray-color intensity in thermography image is coded in Celsius according to temperature scale bar.
area (point 2) when subjected to external convection VHT heating. An increase in temperatures was consistent through replications; therefore, point 2 at the cheek or point 3 at the slowest heating spot may be used as the control points for mangoes during MW-VHT thermal disinfection process.

**Confirmation of MW-VHT and VHT Disinfection Process**

MW-VHT1 and MW-VHT2 yielded 100% mortality of the oriental fruit fly inoculated into the mango (Table 2). VHT provided 96.2% mortality close to predicted survival from the prediction of TDT plot (Fig. 2) and also approximating the kinetics study of Jang (1986) with a prediction of 90% mortality. Mangoes treated with MW-VHT2 exhibited unobservable skin damage, but skin damage was observed after MW-VHT1 and VHT thermal treatments. However, a slight internal tissue damage (~1%) of MW-VHT2 mangoes was observed as a consequence of heat concentrated at the base of the pit. This flesh damage was observed as a white-disrupted dried tissue but not progressive to be rotten. Internal tissue damage of the MW-VHT1-treated mango was more severe than the tissue damage in the MW-VHT2-treated mangoes, while damage in the VHT-treated mangoes was most severe with progressive shrinkage of tissue at the base of the mango.

Considering a time-wise comparison, the preheating periods of MW-VHT1 and MW-VHT2 were 2 min of MW treatment and additional 2 min of VHT, a total of 4 min. The preheating period of VHT required approximately 45 min with 55°C saturated vapor to reach the internal temperature of 47°C. Thus, MW-VHT shortened the process time during the preheating period by about

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Mortality(%)</th>
<th>Fruit damage (%)</th>
<th>General appearances</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>External</td>
<td>Internal</td>
</tr>
<tr>
<td>MW-VHT1</td>
<td>100</td>
<td>15.2</td>
<td>11.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>External skin browning with internal disrupted tissue at the stem and base of the pit but not progressive</td>
<td></td>
</tr>
<tr>
<td>MW-VHT2</td>
<td>100</td>
<td>Unobservable</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>damage</td>
<td>Unobservable damage skin with slightly internal disrupted tissue at the apex of pit but not progressive</td>
</tr>
<tr>
<td>VHT47</td>
<td>96.2</td>
<td>16.2</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>External skin browning, progressive damage with time and internal cooked tissue at the base of fruit</td>
<td></td>
</tr>
</tbody>
</table>
91%. Fig. 4 demonstrates heating–cooling temperature profiles of MW-VHT and VHT treatments of mangoes using 55°C vapor as a heat source.

**Quality of MW-VHT Mangoes**

The TA of mangoes treated with MW-VHT, VHT and the control significantly decreased \((P \leq 0.05)\) during storage at 13°C/80% RH for 10 days (Fig. 5). There was a slight increase in TA at day 13. TSS representing the sucrose of mangoes significantly increased \((P \leq 0.05)\). There was no significant difference \((P > 0.05)\) in TA and TSS among mangoes treated with different treatments. Therefore, MW-VHT1, MW-VHT2 and VHT thermal disinfestations did not affect the changes in structure or composition of mangoes during selected periods of storage, except for minimal heat damage on the mangoes.

Firmness as defined by maximum force at rupture from penetration test and apparent elastic modulus significantly decreased \((P \leq 0.05)\) during 13 days of storage (Fig. 6). No significant difference in firmness \((P > 0.05)\) among mangoes subjected to MW-VHT and VHT thermal disinfestation was observed. Mangoes treated with MW-VHT, VHT and the control were normally soften as mangoes were undergoing ripening process, corresponding to the measured firmness values associated with physiochemical changes of mangoes.

During 13 days in storage, \(L^*\) (lightness index) and \(a^*\) (red-green index) of mango peels significantly decreased \((P \leq 0.05)\) while \(b^*\) (blue-yellow
index) significantly increased \((P \leq 0.05)\) (Fig. 7). Decreases in \(L^*\) and \(a^*\) mean the mango peels were darker and less green, while an increase in \(b^*\) means the mango peels were more yellow. Changes in color indices agree with our observation where mango peels were slightly more saturated yellow during 13 days of storage. There was no significant difference \((P > 0.05)\) among color indices of mango after MW-VHT and VHT thermal treatments. Similar trends of color changes in peels were observed in the mango flesh during 13 days of storage. Both MW-VHT and VHT disinfestation treatments resulted in mangoes with similar physiochemical changes as observed on nontreated mangoes.
FIG. 7. COLOR OF MANGO PEELS AFTER MICROWAVE-VAPOR HEAT TREATMENT (MW-VHT) AND VHT TREATMENTS IN 13°C/80% RELATIVE HUMIDITY STORAGE

Error bars indicate standard errors of mean.
CONCLUSIONS

A TDT and TQT overlay plot for HTST was established to identify the range of disinfestation time and temperature. The oriental fruit fly eggs were effectively disinfested with temperatures higher than 48°C after a minimum holding time of 2 min. Mangoes were susceptible to heat damage with a maximum threshold of quality acceptance at 55°C for a holding time for 2 min.

An MW preheating treatment of MW20/20a followed by MW10/10b increased the internal temperatures of mangoes to 54°C. The internal temperatures started to decrease due to the diffusion of heat outward to the skin after MW preheating treatment. The addition of a VHT heating equalized the temperature throughout the mango after MW preheating treatment, retaining the temperature higher than 47°C.

Mangoes inoculated with oriental fruit fly eggs treated with MW-VHT2 resulted in 100% mortality of oriental fruit fly eggs and were minimally susceptible to heat damage (≈1%). Mangoes treated with either MW-VHTs or VHT were undergoing the same physiochemical changes as in untreated mangoes observed from similar changes in firmness, TA, TSS and color of peels and flesh.

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