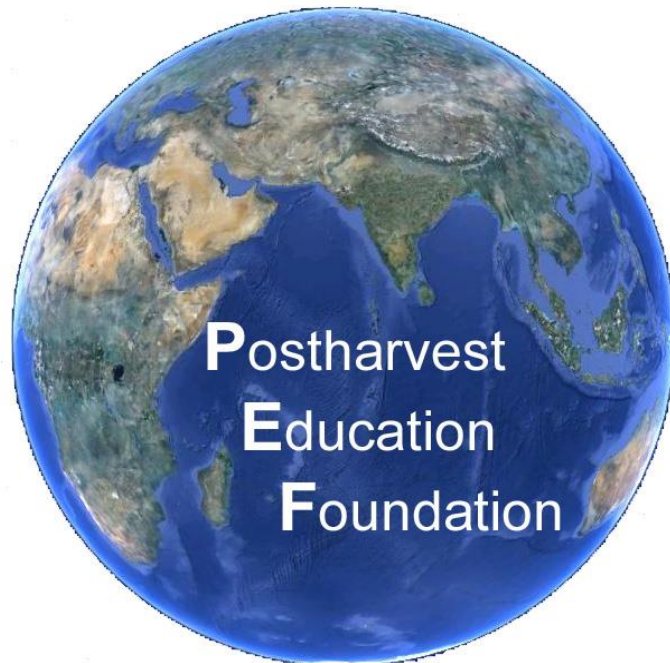


# **Water Relations in Harvested Fresh Produce**

PEF White Paper No. 15-01

**The Postharvest Education Foundation (PEF)**

May 2015



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Deirdre Holcroft, PhD

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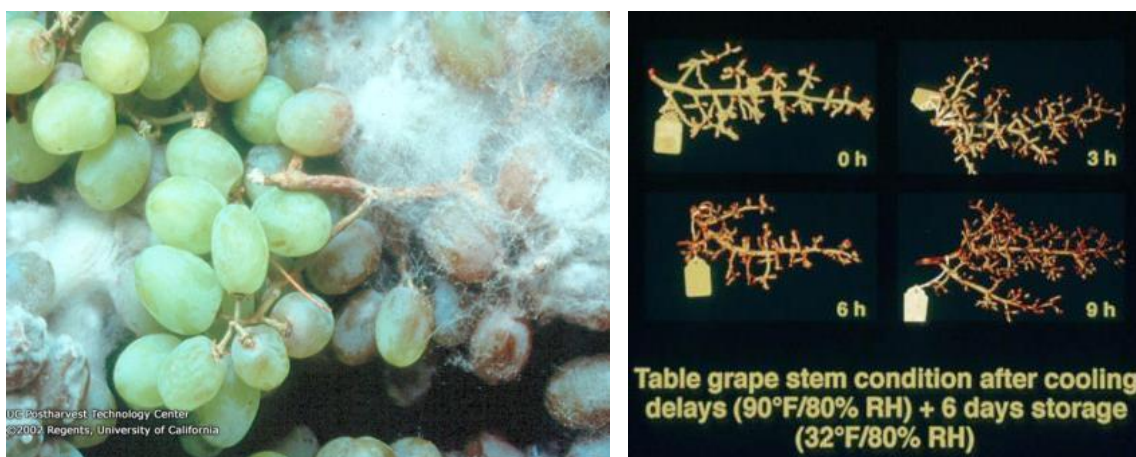
### Introduction

Harvested produce should be handled carefully to minimize both water loss and the presence of free water. Water loss results in weight loss, wilting and shriveling, while free water or condensation facilitates pathogen growth. Understanding and managing water relations is therefore a critical component of postharvest handling, second only to temperature management.

At the time of harvest the water content of fruits and vegetables is very high and produce has a fresh appearance and crisp texture. Harvesting removes the plant part from its water supply and the product begins to lose weight. This loss of water has an immediate economic effect in that it reduces saleable weight. Continued water loss causes wilting and/or shriveling. Consequently, reducing water loss improves produce appearance, quality, shelf life and profitability.

Adding water to the produce or its environment appears to be a simple solution to reduce water loss but it too has consequences. Free water encourages germination and growth of fungal and bacterial pathogens resulting in decay, reduced shelf life and product loss. If the added water is not adequately sanitized it may result in contamination of produce with human pathogens, and possibly an outbreak of food borne illness. Changes in temperature during postharvest handling can cause condensation, i.e. free water, with similar consequences.

This compromise between minimizing water loss and preventing condensation is clearly demonstrated in table grapes where high relative humidity (RH) and free water encourage the growth of gray mold (*Botrytis cinerea*) while low RH causes desiccation and browning of stems and pedicels (Figure 1). Both of these problems affect grape quality and profitability.



**Figure 1** *Botrytis* (gray mold) on grapes encouraged by high relative humidity and free water (left) and stem desiccation caused by low relative humidity (right). (Photos from [www.postharvest.ucdavis.edu](http://www.postharvest.ucdavis.edu) used with permission).

This paper explains water relations in detail and considers some of the misconceptions. Drying of produce for preservation is not in the scope of this document.

## 1. Water loss

### 1.1 Introduction to water loss

Most fruits, vegetables and flowers have a very high water content (80-95%) at harvest (Table 1). Even the exceptions to the high water content, such as banana, potato, or avocado, contain greater than 70% water.

**Table 1** Water content (%) by weight of some common fruits and vegetables (data compiled from Appendices V and VI in Kays & Paull, 2004 and <http://postharvest.ucdavis.edu/>)

<b>Fruit</b>	<b>Water content (%)</b>	<b>Vegetables</b>	<b>Water content (%)</b>
Apple	84	Asparagus	93
Avocado	<b>76</b>	Beans, green	89
Banana, green	<b>76</b>	Broccoli	90
Blueberry	83	Brussels sprouts	85
Cantaloupe	93	Cabbage	92
Cherry	80	Carrot	88
Citrus	89	Cauliflower	92
Grape	82	Lettuce	95
Grapefruit	89	Mushroom	91
Honeydew melon	93	Onion, dry	88
Kiwifruit	82	Pepper, sweet	92
Mango	82	Potato	<b>78</b>
Orange	86	Pumpkin	91
Peach	89	Spinach	93
Pear	83	Squash, summer	94
Plum	87	Squash, winter	85
Watermelon	93	Tomato, firm ripe	94

Water is lost from fruits and vegetables by transpiration. The process of transpiration includes the transport of moisture through the skin of the commodity, the evaporation of this moisture from the commodity surface and the convective mass transport of the moisture to the surroundings.

The point at which water loss affects quality varies for different commodities. For example, leafy vegetables will wilt after about 3-5% water loss while nectarines shrivel after about 19% water loss. The weight loss of individual fruit or vegetables within a box of produce also varies considerably, with some items appearing shriveled and unmarketable while others could still be acceptable for sale and consumption.

**Table 2** Maximum permissible water loss (%) for a number of fruits and vegetables. (Kays & Paull, 2004 and Thompson et al., 2008 compiled the data from Robinson et al., 1975; Hruschka, 1977; Nelson, 1985; Hardenburg et al., 1986).

<b>Commodity</b>	<b>Maximum weight loss (%)</b>	<b>Reference</b>
<b>Fruit:</b>		
Apple (4 cvs)	7.5	Kays & Paull, 2004
Blackberry	6.0	Kays & Paull, 2004
Grape	5	Kays & Paull, 2004
Nectarine	21	Kays & Paull, 2004
Papaya	7*	Paull & Chen, 1989
Peach (5 cvs)	11-16.4	Kays & Paull, 2004; Thompson et al., 2008
Pear (3 cvs)	6	Kays & Paull, 2004
Persimmon	7-13	Kays & Paull, 2004; Thompson et al., 2008
Raspberry	6	Kays & Paull, 2004
<b>Vegetable:</b>		
Asparagus	8	Kays & Paull, 2004
Beans, broad	6	Kays & Paull, 2004
Beans, runner	5	Kays & Paull, 2004
Beetroot	7	Kays & Paull, 2004
Beetroot with tops	5	Kays & Paull, 2004
Broccoli	4	Kays & Paull, 2004
Brussels sprouts	8	Kays & Paull, 2004
Cabbage	6-11	Kays & Paull, 2004; Thompson et al., 2008
Carrot	8	Kays & Paull, 2004
Carrot with leaves	4	Kays & Paull, 2004
Cauliflower	7	Kays & Paull, 2004
Celery	10	Kays & Paull, 2004
Cucumber	5	Kays & Paull, 2004
Leaf lettuce	3-5	Thompson et al., 2008
Leek	7	Thompson et al., 2008
Onion	10	Kays & Paull, 2004
Pepper, green	8	Kays & Paull, 2004
Potato	7	Kays & Paull, 2004
Spinach	3	Kays & Paull, 2004
Squash, summer	24	Kays & Paull, 2004
Squash, winter	15	Thompson et al., 2008
Sweet corn	7	Kays & Paull, 2004
Tomato	4-7	Kays & Paull, 2004; Thompson et al., 2008
Turnip with leaves	5	Kays & Paull, 2004
Watercress	7	Kays & Paull, 2004

## 1.2 Effects of water loss on produce quality

Water loss is the factor that contributes most to weight loss, and for products sold by weight this will have economic consequences. For example a 3% weight loss for blueberries may not affect appearance quality but for a pallet of blueberries weighing 500 kg this accounts for a loss of 15 kg. If blueberries are valued at \$10 per kg, at retail this weight loss results in a loss of \$150 per pallet.

More severe water loss results in a reduction in appearance quality including wilting, shriveling, less gloss, and limpness, which will reduce market value (Figures 2, 3 & 4).



**Figure 2** Effects of water loss, seen as a loss of glossy appearance and shrivel, on tomatoes grown in California (Photo credit: Lisa Kitinoja, 2005).



**Figure 3** A visual rating scale for water loss from green bell peppers where 1= 2%; 2= 4-5%; 3= 7-8%; 4= 10-12%; and 5= 15-17% weight loss. (Photo credit: Marita Cantwell, 2010. Scale developed for WFLO project for BMGF).





**Figure 4** Water loss in fresh amaranth leaves grown in Tanzania and stored at ambient temperature with no package, very thin plastic bag or a rigid plastic clamshell. Any type of package slowed water loss when compared to using no package, but a vented package is best for avoiding condensation. (Photo credit: Lizanne Wheeler & Diane Barrett, 2014).

Water loss can also affect shelf life and nutritional quality. Water stress can induce ripening in climacteric fruit. For example, bananas have a green life of about 22 days at 20°C and 95% RH and only 16 days at the same temperature but 13% RH (Littmann, 1972; cited by Paull, 1999). Conditions favorable to water loss after harvest result in a rapid loss of vitamin C especially in leafy vegetables (Lee & Kader, 2000).

### **1.3 Rate of water loss.**

The rate of water loss from fruits and vegetables is affected by the shape and structure of the produce, the plant factors, as well as the environmental conditions. These plant factors are quantified by the transpiration coefficient or K value (Table 3). Temperature and relative humidity (RH) are the most important environmental variables and these affect the water vapor pressure deficit, or difference, between the fruit or vegetables and its environment (WVPD or VPD). The rate of water loss can be simplified and expressed as:

$$\text{Weight loss (\%/day)} = K \text{ value} \times \text{VPD}$$

This equation does not consider some of the subtle changes in water loss that can occur. Transpiration rates decrease at high vapor pressure deficits probably because the skin tissue dries out or the skin permeability changes. Evaporation of water from the surface of the produce results in cooling which in turn affects VPD. The heat of respiration warms the surface temperature of produce so that it is slightly higher than the ambient air (Becker & Fricke, 1996). However, in practice this equation provides an adequate indication of water loss.

Changes in air pressure can also affect vapor pressure deficit but are of limited importance. Water loss is greater when produce is cooled under vacuum and 2-4% weight loss is common (Thompson et al., 2002). Spraying water on produce before vacuum cooling allows produce that are sensitive to wilting, e.g. green onions and leaf lettuce to be cooled using this method. Two to four or when transported by air.

### **1.3.1 Transpiration Coefficient (K value)**

The shape, surface structure and skin permeability of fruits and vegetables affect water loss (Becker & Fricke, 1996). Leafy tissue has natural openings, stomata, which allow gas exchange and water loss. Stomata can regulate their opening and closing in response to water stress. In fruits like apples and pears there are small openings, lenticels, which function similarly to stomata but cannot regulate their opening and closing. Water and gas exchange takes place through these lenticels. In addition to the size and density of stomata or lenticels, other surface features affect water loss including stem scars, cut ends of stems, cuts and scratches on the skin. If the hairs on the surface of kiwifruit or the trichomes on peaches are broken water loss increases.

Tomato fruit do not have stomata or lenticels and most of the water vapor and other gases move through the stem scar. A traditional practice in some regions of southern Africa is to store tomato fruit upside down, presumably to reduce water loss from the stem scar, while commercial practices include waxing tomatoes.

The cuticle or periderm, which are common outer layers, are much more resistant to water loss than the stomata or lenticels. The waxy cuticle with stomata functions like a plastic package with micro perforations. Gas exchange can occur but it is limited. If the holes increase in size or density then gas exchange increases.

In addition to surface structure, the shape of produce also affects water loss. To be more specific the surface area available for evaporation compared to the volume has a large impact. Round apples or potatoes will lose less water than the same weight of spinach leaves or lettuce heads. Apples may have a waxy surface which further reduces water loss.

Changes in the transpiration coefficient can even be seen between different varieties. For example, 'Ranger' peach loses more water than 'Sunhaven' peach of the same size under the same conditions (Whitelock et al., 1994).



**Table 3** Transpiration coefficients (K) (mg/kg/sec/MPa) of some fruits and vegetables (Thompson et al., 2008 compiled the data from Sastry et al., 1978).

<b>Fruit</b>	<b>Transpiration coefficient (K)</b>	<b>Vegetable</b>	<b>Transpiration coefficient (K)</b>
Apple	42	Brussel Sprouts	6150
Grape	123	Cabbage	223
Grapefruit	81	Carrot	1207
Lemon	186	Celery	1760
Orange	117	Leek	790
Peach	572	Lettuce	7400
Pear	69	Onion	60
Plum	136	Parsnip	1939
		Potato	44
		Tomato	140

### 1.3.2 Vapor Pressure Deficit (VPD)

VPD is a term that describes the driving force for water loss from the produce to the environment. VPD is increased by increasing temperature and decreasing relative humidity. The psychrometric chart gives a graphic representation of the relationship between temperature, RH and water vapor pressure. Therefore if the temperature of the produce is known and the RH is assumed to be 100% (saturated) the vapor pressure can be determined. Likewise the VP of the atmosphere can be determined using temperature and RH. The difference between these two values is the VPD (Tables 4 & 5). These values can be obtained from a psychrometric chart or from an on-line calculator (Appendix 1).

**Table 4** The effect of increasing temperature from 0°C to 30°C, in 10°C increments, at 90% relative humidity on the vapor pressure (mbar) and the vapor pressure difference (mbar) where produce is assumed to be at 100% RH. Vapor pressures obtained using <http://www.sugartech.co.za/psychro/index.php>.

<b>Temperature (°C) (°F)</b>	<b>Vapor Pressure (mbar)</b>		<b>VPD (mbar) at 90% RH</b>
	<b>100% RH (produce)</b>	<b>90% RH (Air)</b>	
0 (32)	6.11	5.50	0.61
10 (50)	12.28	11.05	1.23
20 (68)	23.39	21.05	2.34
30 (86)	42.46	38.21	4.25

**Table 5** The effect of reducing relative humidity from 95% to 5%, in 10% increments, at 10°C (50°F) on vapor pressure (mbar) and vapor pressure difference (mbar) where produce is assumed to be at 100% RH and 10°C i.e. a VP of 12.28 mbar. Vapor pressures obtained using <http://www.sugartech.co.za/psychro/index.php>.

RH (%)	VP air (mbar)	VPD (mbar)
95	11.67	0.61
85	10.44	1.84
75	9.21	3.07
65	7.98	4.30
55	6.75	5.53
45	5.53	6.75
35	4.30	7.98
25	3.07	9.21
15	1.84	10.44
5	0.61	11.67

#### 1.4 Reducing water loss

Water loss is minimized by reducing the transpiration coefficient (k) or the vapor pressure deficit (VPD). The transpiration coefficient can be reduced by any type of packaging, waxing fruit, careful handling to avoid mechanical injury, or removing leaves to reduce the surface area. An extreme example of packaging is shrink wrapping of individual fruit. Wax coatings can be applied to apples, avocados, bell peppers, cantaloupes, cucumbers, eggplants, grapefruits, lemons, limes, melons, oranges, parsnips, passion fruit, peaches, pineapples, pumpkins, rutabagas, squash, sweet potatoes, tomatoes, turnips and yucca. Waxed produce must be labeled. Consumers will see signs in produce departments that say “Coated with food-grade vegetable-, petroleum-, beeswax-, and/or shellac-based wax or resin, to maintain freshness” (Figure 5).



**Figure 5** Citrus labelled as treated with waxes.

The VPD is decreased by reducing temperatures including reducing the time between harvest and cooling, increasing RH and reducing air movement. While this may sound obvious since temperature is controlled in storage, RH is not usually measured accurately or well controlled. RH is affected by the difference between the temperature of the cooling coil and the air temperature of the room. If the coil is small the temperature difference between the coil and room tends to be high. The recommendation to maintain a high RH in a cooler is to keep the refrigerator coils within 1°C of the air temperature (Thompson, 2002b).

There are practical difficulties in maintaining RH in large storage rooms within a narrow range at high relative humidities. In order to achieve 95% RH at 0°C, the mean temperature differential between the air and the evaporator coil must be about 0.5°C; or to maintain 90% RH at 0°C this difference must be about 1°C (Paull, 1999). Maintaining these small differences requires very accurate temperature measurement e.g. platinum resistance elements which are accurate to about 0.16°C (Paull, 1999) and correct sizing of the refrigeration unit (Thompson, 2002a). Coils with a large surface area and good controls can maintain a higher coil temperature resulting in low temperature with high RH. Refrigeration systems that are undersized result in large temperature fluctuations as the system cycles on and off resulting in loss of water and excess frost build up on the coils. In refrigeration systems that are not designed for fresh produce (e.g. domestic refrigerators) the coils are often 6°C lower than the desired temperature. This causes severe condensation on the coils and a decrease to <70%.

Humidification systems can be used in coldrooms to reduce the VPD. The simplest system is wetting the floors while more advanced solutions are fogging or misting systems. Misting is also used on leafy vegetables in retail displays to minimize water loss.

## **2. Condensation**

### **2.1 What is condensation?**

There is a dynamic relationship between temperature and water vapor in the air. Relative humidity is affected by temperature because air can hold more moisture at higher temperatures. When moist air is cooled the decrease in temperature causes the relative humidity to increase. When the relative humidity reaches 100% the water vapor condenses into liquid water. The temperature at which this happens is known as the dew point. Condensation is often referred to as 'sweating' of fruit or vegetables although the mechanism is very different from sweating.

Condensation occurs on cold surfaces. For example, water droplets form on cold soda bottles because the temperature of the air immediately around the bottle decreases until it can no longer hold the water vapor. Cold produce placed in warm humid environments or packed in warm containers may experience water condensing on the produce. Similarly packing warm produce in a plastic container and placing it in a cooler can result in rapid cooling of the plastic surface and condensation on the inside (Linke & Geyer, 2013). At conditions of low temperature (0°C) and high relative humidity (95%) very small differences in temperature (<1°F) can result in condensation on the cooling surfaces.

## **2.2 Effects of condensation**

Free water on the fruit enhances microbial growth. Germination of fungal spores, including grey mold [*Botrytis cinerea*] (Jarvis, 1977), black mold (*Aspergillus niger*) and black bread mold (*Rhizopus stolonifera*) (Witbooi et al., 2000), and growth of bacterial cells e.g. soft rot (*Erwinia carotovora*) (Lund & Nichols, 1970), is promoted by free water resulting in decay and loss of produce. Because condensation usually occurs when cold produce is placed in a warmer environment this combination of free water and increasing temperatures creates ideal conditions for germination and growth pathogens. Therefore the duration of free water presence is important and is considered a key factor in disease development (Jarvis, 1977). Water condensation on the produce surface is almost inevitable in postharvest practice (Rodov et al., 2010).

## **2.3 Recommendations for minimizing condensation**

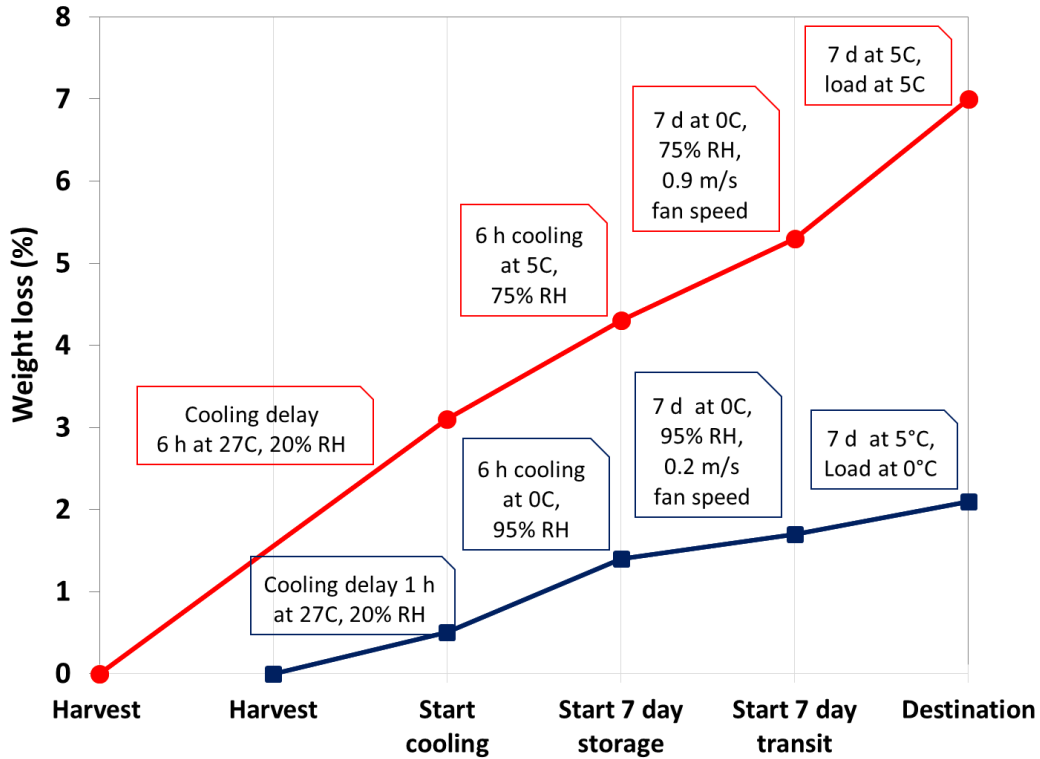
Temperature fluctuations, breaks in the cold chain and insufficient ventilation promote condensation. These changes can occur through poor handling or can be inevitable in the handling process, for example when produce is removed from cold storage for packing or for retail displays. Recommendations to minimize condensation include:

- Storing produce at very stable temperatures (Paull, 1999).
- Maintaining a continuous cold chain.
- Temperature conditioning of packing material, especially plastic bags or clamshells, so that they are at the same temperature as the produce prior to packaging.
- Packing in a cold room (not usually practical).
- Cooling decay-sensitive produce to above the dew point temperature until they are packed and then cooling to the desired storage temperature.
- Faster warming of cold fruit can reduce the length of time the produce is wet and therefore decrease conditions for disease development (Linke et al., 2005; Rodov et al., 2010).

## **3. Misconceptions in water relations**

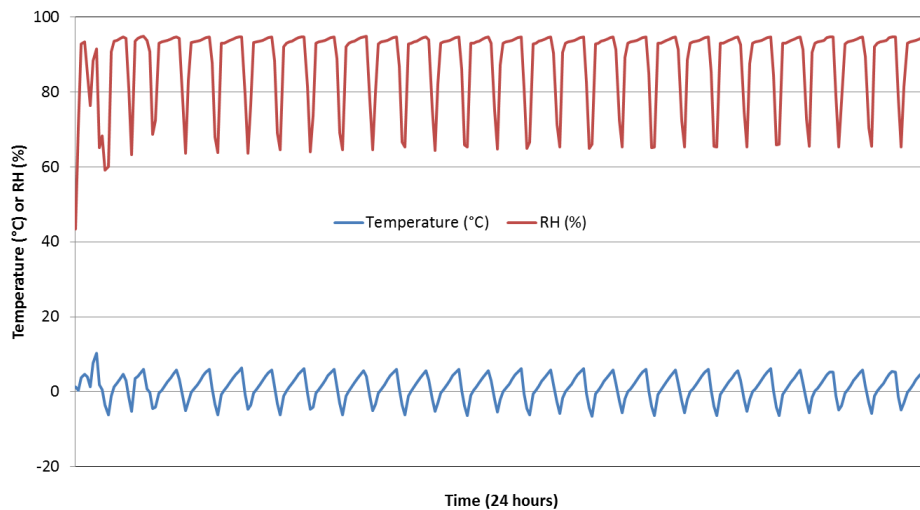
### **3.1 Storing in coolers dries out product**

Storing fruits and vegetables uncovered in a domestic refrigerator results in severe water loss which has led some people to conclude that low temperatures cause water loss. This is not correct. Lowering the temperature reduces the vapor pressure deficit and in turn reduces water loss. Therefore cooling rapidly after harvest and storing produce at low temperatures reduces water loss as shown in Figure 6.



**Figure 6** Weight loss (5) from table grapes resulting from two different cooling and handling regimes (redrawn from Figure 5 in Thompson et al., 2002).

The reason that produce loses water in a domestic refrigerator is that temperature fluctuations are large resulting in periods of a high water vapor pressure deficit followed by periods at freezing temperatures (Figure 7) which causes the water vapor in the air to condense on the coil. A cold room designed for produce with minimal fluctuations is required for fresh produce as described in section 1.4.



**Figure 7** Temperature (°C) and relative humidity (%) measured every 5 seconds over a 24 hour period in a refrigerator intended for storing sodas. The average temperature and relative humidity were 1.2°C and 87.6%, respectively.

### **3.2 Respiration and Transpiration**

Transpiration is the loss of water from fruits and vegetables and includes the transport of moisture through the skin of the commodity, the evaporation of this moisture from the commodity surface and the convective mass transport of the moisture to the surroundings. Respiration is the chemical process by which sugars are converted to energy. The reaction requires oxygen and gives off carbon dioxide, heat and water. The water released by respiration is contained in the cells of plants and is not directly lost. However, respiration gives off heat energy which increases the temperature of produce and therefore increases the VPD. Therefore, in practice produce is always slightly warmer than the ambient air because of the heat of respiration. For example, if a tomato is stored in a coldroom set at 12°C with 90% RH (VP = 12.6 mbar) and the tomato is assumed to be at 12°C and 100% RH (VP=14.0 mbar), the VPD between the air and tomato is 2.6 mbar. However, the heat of respiration will increase this temperature. If we assume that respiration resulted in a 1°C increase in the temperature of the tomato then the VPD would be higher e.g. 3.6 mbar (15.0 - 12.6 mbar).

### **3.3 Forced air cooling**

Forced air cooling increases air flow which increases the VPD between the produce and the air. However cooling slowly will maintain a higher VPD for longer. Therefore the slight loss of water associated with forced air cooling is offset by the rapidity of the cooling. Removing produce from the forced air cooler at 7/8 cooling time is recommended to reduce water loss. For very sensitive commodities high RH forced air coolers can be used.

### **Conclusions**

Water relations in harvested commodities is challenging because of the balance between the disadvantages associated with water loss and those associated with free water. Understanding this topic is important and using environmental variables to measure VPD is helpful and the availability of on-line psychrometric calculators makes it considerably easier to do so.

Newer refrigeration controls, more rugged humidity detectors and humidification technologies have increased the ability to vary both temperature and RH. These controls are now appearing in cold rooms and shipping containers and contributing to better control of RH during storage. However, emphasizing the critical role of temperature (the cold chain) in assuring quality fruits and vegetables is relatively simple but essential for good RH control.

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## Appendix: Psychrometric chart resources

### Psychrometric chart and definitions of terms

- ASHRAE, 2013. <http://www.techstreet.com/ashrae/products/1858361>
- Thompson, 2002c. Chapter on Psychrometrics and perishable commodities.
- Wikipedia: Psychrometrics <http://en.wikipedia.org/wiki/Psychrometrics>
- <http://www.swst.org/meetings/AM05/peralta.pdf> a website explaining use of psychrometric chart. There are no postharvest examples but it is a useful website to understand the chart.

### ASHRAE Psychrometric Chart App

- <https://www.ashrae.org/resources--publications/bookstore/psychrometrics#psychapp>  
This includes a video demonstrating the app which is a useful interactive explanation of a psychrometric chart.

### Online psychrometric calculators

- <http://www.sugartech.co.za/psychro/index.php>
- <http://www.psychrometric-calculator.com/>
- <http://www.daytonashrae.org/psychrometrics.shtml>

### How to measure relative humidity

- <http://v-ipo.caes.ucdavis.edu/Video/vid-ph-psychrometer-relative-humidity-lo-res.mp4>

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