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Development and Application of Citrus Storage Technologies with Concurrent Consideration of Fruit Quality Preservation, Energy Use, and Costs

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Abstract

Three varieties of citrus fruits, namely: 'Liucheng' orange (*Citrus sinensis*), 'Ponkan' mandarin (*C. reticulata*) and 'Tankan' tangor (*C. reticulata* × *C. sinensis*) are grown in large quantities in Taiwan. They have the potential to be stored for several months under proper conditions. Desirable temperature for long-term storage is 15℃, but the fruits can tolerate short spans of lower non-freezing temperatures. High relative humidity (85 – 95%) is desirable if the fruits are not kept in plastic bags. Many pre-harvest factors and pre-storage treatments can affect the storability and post-storage quality of the fruits. Although refrigerated storage is most reliable for quality preservation and storage loss control for the fruits, it may only be needed for long terms of storage. Common storage and cave storage, which are less costly and less energy consuming, are adequate alternatives for shorter periods of storage. Selecting cooler locations to store fruits may also have a merit.

Major Citrus Varieties Grown in Taiwan

Citrus production is widespread in sub-tropical and tropical zones of the world. Being a sub-tropical island, Taiwan is abundant in citrus fruits. Major citrus varieties commercially grown in Taiwan include 'Liucheng' orange (*Citrus sinensis* (L.) Osbeck), 'Ponkan' mandarin (*C. reticulata* Blanco), 'Tankan' tangor (*C. reticulata* × *C. sinensis*), 'Wentan' pummelo (*C. grandis* (L.) Osbeck) and 'Eureka' lemon (*C. limon* (L.) Burm., f.). These five varieties count for much (86 %) of the total citrus production (473,068 M.T. in 2007) of the island. Many other varieties are produced only in small quantities each.

Lemon is an acid-type citrus fruit and 'Wentan' pummelo is an early season variety which is consumed shortly after harvest. Therefore, only three varieties of citrus, namely: 'Liucheng' orange, 'Ponkan' mandarin, and 'Tankan' tangor will be targeted in the following discussion.

A Need of Storage and Losses in Storage

Commercial harvesting season encompasses 'Ponkan' mandarin in November, 'Liucheng' orange in December, and 'Tankan' tangor in January. Earlier harvest sacrifices fruit quality, while delayed harvest often encounters severe fruit drop and damages by insects (particularly fruit flies) and birds in addition to interference with flowering and fruit growth of the crop of subsequent year (Liu et al., 1998). Without proper storage, the fruit has only about one month of marketable life after harvest. In other words, the total marketing period of these three varieties of citrus fruits will be about four months without storage. That situation will create an over supply at the harvest season and lack of supply shortly after harvest. Therefore, a proper storage will be necessary to extend the marketing period while easing off the market pressure at the peak harvesting season.

Storage does generate some losses of fruits. The magnitude of losses is highly variable depending on variety and source of fruits, storage facilities and management, and duration of storage. It varies from one year to another also. Although no statistical or even estimate data are available, field observations revealed substantial storage losses occurred each year. Some fruits become totally unmarketable after storage; and some others decline in quality and market value. From growers' point of view, storage is profitable only if the increase in total sale revenue is greater than storage losses plus storage costs. Therefore, minimizing storage losses is a must.

Major storage troubles are button (calyx plus short stem attached to the fruit) browning or abscission, granulation of juice vesicles, albedo (mesocarp) breakdown or creasing, decay, and stem-end rind breakdown or aging. Eckert (1978) described four kinds of most common postharvest diseases in citrus fruits: stem-end rots (incited by *Diplodia natalenses* or *Phomopsis citri*), *Alternaria* rot, *Phytophthora* brown rot and *Penicillium* molds incited decay. We found all of them with stem-end rots and *Prencillium* decay being most prevailing in Taiwan citrus fruits.

In Quest of Optimum Storage Conditions

In order to develop practical storage technologies for our citrus fruits, we engaged in a series of research as well as field observations to find out optimum storage conditions and treatments for the fruits. We also wanted to know what would be the maximum storage life span for each variety under the optimum storage condition. Some of our major endeavors and findings are presented below.

Pre-storage Treatments

Citrus fruit growers as well as some commercial storage house operators in Taiwan have been engaged in citrus storage for years. They gradually developed the technologies either by try and error or in reference of earlier research results. Currently adopted pre-storage treatments for freshly harvested citrus fruits were generally sound according to our observation.

The harvested citrus fruits, with or without pre-sorting (to remove culls) or pre-sizing, are dipped briefly in a liquid mixture containing a fungicide and a plant growth regulator. The most commonly used fungicide was thiabendazole (at a concentration of 800 mg • L^{-1} or ppm) in the past and is iminoctadine (at a concentration of 125 mg • L^{-1}) at present. The latter is very effective in controlling decay under good storage conditions. A plant growth regulator, 2,4-D, added into the dipping mixture provides some protection from premature button senescence which may encourage fruit decay. Various concentrations of 2,4-D have been applied by different users and for different varieties. Our experimental data indicated that 10 ppm had a striking effect in ‘Ponkan’ mandarin, but 25 to 50 ppm provided better protections and 100 ppm near perfect protection even under an adverse storage condition (data not shown). For long-term storage of ‘Liucheng’ oranges, 50 to 100 ppm might be necessary for satisfactory protection (data not shown). According to our experiences, 25 ppm was adequate for ‘Tankan’ tangor, however (data not shown). We found little, if any, adverse side effects of 2,4-D applied at above mentioned adequate concentrations. Application of up to 50 ppm for ‘Ponkan’ had residue levels well below our national tolerance (2 ppm) according to our most recent studies (data not shown).

After dipping and fruit-surface drying in the ambient air, the citrus fruits are wrapped in small polyethylene (0.02 mm in film thickness) bags. Larger fruits are wrapped individually, one fruit per bag. Two to three smaller fruits may be wrapped in a bag, however. The open end of each bag is then closed either by machine sealing or by hand twisting. Bagging in polyethylene films prevent the fruit from excessive desiccation and avoid spreading molds from one fruit to another via direct peel contact.

Storage Temperature

Grierson and Ben-Yehoshua (1986) stated “typical storage conditions for citrus fruits” including storage temperatures of 0 - 6.7℃ for oranges and 6 - 7℃ for ‘Coorg’ mandarins and the estimated storage life of the former being 6 - 8 weeks and that of the latter 8 weeks. We found such storage life span too short to satisfy our need and the storage temperature ranges unsuitable for longer storage of the varieties grown in Taiwan. We therefore conducted many experiments in search of the optimum storage temperature for each of our major citrus varieties. We still dare not say “optimum” temperatures have been found, but we have had sound basis to recommend a “proper” or “desirable” temperature for long-term storage for each variety.

‘Liucheng’ orange tolerated 0℃ or 5℃ cold storage for 30 to 45 days, but chilling symptoms appeared in longer storage periods (Liu, 2009). Storing ‘Liucheng’ at 10℃ for 60 days or longer also developed low temperature disorders (Liu, 2009) or frequent excessive decay (Liu et al., 1997). Repeated trials of 5-month long storage confirmed that 15℃ was a good temperature while 20℃ resulted in higher weight losses and occasional higher incidence of decay (Liu, 2005; Liu et al., 1997).

Storing ‘Ponkan’ mandarins at 5℃ for 3 months resulted in severe chilling injury followed by decay which caused almost a total loss of the fruit (Liu et al., 1998). When the results of 3 to 4 months of storage at 10, 12.5, 15 and 20℃ were compared, ‘Ponkan’ mandarins stored at 12.5° and 15℃ had the least storage losses and had the best quality preservation, while those stored at 10℃ appeared light chilling symptoms or slight off-flavors (Liu et al., 1998).

‘Tankan’ tangors stored at 0℃ for 3 months or 5℃ for 4 months developed severe chilling injuries (Liu et al., 1998). When the results of 4 to 5 months of storage at 10, 12.5, 15 and 20℃ were compared, 20℃ resulted in higher decay and higher weight losses, while the lower storage temperature the more soluble solids depression during storage (Liu et al., 1998). It seemed, therefore, that 15℃ was the best choice for long term storage of 'Tankan'.

Based on these experiment results plus some observations made in more recent years, 15℃ is a good storage temperature for all 3 major citrus varieties grown in Taiwan. Lowering the storage temperature to 12.5℃ had little benefits for 'Ponkan' mandarin and 'Liucheng' orange while having some risks of accelerating quality loss in 'Tankan' tangor. Storing any of these 3 varieties continuously at or below 10℃ is undesirable. Storing them at 20℃ generally accelerated decay incidence and weight loss but the remaining fruits had acceptable quality.

Storage Humidity

Grierson and Ben-Yehoshua (1986) stated "typical" storage relative humidity for oranges and mandarins being 85-90%. Since practically all citrus fruits for long-term storage in Taiwan were pre-bagged in water-impermeable polyethylene films, transpirational water loss is not a problem even in storage rooms without humidity control. In one of our experiments, 'Ponkan' mandarins lost only 3.5% of weight in 3 months of storage and 'Liucheng' orange and 'Tankan' tangor lost about 5% of weight in 5 months of storage (Fig. 1). Nevertheless we conducted a series of experiments on the effect of humidity on storage weight losses of our three major citrus varieties without bagging. We demonstrated the close relationship between storage relative humidity and fruit weight loss as well as linear regressions between the weight loss and vapor pressure deficit (VPD) in 1 to 3 months of storage experiments (Liu et al., 2005a).

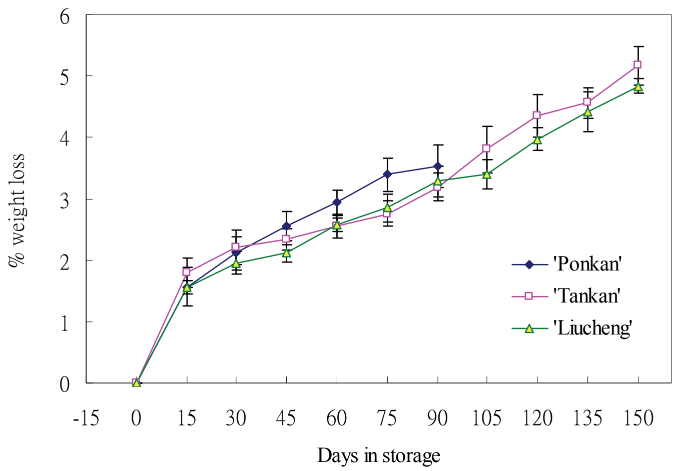

Fig. 1. Weight losses of 'Ponkan' mamdarin, 'Tankan' tangor, and 'Liucheng' orange during storage. Means of 4 tree-replicates (20 fruits per replicate) with standard deviations. (Adopted from Liu et al., 2005).

Wells (1962) reported that "at a constant temperature and for limited periods, the rate of weight loss (of fruits) increased about 50 percent for each 100 percent increase in vapor pressure deficit." That result of 6 - 8 days of storage experiments has been cited extensively by postharvest physiologists worldwide. However, a constant percentage of weight-loss increase for each 100% increase in VPD was not found in our 1 to 3 months of storage experiments. On average of 5 experiments for 3 varieties of citrus fruits, the rate of weight loss increased 58.2±3.7%, 73.8±3.2% and 80.6±2.4% when VPD increased from 0.5 to 1.0 mbar, 1.0 to 2.0 mbar and 1.5 to 3.0 mbar, respectively (Liu et al., 2005a). At the higher VPD, the higher rate of weight-loss increase by doubling the VPD.

For practical applications, we recommend at least 85 to 90% (preferably 90%) RH for 1 month of storage and 90 to 95% (preferably 95%) RH for ≧2 months of storage when un-bagged citrus fruits are stored at 15℃. The weight losses under such conditions were below 5% and the fruit did not shrivel for up to 2 months of storage for 'Ponkan' mandarin and up to 3 months of storage for 'Liucheng' orange and 'Tankan' tangor (Liu et al., 2005a).

Changes in Fruit Quality during Storage

Fruit quality factors include appearance, texture and flavor. We made comprehensive studies on changes in rind color, button condition, juice content, soluble solids in juice, and acidity in the three varieties of citrus fruits in long-term storage (Liu et al., 2005). Parts of the results are summarized below.

'Ponkan' mandarins are half-green and half-yellow while 'Liucheng' oranges are nearly all yellow and 'Tankan' tangor is uniformly yellow orange at harvest. Stewart and Wheaton (1971) reported that Hunter a/b values were highly correlated with USDA color standards and visual color observations for citrus fruits, higher values representing more yellow to yellow orange. We used CIELAB a*/b*, which has similar meaning of Hunter a/b, to represent the color of our citrus varieties. 'Ponkan' mandarins had a rapid increase of a*/b* in the first month and slow increases of that in the second and third month of storage at 15℃ (Fig. 2) corresponding to rind color changes from partially green to completely yellow and then adding more orange hue. 'Liucheng' orange appeared a slow and steady increase of a*/b* for the first 3 months and broke the increasing trend afterward (Fig. 2). 'Tankan' tangors only showed a small increase of a*/b* during the first month and no further increase in later months of storage (Fig. 2). After the citrus rind has turned to yellow, further increase of a*/b* means tuning toward more orange in color.

'Ponkan' mandarins had little change in juice contents in 3 months of storage (Fig. 3). 'Liucheng' oranges and 'Tankan' tangors showed little changes in juice contents in 4 months of storage but had a tendency to decline slightly in the fifth month (Fig. 3).

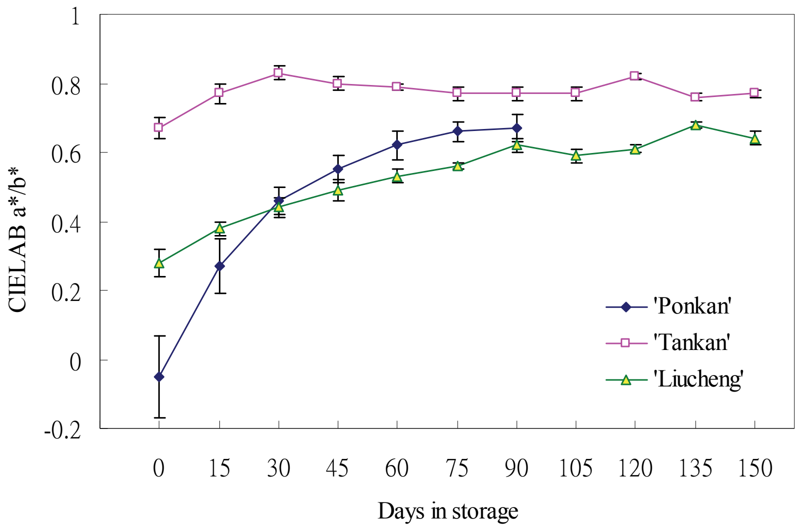

Fig. 2. Changes in CIELAB a*/b* values of rinds of ‘Ponkan’ mandarin (—◆—◆—), ‘Tankan’ tangor (—□—□—) and ‘Liucheng’ orange (—△—△—) in storage. Means of 4 tree-replicates (20 fruits per replicate) with standard deviations. (Adopted from Liu et al., 2005).

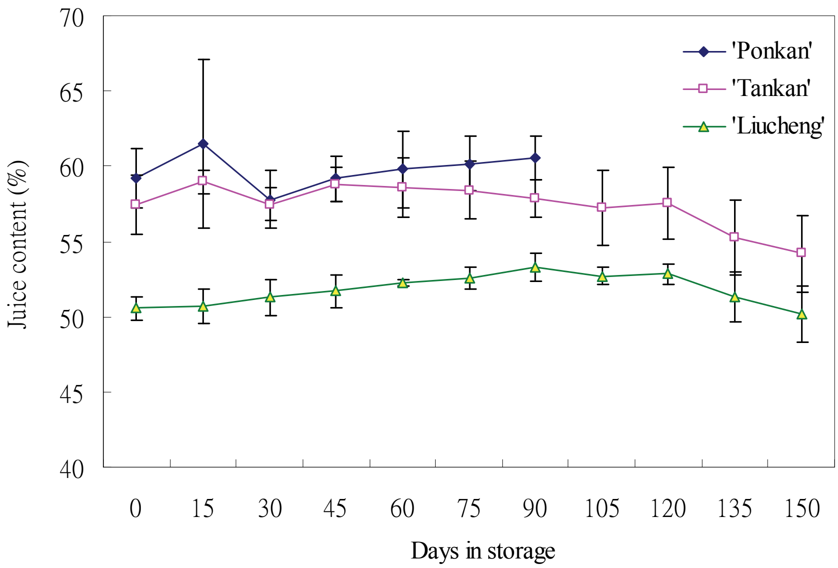

Fig. 3. Changes in juice contents of ‘Ponkan’ mandarin (—◆—◆—), ‘Tankan’ tangor (—□—□—), and ‘Liucheng’ orange (—△—△—) in storage. Means of 4 tree-replicates (20 fruits per replicate) with standard deviations. Data of 2003-2004 storage season.

All three varieties of citrus fruits had a trend of slight increases of soluble solids contents in the first month and slow decreases of soluble solids contents in the later months of storage (Fig. 4). 'Ponkan' mandarins had a slow decline of acidity in the first month and more rapid decline of acidity in later months of storage, while 'Liucheng' oranges and 'Tankan' tangors had a steady slow decline in acidity throughout the 5-month storage period (Fig. 5). When soluble solids and acidity values were converted into total soluble solids / titratable acidity (TSS/TA) ratios, 'Ponkan' mandarins had a slow increase in the first month and rapid increases in the second and third month while 'Liucheng' oranges and 'Tankan' tangors had steady slow increases throughout the 5-month storage period (Fig. 6).

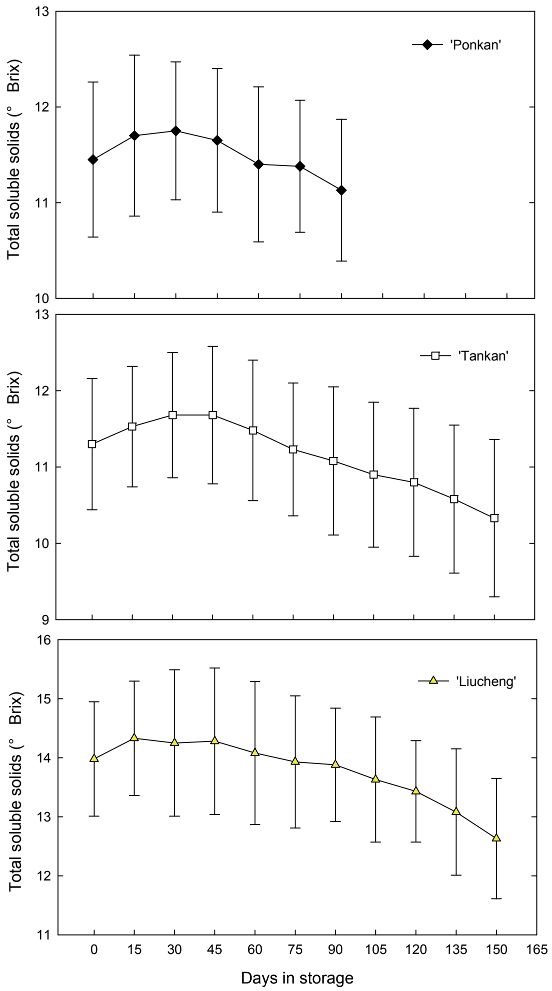

Fig. 4. Changes of total soluble solids in 'Ponkan' mandarin, 'Tankan' tangor, and 'Liucheng' orange in storage. Means of 4 tree-replicates (20 fruits per replicate) with standard deviations. (Adopted from Liu et al., 2005).

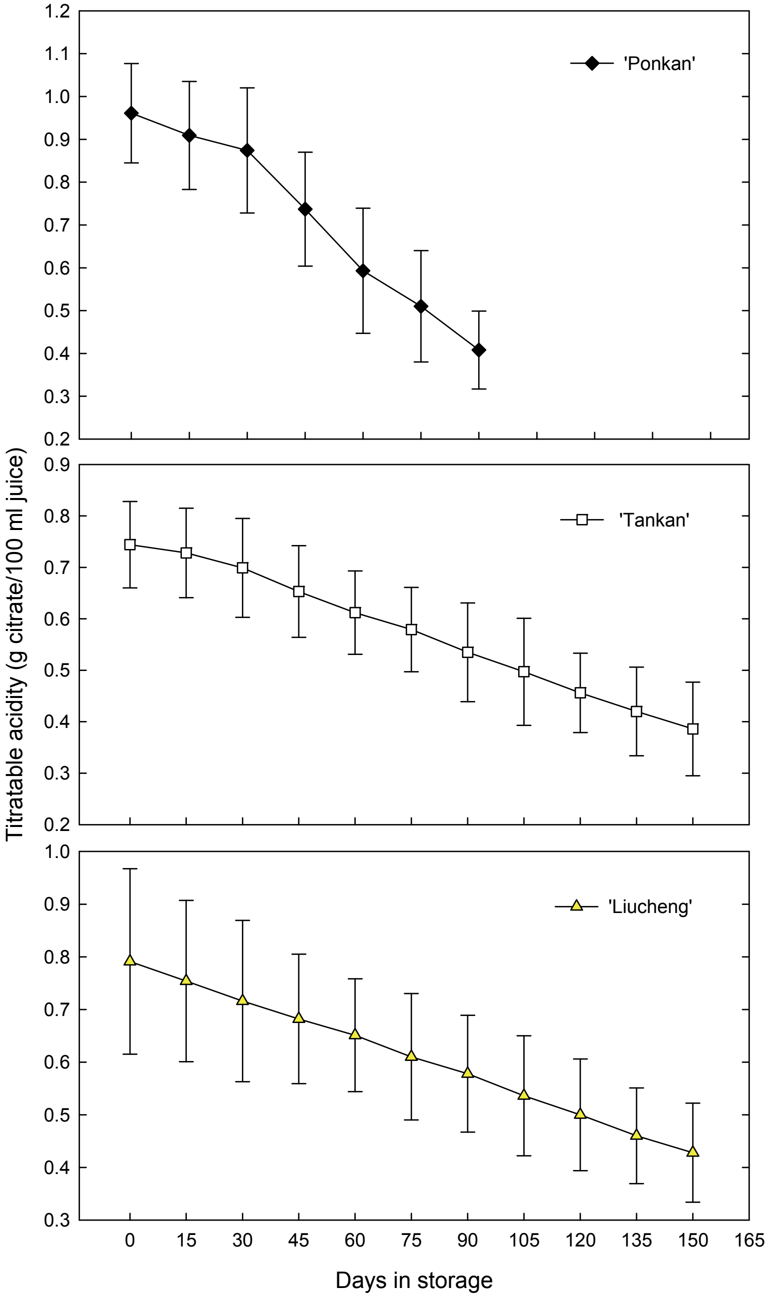

Fig. 5. Decreasing trends of titratable acidity in ‘Ponkan’ mandarin, ‘Tankan’ tangor, and ‘Liucheng’ orange in storage. Means of 4 tree-replicates (20 fruits per replicate) with standard deviations. (Adopted from Liu et al., 2005).

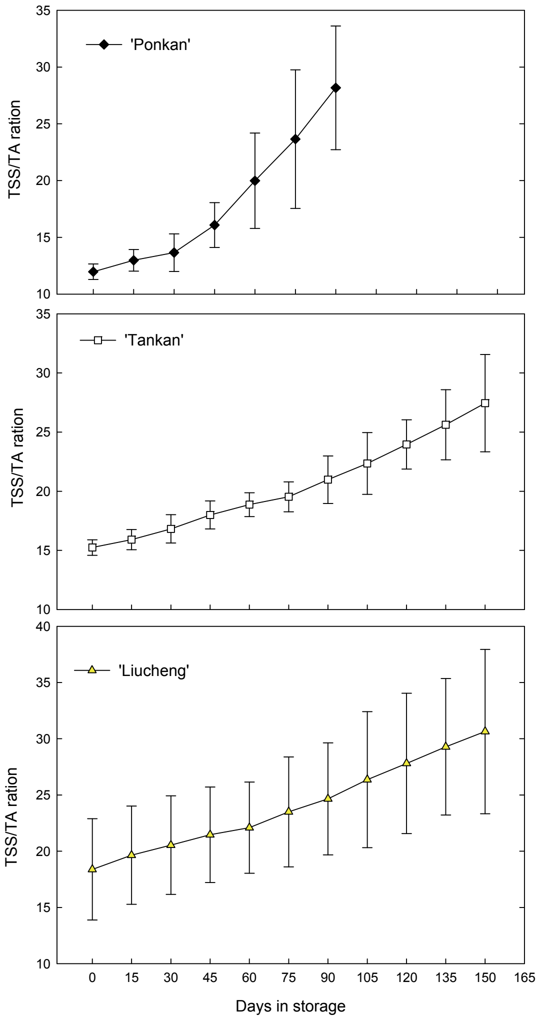

Fig. 6. Increasing trends of TSS/TA ratio of ‘Ponkan’ mandarin, ‘Tankan’ tangor, and ‘Liucheng’ orange in storage. Means of 4 tree-replicates (20 fruits per replicate) with standard deviations. (Adopted from Liu et al., 2005).

Most consumers prefer deeper orange to pale yellow or greenish yellow rind color in oranges and mandarins. Most consumers also prefer juicier citrus fruits to dryer ones. Therefore, higher a*/b*values as well as higher juice contents are desirable quality attributes. However, people’s preferences differ greatly in sweetness and sourness in citrus fruits, and therefore, difficult to define what SS and TA numbers represent the best flavor of citrus fruits. In the authors own judgment, the eating quality of all above discussed three varieties of citrus fruits improved in the first month of storage and then declined at various rates in later months of storage.

Traits of Fruit that Affect the Quality and Storability

Harvest maturity greatly affected the rind color, juice content, soluble solids and acidity, and therefore, the overall quality of three varieties of citrus fruits (Liu et al., 1998). Harvest maturity also affected decay losses in some citrus fruits. 'Ponkan' mandarins harvested late (in early December) had a tendency to have more decay than similar fruits harvested earlier (in November) when they were subjected to long-term storage (Liu, et al., 1997). 'Liucheng' oranges harvested late (near the end of December and early January) also had a trend to have more decay than similar fruits harvested earlier (earlier dates in December) when they were subjected to 4 to 5 months of storage (Liu et a1., 1997). However, no consistent relationship between harvesting date and decay in 4 to 5 months of storage was found in 'Tankan' tangors when the fruits were harvested in January through mid-February (Liu et al., 1997).

Fruit size has significant effects on the storability of citrus fruits. Large (21~23 cm in equatorial perimeter) 'Liucheng' oranges had an earlier incidence and severer cases of granulation in storage than medium sized (19~21 cm in perimeter) ones (Liu, 2009). Similar trend was noticed in 'Ponkan' mandarins and 'Tankan' tangors although no statistical data have been collected.

Fruit location on the tree before harvest affects both fruit quality (Sites and Reitz, 1949; Cohen, 1988) and storability of citrus fruits. We found that 'Ponkan' mandarins and 'Liucheng' oranges harvested from outside or on the canopy of the trees had less decay in storage and had higher soluble solids contents after storage when compared with those harvested from inside of trees (Table 1). The effects of fruit location within trees on the fruit button senescence, granulation, and acidity were less significant (data not shown).

Table 1. Effect of fruit location within the tree on fruit decay in storage and soluble solids contents after storage of 'Ponkan' mandarin and 'Liucheng' orange.[1]

Varity	Duration of storage (months)	Fruit location on the tree	Total number of fruits in each treatment[2]	Decay (%)	Soluble solids (°Brix)[3]
'Ponkan' mandarin	3	Outside and Canopy	282	1.1	10.0
		Inside	161	8.1	9.5
'Liucheng' orange	5	Outside and canopy	194	0.5	13.0
		Inside	173	3.5	12.0

[1] Means of 4 tree-replicates.
[2] The sum of 4 replicates; every replicate of the same treatment had roughly equal number of fruits.
[3] Means of 4 tree-replicates; only 20 fruits per replicate were evacuated.

Other Factors that Affect the Storability and Quality

Griserson and Hatton (1977) mentioned that preharvest factors including rootstock, weather, grove treatments, tree condition and fruit maturity, proper harvesting or not, postharvest factors involving all conditions between picking and storage, and ambient conditions between operations can affect the response of citrus fruits to cold storage. We found that 'Ponkan' marndarins harvested at about the same time from 3 orchards not too far apart had significantly different level of losses and different fruit quality after storage under same conditions (data not shown). We also found that 10 different 'Ponkan' trees on the same orchard produced fruits of substantially different quality and that the rank order of superiority of the same 10 trees varied from one year to another (data not shown). In 11 storage experiments of 'Liucheng' oranges conducted in recent years, we found dramatic differences in the incidences of storage disorders even though they were stored under the same conditions (Table 2).

Storage should be terminated before the severity of storage disorders or losses, or the fruit quality deterioration approached an intolerable point. Since there are so many preharvest and postharvest factors affecting the development of storage disorders and affecting the quality of citrus fruits, it is only next to impossible to define the storage life span of a variety even if the storage conditions are pre-determined. Furthermore, acceptable quality standards vary with different markets or different consumers; and the market price increment of the fruit during it's storage period may change the tolerance of storage losses. Therefore, the potential storage life span of a fruit can only be estimated at best but not clearly defined. Based on our experimental results and field and market observations, we estimated the potential storage life span under currently known good storage conditions being 3 months for 'Ponkan' mandarins, 4 months for 'Tankan' tangors, and 5 months for 'Liucheng' oranges.

Table 2. Percentage of 'Liucheng' oranges developed storage disorders in 5 months of refrigerated storage in 11 experiments.[1]

	% fruits developed the disorder		
Kind of disorder	The highest	The lowest	Average
Button senescence	73.7	11.0	43.2
Granulation	51.3	1.3	24.8
Mesocarp breakdown	25.0	1.3	9.6
Decay	20.0	1.3	8.1
Stem-end rind breakdown	17.5	0.0	4.0

[1] There were 4 tree-replicates, 20 to 25 fruits per replicate, in each experiment. Data adopted from Liu (2009).

Storage Methods

Common storage is widely adopted for storing citrus fruits in Taiwan. The use of refrigerated storage is on the rise in recent years. Cave storage is still in the early experimental stage, but may get into commercial application in the future. These three storage methods will be discussed below.

Common Storage

Common storage does not use mechanical refrigeration. Cooling is done by natural air or water. Good common storage does have an insulated storage room and a ventilation system either operated manually or automatically with electronic devices. When cool air is available outdoors, it is introduced into the storage room via air inlet near the floor. Warm air in the storage room is pushed or sucked out via air outlet on or near the ceiling. Electric fans may be used to accelerate air change and ventilation. When outdoor air temperature is too high, air change openings are closed, thereby temperature inside the storage room may be maintained somewhat lower than outside owing to insulation. Common storage may use very simple or rather sophisticated structures and facilities (Booth and Shaw, 1981).

Citrus growers in Taiwan use various types of common storage. The most primitive type simply pile the fruit under the plastic tent which is often installed under tree shade. Some growers store small quantities of citrus fruits in whatever space available in their own residential houses. There are also many warehouses built purposely for storing citrus fruits. Most of them have inadequate insulation and poor ventilation control, however. When citrus fruits are stored in these substandard storage facilities, rapid decline in fruit quality and heavy storage losses are often unavoidable. We assisted growers to build a couple of insulated common storage with proper air-ventilation control for demonstration purposes. We will continue to do research on the application and improvement of common storage.

Refrigerated Storage

Refrigerated storage, also known as cold storage, has at least an insulated storage room and a mechanical cooling unit. Modern cold storage also has a proper internal air circulation system, automatic control devices, and often a humidity control. Such storage facilities provide desirable temperature or temperature and humidity for the fruits.

Citrus fruits stored in a refrigerated storage regulated at the desirable temperature and humidity can best maintain their quality and minimize storage losses. We have found the desirable storage temperature being 15℃ for three major varieties of citrus fruits grown in Taiwan. We used this temperature for many storage related experiments for years and found it always suitable. Many growers and commercial storage managers use 13° to 15℃ range and avoid temperatures above 15℃. Since we found 12.5℃ also acceptable in our experiments, setting storage temperature range between 13° to 15℃ seems proper. As long as citrus fruits are bagged in polyethylene bags in storage, humidity control in refrigerated storage is not critically important and is often ignored. If citrus fruits are stored for only about a month, bagging may not be necessary, but the relative humidity should be maintained at ≧85% in cold storage. For longer periods of storage for unbagged citrus fruits, the relative humidity needs to be maintained at ≧90% or even 95% according to our experiment results.

Cave Storage

Cave storage was once a very popular method for apples in northwest China. We learned basic principles developed there and made a lot of modification in constructing our experimental cave storage. The first one we built in a grower's orchard had the shape and dimensions (3m floor width x 3m wall height x 20m cave length, with pyramidal ceiling) very similar to apple storage caves in China. The major modifications we made were concrete lining of the cave, adoption of a modern refrigerated storage door, and installation of a ventilation fan with automatic control devices. The grower stored citrus fruits in the cave successfully in two years, but then sold the whole orchard to a developer who destroyed the cave for building vacation homes later.

We therefore build a second cave which cost much less when we had a budget difficulty. We connected several huge concrete drainage tube sections and covered them with soils. The tube has an inside diameter of 210 cm. The cave made by connecting tube sections lined up in the north to south direction has a length of 15 m. A door of refrigeration storage was installed at each end of the cave. An exhaust fan with automatic control was installed at the south end. Such a cave is far from ideal. The soil coverage above the cave should be ≧3 m but we have only about 2 m. The length of the cave should be ≧20 m but we have only 15 m. Nevertheless, it has been a useful tool for our experiments in last few years.

The theory to use cave storage for our citrus fruits is rather simple. Our citrus fruits have a desirable storage temperature of 15℃, and they can tolerate short spans of non-freezing low temperatures. In a location where non-freezing cool (0° to 15℃) ambient temperature is frequently available in winter and early spring, citrus fruits are stored in a cave. Whenever the out door temperature is lower than the temperature in the cave, open up the cave ventilation to let the cool air in to cool the fruits, the air in cave, as well as the cave wall and the soil surrounding the walls. When the outdoor temperature is higher than the cave temperature, ventilations are closed. Then the thick soil layer surrounding the cave not only provides a good insulation for the cave, but also, after being cooled, absorbs the heat generated by fruits respiration and by heat leakage from outdoors. After spring comes, outdoor cool air becomes scarce, and the cave ventilation may be closed most of the time. The cave temperature can still be kept cool for a period of time. The thicker soil layer above the cave and the cooler soil layer, the longer cool period can last. Eventually the surrounding soil temperature raises to a point beyond which maintaining an acceptable cave temperature becomes difficult. That will be the time when cave storage should be terminated. We found that a cave storage located in Miaoli County, Taiwan, has been useful for storing citrus fruits during the period between late December and April of the following year. That covers a great portion of the citrus storage season.

Temperature Differences in the Three Storage Facilities

Temperature changes during the storage season of citrus crops of 2009 were monitored in three types of storage facilities which had been installed at the same place in Tahu Township, Miaoli County. The refrigerated storage is a popular type which has been widely used in small scale operations in rural Taiwan. The cave storage has just been described above. The common storage is an insulated small room with a little ventilation control but far from ideal. Each storage facilities was only partially filled with citrus fruits during the period of temperature monitoring.

The temperature of refrigerated storage remained constant at 14° ± 1.5℃, while the temperatures of common storage and cave storage fluctuated due to the ambient temperature fluctuation. During the period from late December, 2009 to May, 2010, the 10-day interval mean temperature of the cave was significantly lower than that of the ambient air for most of the time (Fig. 7). The difference between the two temperatures was smaller up to mid-February when low ambient temperatures were available frequently, but the difference widened afterward (Fig. 7). The mean temperature of the common storage was not lower than that of ambient air for most of the time, however (Fig. 7). That indicates a need for improvement of the common storage facilities. The differences in mean maximum temperatures of the three measuring spots (ambient air, common storage and cave) were much greater than the differences in mean temperatures (Fig. 7) owing to the effects of insulations in the storage. The differences in mean minimum temperatures of the 3 measuring spots were small (Fig. 7) because ventilations in the storage were open when outdoor temperatures were low, and therefore low-temperature air could enter the storage. Another important difference was that the gap between mean maximum and mean minimum temperatures was wide in the ambient air, was subsaintially narrower in common storage, and was very narrow in cave storage (Fig. 8).

Preliminary Resuts of Storage Trials in the Three Storage Facilities

When small samples of ‘Ponkan’ mandarins were stored in the three storage facilities for 2 to 3 months in the storage season of 2008-2009, very little decay, button senescence, or granulation occurred and differences among the 3 storage facilities were insignificant (Table 3). Fruits stored in the three storage facilities also had similar rind color and soluble solids content (Table 3). When small samples of ‘Tankan’ tangors were stored in the three storage facilities in the same storage season, slight differences in the occurrence of granulation and a*/b* values were noticed in 3 months, and the differences in the two items became greater in 4 months (Table 3). Refrigerated storage and cave storage seemed to be slightly better than common storage for 3 to 4 months of storage for ‘Tankan’ (Table 3). When somewhat larger fruit samples of ‘Liucheng’ oranges in storage were examined in the subsequent storage season, the fruits in common storage seemed to have higher percentage of disorders than those in cave or in refrigerated storage after 4 months, and the fruits in cave storage had higher percentage of disorders than those in refrigerated storage after 5 months (Table 4).

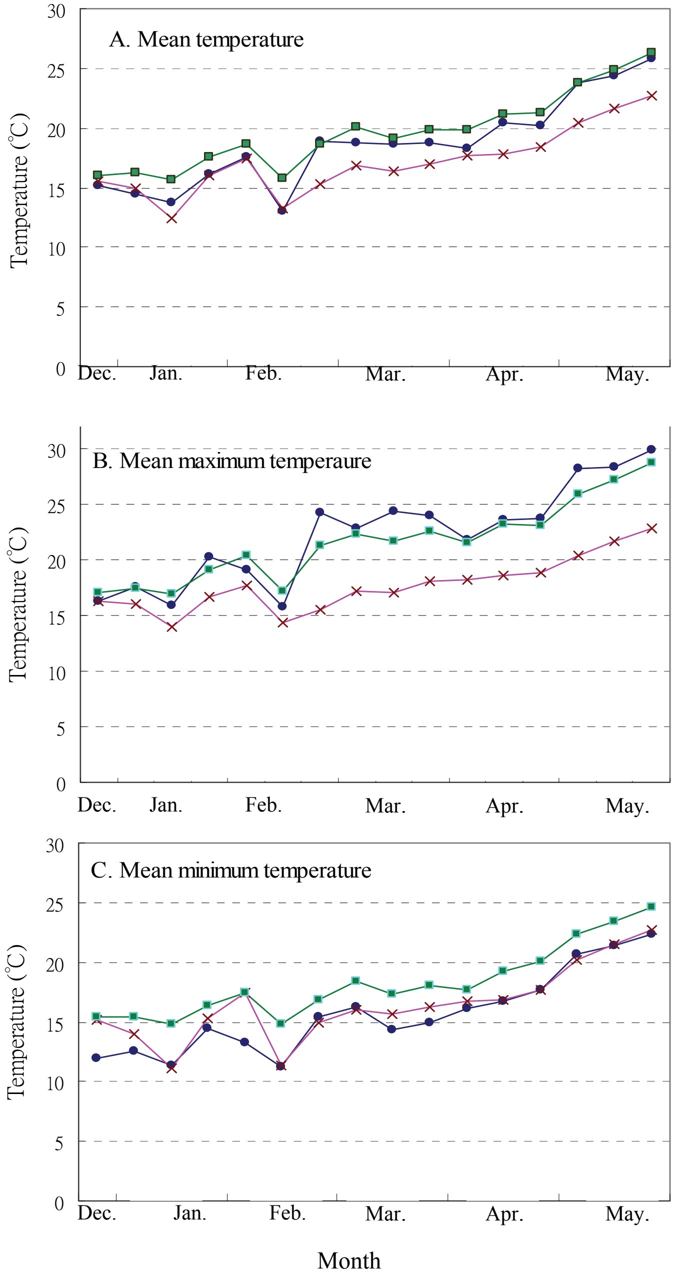

Fig. 7. Comparison of temperatures in ambient air (●●), in common storage (■■) and in cave storage (××). Data of 2009-2010 storage season.

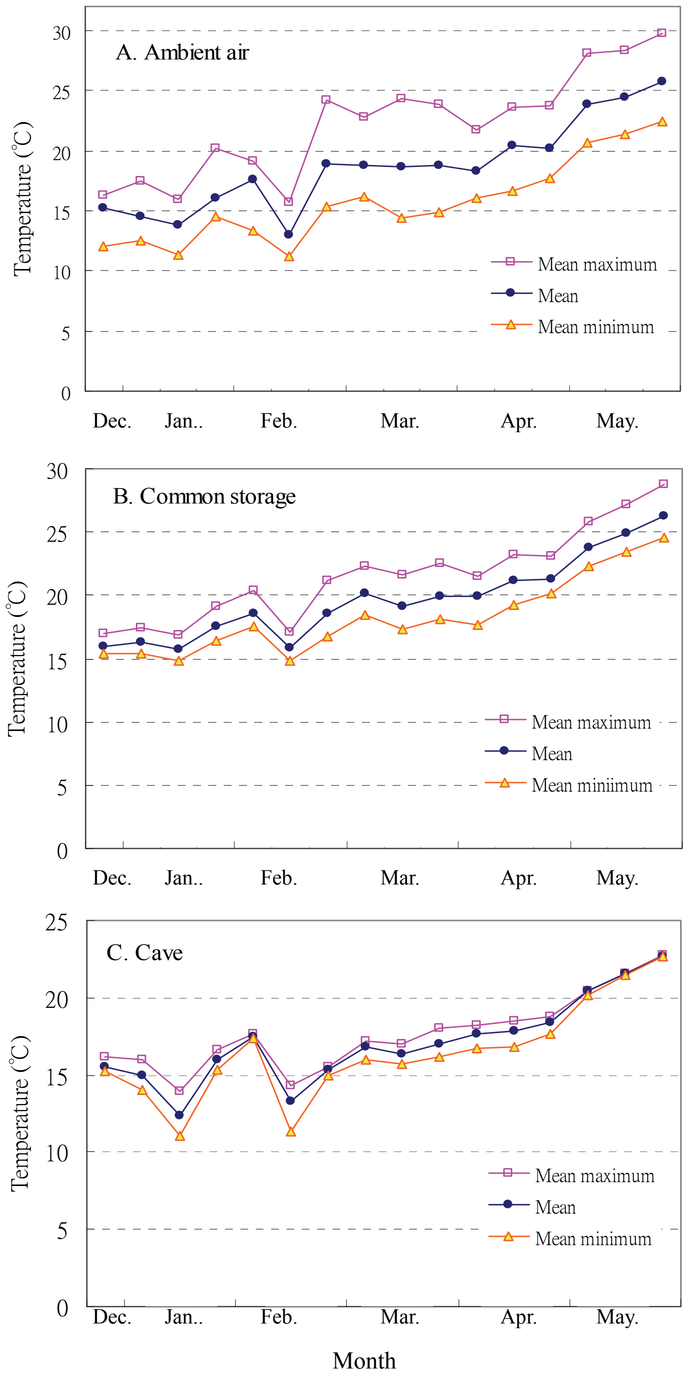

Fig. 8. Comparison of mean-maximum and mean-minimum temperature gaps in ambient air, common storage and cave storage. Data of 2009-2010 storage season.

Table 3. Differences in storage losses and post-storage quality of 'Ponkan' mandarin and 'Tankan' tangor stored in 3 types of storage facilities.[1]

Variety	Duration of storage (months)	Type of storage	Decay (%)	Button senescence (%)	Granulation		Rind color (a*/b*)	Soluble solids (°Brix)
					Slight (%)	Severe (%)		
'Ponkan'	2	Common	0	0	0	0	0.66	10.2
		Cave	0	0	0	0	0.66	10.2
		Refrigerated	0	0	0	0	0.66	10.2
	3	Common	2.5	2.5	5.0	0	0.69	9.9
		Cave	0	0	2.5	0	0.68	10.0
		Refrigerated	1.3	2.5	5.0	0	0.68	9.9
'Tankan'	3	Common	0	0	21.6	2.3	0.61	9.2
		Cave	0	0	18.2	1.1	0.63	9.2
		Refrigerated	0	0	11.4	2.3	0.63	9.3
	4	Common	0	3.4	25.0	12.5	0.62	8.8
		Cave	1.1	1.1	20.5	6.8	0.64	8.7
		Refrigerated	0	3.4	23.9	7.9	0.67	8.8

[1] Means of 4 tree-replicates, 20 fruits per replicate for 'Ponkan' and 22 fruits per replicate for 'Tankan'. Data of 2008-2009 storage season.

Table 4. Differences in the development of storage disorders of 'Liucheng' orange stored in 3 types of storage facilities.[1]

Duration of storage (months)	Type of storage	Decay (%)	Button disorder (%)	Mesocarp breakdown and other visible disorders (%)	Total (%)
4	Common	2.66	2.04	—	4.70
	Cave	1.47	0.84	—	2.31
	Refrigerated	2.10	0.21	—	2.31
5	Cave	8.54	5.83	1.67	16.04
	Refrigerated	4.34	1.24	1.86	7.44

[1] Means of 4 replicates, 1 box per replicate. Each box had 476 to 489 fruits. Data of 2009-2010 storage season.

When small samples of fruits were used in storage tests, every piece of fruit was carefully handled, and every storage container, being trays or boxes in our studies, were well exposed and well ventilated in the storage. Besides, the storage spaces were mostly empty. But in commercial storage, fruit boxes are more tightly stacked and the storage spaces are fully filled. Therefore, the results of small sample storage and large volume commercial storage may be different. We shall conduct larger scale storage tests to verify our small sample experiment results in the future. Nevertheless, preliminary studies suggested that common storage might be adequate for short-term storage while cave storage might be needed for longer terms and refrigerated storage for the longest terms of storage. Varietal differences in response to storage types may exist also.

Considerations for Costs and Energy Use of the Three Storage Methods

Common storage requires rather simple structures and is easy to build. It's building cost shall be lower than that of other two types of storage facilities. Since the storage is cooled by ventilating natural cool air, electric energy use shall be minimal. Common storage facilities are convenient for use and easy to operate.

The construction cost of cave storage would be fairly high if a thick layer of concrete liner is used. Such liner is necessary in a place like Taiwan where heavy rains and earthquakes are quite common. Once constructed, the structure is durable and requires little maintenance and repair costs, however. Well constructed cave storage facilities can be used for decades or even centuries if without natural or man-made destructive disasters. Cave storage may or may not have ventilation or exhaust fans. Even if fans are used, electric energy use shall be low. Since the cave must be narrow and elongated in shape, it is not convenient for loading and unloading fruits in the storage operation. Therefore, it may not suit for very large volumes of fruit storage.

Refrigerated storage facilities require sufficiently effective insulation and refrigeration machines and equipment. The initial construction cost should be the highest among the three types of storage facilities. The facilities also needs periodical maintenance services and even repairs only professionals can perform. The storage is cooled by mechanical refrigeration which requires a lot of electric energy. In general, the higher ambient temperature the more energy consumption; and the poorer insulation the more energy waste.

Among all three types of storage methods, refrigeration storage has the highest construction as well as maintenance costs and the highest energy use. Cave storage has high construction costs but low maintenance cost and low energy use, while common storage has the lowest costs and lowest energy use.

More Thoughts Concerning Commercial Storage

When selecting a storage method for commercial fruit storage, both technological and economic factors have to be considered. Whenever possible, environment friendliness of the method should also be considered. We therefore should use all of our knowledge about the requirements of the fruits, available technologies, economic feasibilities, and the environment to make a judicious choice.

Storing fruits in cooler locations

In citrus fruit storage under sub-tropical climate, cooling and maintaining coolness in the storage are usually desirable or even necessary processes. It would be wise, therefore, to select cooler locations to store fruits if economically feasible. The cooler the climate, the better chance to utilize cool ambient air in storage. Cooler ambient air also helps reducing the cost of refrigeration when refrigeration is used. That is because less heat energy to be transferred into the storage by means of conduction and convection and therefore less heat energy to be transferred out of the storage by mechanical means.

Most of our ‘Ponkan’ mandarins are grown in the central and southern Taiwan, and most of our ‘Liucheng’ oranges are grown in the southern Taiwan. During the storage seasons (i.e., winter and spring) of these citrus fruits, the ambient air temperature is much lower in northern Taiwan than in the central or southern Taiwan. For instance, when three spots of interest are compared, Miaoli has significantly lower temperatures than Chiayi which in turn has significantly lower temperatures than Tainan (Fig. 9). Miaoli is located in the north and is the place where our experimental cave and common storage facilities are located. Both Chiayi and Tainan are located in the south and are the places where lots of mandarins and oranges are grown. The farthest distance between any two spots of the three is >150 km. When considering other factors, more than half of the population of the main island of Taiwan resides in the northern part and the main south to north highways and railways pass through Miaoli. Wouldn’t it be wise to store at least part of southern grown citrus fruits in appropriate places like Miaoli in the north? This is a good example for studies on selecting cooler places for citrus storage.

Uses of various storage methods in combination

Common storage has virtues of being low cost and environment friendly. Cave storage is also environment friendly but is more costly and more difficult to build and less convenient to use. Refrigerated storage is most costly among the three storage methods, and it also requires a lot of electric energy consumption which is considered environment unfriendly. Therefore, while selecting a storage method for a predictable lot of fruits, common storage should be considered first followed by cave and refrigerated storage provided that satisfactory storage conditions for the lot of fruits can be met.

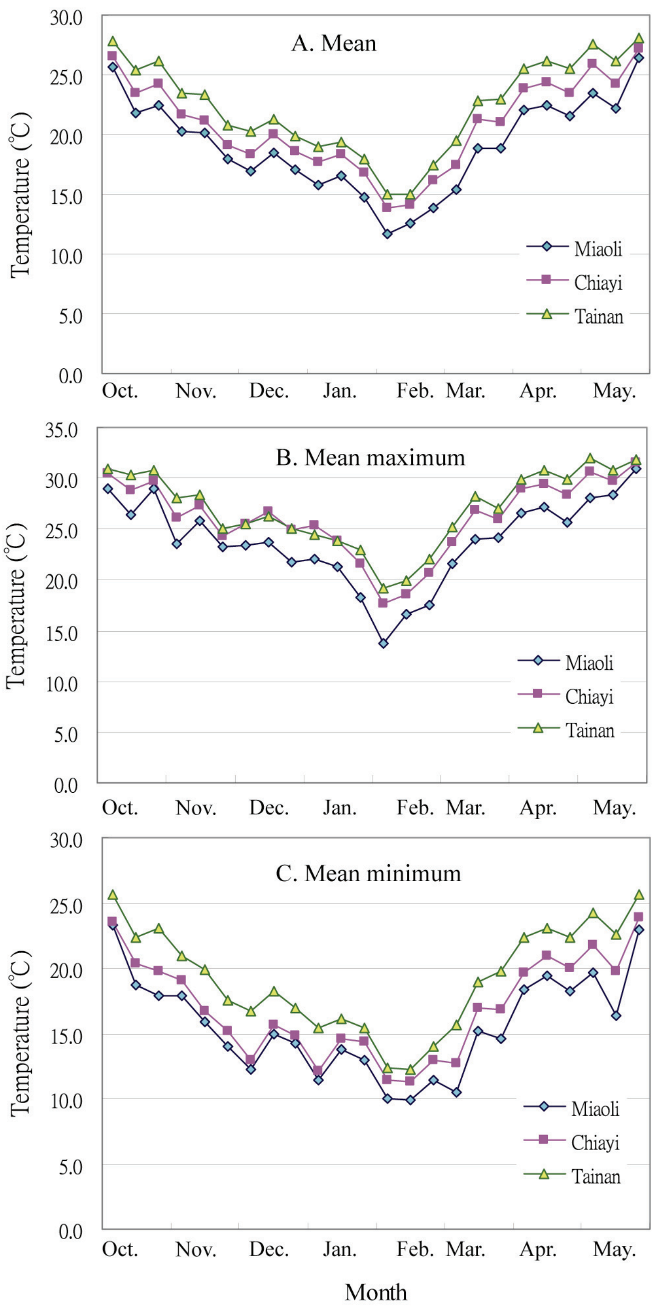

Fig. 9. Comparison of ambient temperatures of Miaoli ( ), Chiayi ( ) and Tainan ( ) in the citrus harvesting and storage season of 2007-2008. Based on data published by Taiwan Weather Bureau.

According to our research results and field observations, ‘Ponkan’ mandarins and ‘Tankan’ tangors grown in the northern part of Taiwan may be stored in common storage in the north for 1 to 3 months without severe losses. Cave storage or refrigerated storage may be used for longer periods of storage in order to maintain better fruit quality and to minimize storage disorders. Common storage in the southern region is less useful for lack of cool ambient air in the region. Building cave storage in the south may not be advisable either for the same reason. Therefore, southern grown citrus fruits may be stored in common storage in the south for only a short period (1 to 2 months). The fruits may be shipped to the north and stored in either common storage or cave storage for longer periods (2 to 4 months), however. Refrigerated storage can, of course, be built in any region, but is needed only for long terms (4 to 5 months) of storage for Taiwan citrus. Refrigeration cost would be lower in the north than in the south due to lower ambient temperatures in the former. A good combination of three types of storage facilities, particularly when built in cooler locations, will save money and energy while providing adequate protection for citrus fruits.

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