not consistent in the 2 experiments.

Frequency measurements had the lowest coefficient of variation, while the factor $f^2$ had the highest. The CVs for these values tended to be lower than those found for force-to-shear, work-to-shear and taste panel methods (Table 3).

Strong interrelationships among the dynamic elastic factors are evident in both cultivars in Experiment 1 (Table 4), but these relationships are not as apparent in Experiment 2 (Table 5).

In Experiment 1, frequency, quotient and $f^2$ values correlated significantly with tenderness, crispness and juiciness in ‘Winesap’ and with crispness in ‘Golden Delicious’ apples (Table 4). Further significant relationships were found with the sphere values in both cultivars (Table 4). However, none of these correlations were repeated in Experiment 2 (Table 5).

The complexity of the equipment required to measure dynamic elastic properties and the difficulties in attaching equipment to the individual apple account, at least in part, for the greater variability in these data as compared to the sphere results. Finney (5) has pointed out that the dynamic elastic index $f^2$ has potential value as a nondestructive measure of apple texture but is less reliable than the taste panel or pressure test (Magness-Taylor) techniques. Our results substantiate Finney’s observations.

The static sphere test described herein is a nondestructive method of measuring textural quality of raw apples. In ‘Winesap’ apples it correlates with force-to-shear and work-to-shear values as well as with crispness, tenderness and juiciness as evaluated by the sensory method. Since the results for ‘Golden Delicious’ apples were not as positive as for ‘Winesap’ apples, tests should be made with several other cultivars representing a wide spectrum of apple texture. The dynamic elastic property method was neither as precise nor as consistent as the sphere test.


Low Pressure (Hypobaric) Storage of Limes1

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Additional index words. reduced atmospheric pressure, Citrus latifolia, postharvest storage, yellowing, decay, fungicides

Abstract. ‘Tahiti’ (‘Persian’) limes (Citrus latifolia Tanaka) retained green color, juice content, and flavor acceptable for marketing and had a low incidence of decay during storage at a low atmospheric pressure of 170 mm Hg for up to 6 weeks at 10.0°C or 15.6°C and a relative humidity (RH) of 98–100%. Check fruits turned yellow within 3 weeks at normal atmospheric pressure (760 mm Hg). Limes stored for 4 weeks at 170 mm Hg at 2.2°C and 98–100% RH developed as much chilling injury as comparable limes stored at normal atmospheric pressure. Limes coated with wax containing 0.1% of either thiaobendazole or benomyl remained green and suitable for marketing after 3–4 weeks at 170 mm Hg at 21.1°C.

Tolle (11) defined low pressure (LP) or hypobaric storage as refrigerated storage of produce under gas pressures totaling less than 760 mm Hg. Stoddard and Hummel (10), who first reported the use of LP storage, showed that the normal storage life of fresh produce could be extended by installation of an LP unit within a standard refrigerator. The pressures they used were 600 mm Hg — only slightly less than normal atmospheric pressure at sea level (760 mm Hg). Burg and Burg (2), using pressures down to 125 mm Hg, reported marked prolongation of the storage life of various fruits and vegetables. For example, ‘Tahiti’ (‘Persian’) limes were still green after 8 weeks at 150 mm Hg and 15°C, whereas 50% of control fruits turned yellow in 10 days. Spalding and Reeder (8) showed that limes stored at 152 mm Hg were still in excellent marketing condition after 6 weeks at 10°C and were far superior to similar limes stored in air or in a controlled atmosphere of either 5% O2 with 7% CO2

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Literature Cited

or 21% O₂ with 7% CO₂.

We now present information on the optimum pressure range for storage of limes and compare the effectiveness of that pressure for maintaining the quality of limes at various temp. Fungicidal wax treatments were evaluated for their effects on decay development, shriveling and weight loss of limes stored under LP.

Materials and Methods

**Limes.** Freshly harvested 'Tahiti' limes were selected for uniform appearance and size (5.0–5.4 cm diam) from bulk bins at local packinghouses. Limes free of decay and blemishes were sorted by color into similar samples of 30 limes for each storage treatment. Rind color of limes was measured by comparison with color plates specially prepared to simulate the range of lime colors and having numerical ratings from 9.03 to 1.00 (dark green to yellow). A fruit was assigned the value of a color plate if at least 75% of the lime matched the plate. The color ratings of the plates were calculated from Hunter Color-Difference meter readings by use of a formula (15) for computing color from objective color measurement. Each value was multiplied by −0.1389 to give the yellowest plate a rating of 1.00. After color sorting each sample was placed in a plastic mesh bag for ease of handling. Three orchard lots were used for replication of treatments.

Acceptability of limes was based on a minimum color index of 3.18 (corresponding to USDA, PL-2, lower limit “mixed” used by federal fruit inspectors), a minimum juice content of 42%, and freedom from rind disorders and decay (12). All limes initially met or exceeded standards for U.S. No. 1 grade (12).

Each sample of limes was evaluated for general appearance, decay and rind color before and after storage. Rind thickness, juice content, total acids, soluble solids, ascorbic acid, and flavor were determined on a representative sample of 10 decay-free limes for each treatment replicate before and after storage. Rind thickness of lime halves was measured at 3 points around the equator of the fruit. Juice content, total acids (expressed as citric acid), soluble solids (expressed as sucrose) and ascorbic acid were analyzed by standard methods (1, 7). Refractometer readings for soluble solids were corrected for acid content (9). We evaluated flavor informally and rated it acceptable if objectionable off-flavors were not detected. Samples for tasting were prepared by diluting a composite sample to 20% by volume with tap water. Each sample was then assigned a code number.

Fungicides in wax were tested by dipping limes in a 0.1% (w/v) suspension of either methyl 1-(butylcarbamoyl)-2-benzimidazolcarbamate (benomyl) or 2(4'-thiazolyl)-benzimidazole (thiabendazole), referred to here as TBZ, prepared in a water emulsion wax (Sealbrite 71, American Machinery Corp., Orlando, FL) previously diluted to approx 10% solids by addition of an equal volume of distilled water. The dipped limes were rolled dry on a wire grid placed over a stream of hot air (ca. 50°C) blowing from small electric space heaters. The limes were rated for shriveling after storage by a subjective system in which 1=trace (barely noticeable), 2=slight (slightly noticeable), 3=moderate (obvious, but still acceptable), and 4=severe (not salable). Each bag of limes was weighed before and after storage to determine weight loss.

Chilling injury (CI) to the rind was rated in 3 lots of limes stored under LP (170 mm Hg) or normal atmospheric pressure (NP) at 2.2°C for 4 weeks followed by holding under NP at 21.1°C for an additional 4 days to allow time for complete development of all Cl symptoms. Sixty limes were used for each treatment. A subjective rating system was used in which 1=none, 2=slight, 3=moderate, 4=slight (barely noticeable), 7=severe, and 9=extreme Cl (5).

Temperatures used in this study were converted to °C from °F and are accurate to ± 0.5°C.

**LP apparatus.** The equipment used to store limes under LP is diagrammed in Fig. 1. High humidity in the chambers (60 liter drums) was maintained by bubbling incoming air through an air-diffusion stone submerged in a tray of water in the bottom of each chamber. Relative humidity in each chamber was measured with an electric hygrometer (Hygrodynamics, Inc., Silver Spring, MD). Air flow through each chamber was measured with a flow meter and adjusted with a needle valve at the inlet to the chamber to provide 1 air change/hr. Pressure within each chamber was measured with a mercury manometer and was regulated with a cartesian diver type vacuum regulator (Roger Gilmont Instruments, Inc., Great Neck, NY).

![Fig. 1. Schematic diagram of equipment used for low pressure storage tests. For convenience, only 2 chambers are shown, but more can be added to the system. Components are identified as follows: (1) vacuum pump (35 liters/min), (2) exhaust to outdoors, (3) needle valve to shut off vacuum, (4) copper manifold with individual needle valves for up to 5 chambers, (5) cartesian diver type vacuum regulator, (6) chamber suction port, (7) chamber inlet with needle valve to regulate rate of air change measured with a flow meter, (8) sandstone air diffuser, (9) polyethylene dishpan filled with water and fitted with a metal-mesh lid to support fruit, (10) steel drum (60-liter capacity) with gasket and lid, (11) vacuum measurement port, (12) needle valve for bleeding vacuum measurement line, (13) mercury manometer with scale in 1 mm increments from 0 to 760 mm and an adjustable baseline, (14) humidity sensor, (15) humidity sensor line connectors, and (16) electric hygrometer.](image-url)
Table 1. Quality of 'Tahiti' limes stored 6 weeks at 10°C at various atmospheric pressures.2

<table>
<thead>
<tr>
<th>Storage pressure (mm Hg)</th>
<th>Rind color index</th>
<th>Juice content (%)</th>
<th>Rind thickness (mm)</th>
<th>Decay (%)</th>
<th>Soluble solidsx</th>
<th>Total acids w</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prestorage</td>
<td>4.61a</td>
<td>46.7bc</td>
<td>2.7ab</td>
<td>0.0a</td>
<td>9.6a</td>
<td>6.8a</td>
</tr>
<tr>
<td>760</td>
<td>1.44b</td>
<td>49.8a</td>
<td>2.5b</td>
<td>3.3a</td>
<td>9.1a</td>
<td>6.7a</td>
</tr>
<tr>
<td>190</td>
<td>4.51a</td>
<td>47.5b</td>
<td>2.6b</td>
<td>2.2a</td>
<td>9.7a</td>
<td>6.5a</td>
</tr>
<tr>
<td>152</td>
<td>4.36a</td>
<td>47.3b</td>
<td>2.6b</td>
<td>2.2a</td>
<td>9.2a</td>
<td>6.5a</td>
</tr>
<tr>
<td>114</td>
<td>4.39a</td>
<td>45.3c</td>
<td>2.9a</td>
<td>4.4a</td>
<td>9.1a</td>
<td>6.4a</td>
</tr>
</tbody>
</table>

*Each figure is the mean for 90 limes (3 replications of 30 limes per treatment). Mean separation in columns by Duncan's multiple range test, 5% level.

*Based on comparison with color plates in which, for example, yellow is 1.00 and "good green" (USDA, PL-2, 1962) is 4.71.

*xExpressed as sucrose.

wTotal titratable acidity expressed as citric acid.

Results

Quality of limes stored under various pressures with temp constant. Limes stored at either 152 or 190 mm Hg for 6 weeks at 10°C maintained excellent quality and appearance and did not differ significantly in color, juice content, rind-thickness, percentage decay, soluble solids, and total titratable acidity (Table 1). Limes stored at 114 mm Hg were also of acceptable quality, but had significantly lower juice content, significantly thicker rinds, and tended to develop slightly more decay than limes stored at higher pressures. Control limes stored at NP of 760 mm Hg turned yellow within 3 weeks and were, therefore, not acceptable. The data suggest that under the conditions tested limes can be stored equally well within the range of 152 to 190 mm Hg. Consequently, all subsequent tests were run at 170 mm Hg (LP).

Quality of limes stored at various temp with pressure constant. Limes stored under NP turned yellow rapidly and only about half were acceptably green after 2 weeks at 15.6°C or 21.1°C or after approx 3 weeks at 10.0°C (Fig. 2). In contrast, 100%, 80%, and 50% of limes stored under LP were acceptable when stored for 6 weeks at 10.0°C, 15.6°C, and 21.1°C, respectively. Thus, even at 21.1°C, the desirable green rind surface was retained 3 times as long under LP as under NP. The incidence of decay in limes stored for 6 weeks under NP did not differ significantly from that of limes stored under LP, regardless of temp (Fig. 3). The incidence of decay was much higher in limes stored at 21.1°C with 98–100% RH under NP and 81–83% RH under LP than in limes stored at either 10.0°C or 15.6°C with 98–100% RH.

Juice content (initially 49.4–49.7%) of limes decreased significantly during the 6-week storage under LP at 10.0°C, 15.6°C, or 21.1°C, but was well above the minimum 42% volume permitted for shipping and did not vary significantly with temp (data not shown). Soluble solids (initially 8.6%) and total titratable acidity (initially 6.2%) did not differ significantly from prestorage concn and did not vary significantly with temp (data not shown).

The percentage of acceptable limes based on color, juice content, and freedom from decay and off-flavors was higher for limes stored under LP for 6 weeks than for similar limes stored under NP for 2 weeks at the same temp (Fig. 4). Quality decreased sharply in limes stored under LP for more than 6 weeks. Limes stored best under LP at 10.0°C.

Chilling injury of the rinds of limes stored under LP at 2.2°C for 4 weeks followed by 4 days under NP at 21.1°C did not differ in appearance or average rating (6.4 or moderate CI) from injury of similar limes stored under NP continuously (data not shown). No chilling injury developed in limes stored at 10°C.

Weight loss and decay of limes treated with a fungicidal wax. In an initial 3-week test at 21.1°C, limes treated with wax containing either 0.1% benomyl or 0.1% TBZ did not develop decay during storage under LP or NP, whereas untreated limes developed 9% decay under LP and 36% decay under NP. Decay in the preceding and following test was mainly green mold rot caused by *Penicillium digitatum* Sacc. and stem-end rot caused by *Phomopsis citri* Fawc. In the test shown in Table 2, 0.1% TBZ in wax protected limes from decay during 4 weeks under LP at 21.1°C. Unwaxed limes developed significantly less decay.
Table 2. Quality of 'Tahiti' limes treated with a fungicidal wax and stored under normal (NP) or low pressure (LP) for 4 weeks at 21.1°C followed by holding for 1 week under NP at 21.1°C.*

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Decay (%)</th>
<th>% weight loss</th>
<th>Shriveling index</th>
<th>Rind color index</th>
</tr>
</thead>
<tbody>
<tr>
<td>NP (760 mm Hg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No wax</td>
<td>19a</td>
<td>2.5a</td>
<td>0.7a</td>
<td>1.24a</td>
</tr>
<tr>
<td>Wax + TBZu</td>
<td>3c</td>
<td>4bc</td>
<td>1.7a</td>
<td>1.75c</td>
</tr>
<tr>
<td>LP (170 mm Hg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No wax</td>
<td>8bc</td>
<td>4.0a</td>
<td>1.3a</td>
<td>4.24a</td>
</tr>
<tr>
<td>Wax + TBZ</td>
<td>0c</td>
<td>3c</td>
<td>1.7a</td>
<td>4.23a</td>
</tr>
</tbody>
</table>

*Each figure is the mean for 75 limes (3 replications of 25 limes per treatment). Mean separation among values in the 2 columns under each heading is by Duncan’s multiple range test, 5% level.

YOn removal from storage.

XOne week under NP at 21.1°C after removal from storage.

In the rating system, 1=trace, 2=slight, 3=moderate (obvious, but acceptable), 4=severe (not saleable).

See Table 1, footnote Y. Mean prestorage color index = 4.57.

UTBZ (0.1% w/v) in a 1:1 dilution of a water emulsion wax (Sealbrite 71).

Discussion

Previous data (8) showed that limes stored at 228 mm Hg were significantly less green than limes stored at 152 mm Hg. These earlier published results together with present results with limes suggest that a pressure range of 152–190 mm Hg is most suitable for maintenance of quality of limes for up to 6 weeks at 10°C. LP storage markedly retarded the yellowing of limes, a major problem during NP storage (3). Since the LP system used did not provide protection against CI, we suggest a minimum nonchilling temp of about 10°C during storage or shipping. Results indicate that limes could be safely stored and shipped at 10.0–15.6°C and 170 mm Hg. A temp as high as 21.1°C could even be used in conjunction with LP for 2–4 weeks, provided a fungicidal wax is applied to the limes before storage.

The higher incidence of decay in limes stored under LP at 21.1°C than in similar limes stored at 10.0°C and 15.6°C is probably due mainly to the effect of temp on fungal growth. However, since the RH in LP chambers was not the same at all 3 temp, humidity possibly contributed to the observed differences along the lines shown by van den Berg and Lentz (13) in which less decay was found in vegetables stored at 98–100% RH than at 90–95% RH. This possibility is not likely because the RH in the NP controls was the same (98–100%) at all 3 temp. Moreover, unreported results of Spalding and Reeder show no significant difference between the incidence of decay of avocados stored under LP at 80–85% RH and similar avocados stored under the same LP at 98–100% RH.

The low RH of 81–83% obtained in the LP system at 21.1°C did not cause excessive moisture loss from limes. Shriveling of limes during LP storage for up to 4 weeks at 21.1°C was not sufficiently detracting from appearance to reduce salability. However, results indicated that use of a fungicidal wax similar to that used with oranges (6) would be advantageous for control of decay during storage and marketing. Wax-coated limes are exceptionally susceptible to low-O2 injury (4). The recommended pressure range for limes, 152–190 mm Hg, corresponding to 4.2–5.2% O2, caused no apparent injury in our tests. A pressure of 76 mm Hg, corresponding to 2.1% O2, was previously shown to increase decay of limes (8). The increased decay at pressures below 152 mm Hg may be due to an increased susceptibility of the tissues to microorganisms brought on by low-O2 injury. The sour rot organism (Geotrichum candidum Lk. ex Pers.), a common cause of decay in limes stored in CA or an LP of 76 mm Hg (8), grows faster under low-O2 than in air (14). Our storage tests suggest that an LP of 152–190 mm Hg retards senescence in limes without injuring them and thereby helps maintain a high resistance to fungal infection. Both low-O2 and removal of ethylene were suggested to be involved in the retardation of ripening (2).

Low pressure appears to be the most promising method for extending the storage and shipping life of limes that has thus far been devised. The system is presently under commercial development and further evaluation should be done in a commercial size unit. Laboratory results suggest that use of the LP system by industry would allow long-distance surface shipment of limes to Europe and Asia. Use of LP warehouses for storage of limes could provide more flexibility in marketing than is currently available and could be economically attractive.

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