Stewart Postharvest Review
An international journal for reviews in postharvest biology and technology

Pre-cooling systems for small-scale producers

Lisa Kitinoja[1*] and James F Thompson[2]
[1]Extension Systems International, Quartzsite, Arizona, USA
[2]Department of Biological and Agricultural Engineering, University of California, Davis, California, USA

Abstract
Purpose of review: To identify pre-cooling systems and cooling methods that are suitable for smaller scale horticultural producers
Findings: A range of pre-cooling systems are available for small-scale horticultural producers and their suitability is described, in terms of availability, ease of use, capital cost, energy requirements. Expected benefits of using pre-cooling are also discussed.
Limitations: Many of the mobile pre-cooling systems currently available on the market have been developed by commercial companies and most have not been scientifically evaluated in comparison to known stationary systems such as a cold wall. There is relatively little published information about the suitability of small-scale hydro-cooling, evaporative cooling and mobile forced-air cooling systems, especially regarding the range of crops and environments found in developing countries.
Directions for further research: Future research needs include identification and characterization of lower cost pre-cooling methods and continued efforts to improve their cooling efficiency and reduce their energy use. Efforts to standardize and test management practices that conserve energy should be undertaken in order to further improve financial benefits.

Keywords: pre-cooling systems; portable; mobile; small-scale; postharvest

Abbreviations

FA	Forced Air
GI	Galvanised Iron
ZECC	Zero Energy Cool Chamber

***Correspondence to:** Dr Lisa Kitinoja, Extension Systems International, PO Box 3130 Quartzsite, Arizona 85359, USA. Tel:+1 916 708 7218; email: kitinoja@postharvest.org

Stewart Postharvest Review 2010, 2:2
Published online 01 June 2010
doi: 10.2212/spr.2010.2.2

© 2010 Stewart Postharvest Solutions (UK) Ltd.
Online ISSN:1945-9656
www.stewartpostharvest.com

Introduction
Cooling is considered one of the most important steps in the postharvest handling chain. Reducing the temperature of fresh produce after harvest greatly reduces respiration rate, extends shelf-life, and protects produce quality, while reducing volume losses by decreasing the rates of water loss and decay. This first cooling step is usually referred to as "pre-cooling" since it is done as soon as possible after harvest and ideally accomplished before produce is placed into cold storage or loaded into refrigerated trucks or marine containers for shipment to market.

Pre-cooling systems for horticultural products were previously reviewed by Brosnan and Da-Wen Sun [1] and have been fully described by Thompson *et al.* [2], Thompson *et al.* in Kader [3] and by Thompson in the USDA Handbook 66 [4]. Pre-cooling methods include room cooling, hydro-cooling, forced-air cooling, vacuum cooling, and use of ice. These systems usually employ mechanical refrigeration, although there are some low cost alternatives such as radiant cooling, night air ventilation and evaporative cooling. Many of the most well known pre-cooling systems believed to be suitable and cost effective for smaller scale producers have been previously described by Kitinoja and Gorny [5], and Kitinoja and Kader [6].

Technical aspects

The need to pre-cool fruits and vegetables is well accepted, and is especially important for high-value and for highly perishable produce. Benefits include longer postharvest life, better maintenance of quality, lower losses due to weight loss, decay and water loss. Accrued benefits all contribute to improved earnings and higher profits, if pre-cooling systems are selected wisely.

Cooling involves heat transfer from fresh produce to a medium such as cold water, ice or cold air. Heat transfer processes include conduction, convection, radiation and evaporation. Vacuum cooling is used in developed countries for cooling some leafy vegetables. However it has a high capital cost and is rarely suited for use by small-scale operations.

If a ready supply of electricity is available, mechanical refrigeration systems provide the most reliable source of refrigeration. A new controller for air conditioners allows a low cost wall-mounted unit to operate as a low temperature refrigeration unit capable of reaching 0^{o}C [7]. Evaporative cooling is a low cost method of refrigeration that uses water-soaked media in “swamp coolers” or “desert coolers” requiring only the use of an electric fan [8] or require no electricity use in passive systems such as “clay in clay” cool boxes [9], “zero-energy” chambers made of bricks and sand [10], or some kind of fibre, rice hulls, straw or charcoal filled walls [11–14]. A variety of portable forced-air coolers have been designed for use inside cold rooms by small-scale growers and handlers [15–17] and these will be described. Table 1 provides a summary of the types of small-scale equipment and pre-cooling systems that are currently available.

Selection of the most appropriate pre-cooling system

Table 2 provides a comparison of the typical characteristics and relative costs of pre-cooling systems suited to small-scale operations. When selecting a pre-cooling system producers need to consider the characteristics of their crops (their chilling sensitivity, water tolerance), the volume to be cooled per day or per hour, initial temperature versus target temperature, capital and operating costs of the pre-cooling system, and the expected improvement in earnings associated with using pre-cooling.

Room cooling

Room cooling is a relatively low cost but very slow method of pre-cooling. Produce is simply loaded into a cold room, and cold air is circulated around the cartons, sacks, or bins. This cooling method is best suited to less perishable commodities such as potatoes, onions, apples, sweet potatoes and citrus fruits, since more highly perishable crops will deteriorate before being adequately cooled. Room cooling may be well suited to chilling sensitive crops that are cooled from relatively cool early morning harvest temperatures to storage temperatures of 10–13ºC (50–55 ºF).

It is important to leave adequate space between stacks of boxes inside the refrigerated room in order for produce to

Table 1. Examples of pre-cooling technologies and systems available in 2010 for small-scale producers [1–18].

Refrigerated room cooling (slow cooling)	Passive evaporative room cooling (use of water soaked media)	Forced-air cooling (use of cold air forced through packages to speed cooling)	Hydro-cooling (use of cold water for rapid cooling)	Other
Pre-fabricated traditional cold rooms	“Clay in clay” passively cooled storage chambers	Portable FA pre-coolers	Shower type batch hydro-coolers	Harvesting early in the morning (except citrus crops)
Self-built traditional cold rooms	“Zero-energy” cool chambers (bricks and sand)	Cool & Ship – an insulated pre-cooling box with A/C unit designed by NCSU [19]	Immersion type conveyor hydro-coolers	Use of shade after harvest
Retrofitted refrigerated container trailers (new and used)	Charcoal or fibre filled walls of non-refrigerated cold rooms	Portable three-bay FA coolers	Mobile hydro-coolers	Use of package ice (crushed or slurry ice)
CoolBot unit for window style air conditioner in cold room		TORNADO mobile forced pre- cooling systems		Night air ventilation of insulated non-refrigerated cold rooms
USDA Porta-cooler (small trailer mounted pre-cooler)				Underground cooling (caves, root cellars)
Electric powered “desert coolers” (aka “swamp coolers”) on insulated non-refrigerated cold rooms				High altitude cooling where ambient air temperatures are lower than average
				Solar chiller

Table 2. Comparison of typical product effects and relative cost for six common cooling methods (modified from [2]).

	Room	Forced-air	Hydro	Electric evaporative	Passive evaporative	Package ice
Typical cooling time (h)	20–100	1–10	0.1–1.0	20–100	40–100	0.1–0.3
Produce moisture loss (%)	0.1–2.0	0.1–2.0	0–0.5	No data	No data	No data
Water contact with produce	No	No	Yes	No	No	Yes
Potential for decay contamination	Low	Low	High	Low	Low	Low
Capital cost	Low to medium	Low	Low	Low	Low	High
Energy efficiency	Low	Low	High	High	High	Low
Portability	No	Sometimes	Rare	No	Possible	Yes
Limitations and concerns			*	**	**	***

*Re-circulated hydro-cooler water must be constantly sanitised to minimise buildup of decay organisms
** Evaporative cooling to a few degrees above the ambient wet bulb temperature is possible
*** Melting ice can cause physical hazards during transport and unloading; packages need to be moisture proof and therefore tend to be expensive

cool more quickly. According to Thompson *et al.* [3], about 4–6 inches (10–15 cm) is sufficient to allow cold air to circulate around individual boxes or pallet loads. Produce in vented boxes will cool much faster than produce packed in un-vented boxes. In many small-scale cold rooms, produce is loaded into the room so tightly that cooling cannot take place at all, and despite the cost of running the refrigeration system, the produce temperature never decreases to recommended levels.

Stacks of produce inside the cold room should be narrow, about one pallet width in depth (two or three cartons). Fans should be installed to move the cold air throughout the room. Air circulating through the room passes over surfaces and through any open space, so cooling from the outside to the center of the stacks is mostly by slow air infiltration. It is important to monitor the temperature of the produce within the packages at various locations in the room to determine that the produce is being cooled as quickly as desired, and to rearrange the stacks and measure the rate of cooling until the right stacking pattern is determined for each cold room.

Mechanical refrigeration is the only commercially-available method for obtaining precise low temperature control for perishable commodities. Alternate methods like evaporative cooling do not provide the 0 to 5°C (32–41°F) temperatures needed for temperate and sub tropical fruits and vegetables, and in many highly humid areas will not even provide the temperatures near 12–13°C (54–56°F), which are recommended for tropical produce.

Small-scale commercial refrigeration systems are available in most parts of the world and are widely used for restaurants, stores and other small-scale cold room needs. The system consists of an air-cooled compressor/condenser unit installed outside and an evaporator unit (refrigeration coil) installed inside the cold room. A complete installation also requires electrical connections, a thermostat controller, refrigeration piping to connect the compressor/condenser with the evaporator, and a charge of refrigerant. A system installed in the USA costs about $7,000 for 3.5 kW (1 ton) of refrigeration capacity and about $8,500 for 7 kW (2 tons) of refrigeration capacity (Table 3). Costs will vary widely depending upon whether the cold room is pre-fabricated (new or used), owner built or a retrofitted highway van or marine container (Table 4).

The refrigeration capacity shown in Table 5 will be affected mainly by the climate in which the cold room is located. The lower number in each range will be the case for moderate climates where the temperatures do not vary widely, such as those found near oceans. The higher number in each range will be for the hottest times of the year or for hot climates such as the lowland tropics or semi-arid regions. Approximately 60% of the floor space is usable for storage, as the rest is taken up by doorways, aisles and open space left along the walls. A conservative estimate of energy use for cold storage electricity use is the 55 kWh/MT factor for forced-air (FA) coolers in California, since these operate in a relatively warm environment and handle large volumes of fruit each day [21].

ColdBot-equipped cold room

Another option for providing refrigeration is to use a modified room air conditioner, a method originally developed by Boyette and Rohrbach in 1993 [26]. The control system of the unit is modified to allow it to produce low air temperatures without building up ice on the evaporator coil. The ice buildup restricts airflow and stops cooling. Recently a company developed an easily installed controller that prevents ice build up but does not require modifying the control system of the air conditioner (Cool-Bot, Store It Cold, LLC, http://

Table 3. Costs (2009) of installing a commercial refrigeration system for a small-scale cold room for fresh produce.

	Cost (USD per m²)	
Refrigeration capacity	3.5 kW (1 ton)	7 kW (2 tons)
Cold room area	9.3 – 19 m² (100 – 200 ft²)	19 – 37 m² (200 – 400 ft²)
Commercial refrigeration system		
Refrigeration equipment	3,000	4,500
Electrical, piping, refrigerant	2,000	2,000
Labour	2,000	2,000
Total for commercial refrigeration	7,000	8,000

Table 4. Cost (2009) of buying and installing small-scale cold rooms in the USA.

	Cost (USD per m²)
New prefabricated	800
Used prefabricated	180 – 530
Highway van	590 – 800
Refrigerated marine container	620 – 760
Owner built	180 - 360

Table based on Thompson and Spinoglio [20] for facilities with about 40 m² floor area. Costs were multiplied by 1.65 to account for inflation. Adjustment was based on the USA consumer price index for other goods in an average USA city.

Table 5. Approximate refrigeration capacity for small-scale cold rooms.

Size of cold room (m²)	Storage capacity (MT)	Range of refrigeration capacity (kW)	
		Target = 1°C	Target = 13°C
10	3	3.5	2.6
20	6	5.3–8.8	3.5–5.3
40	12	12.3–14.1	7.0–10.6
60	18	17.6–22.9	10.6–14.1
80	24	22.9–29.9	14.1–19.4
100	30	26.4–35.2	15.8–24.6

Sources: Thompson and Spinoglio [20], modified from Winrock Int'l [21].

storeitcold.com). Assuming prices in USD, a room air conditioner with a Cool-bot control system costs about 90% less than an equivalent capacity commercial refrigeration system (Table 6). The control system is designed so that any moisture condensed on the refrigeration coils is returned to the cold room air and the system will likely cause less product moisture loss than a commercial refrigeration system.

The total cost of three sizes of panellised cold rooms with refrigeration is summarised in Table 7. The least expensive option per m², the larger room with the room air conditioner, is about 40% less expensive than the most expensive option, a small room with a commercial refrigeration system. The majority of the cost is the insulated walls and ceiling, particularly when using the room air conditioner. In the USA, the room cost can be reduced by about 50% by buying used insulated panels. Owner constructed rooms also reduce cost by about half. Wood-frame construction with fibreglass insulation is the most common technique. It is the same method for houses except a continuous plastic film vapour barrier must be installed on the outside surface of the insulation to prevent water vapour condensing in it.

Forced-air cooling

FA cooling pulls or pushes air through produce containers, greatly speeding the cooling rate of any type of produce. Many types of forced-air coolers (aka, pressure coolers) can be designed to move cold air past the commodities. Examples include a fixed unit, where a fan is housed inside the wall of a cold room [22], or a portable fan unit that can be moved around inside the cold room as needed [16]. When utilising a tunnel-type forced-air cooler, the canvas sheets must be well sealed over the top of the load, and pallet openings blocked for the cooler to function properly. Package vents must be aligned between boxes to allow the air to flow across a pallet of boxes (Figure 1).

Forced-air cooling reduces the cooling time of a batch of packaged produce from one or more days in a room cooler to a few hours. If a cold room with adequate refrigeration capacity is available, adding a portable forced-air cooling tunnel that can cool 4 pallets at a time will increase the fan's power use by only 800 to 1,500 W/h. A cold room with 17.6 kW (5 tons) of refrigeration can cool 3 MT of horticultural produce from an initial temperature of 27°C to a target temperature of 2°C in 6 to 8 hours [21, 23].

Forced-air coolers were first used in California in the 1950s [24]. A simple portable FA cooler is constructed using a canvas or polyethylene sheet [15]. The sheet is rolled over the top and down the back of the boxes to the floor, sealing off the unit and forcing air to be pulled through the vents of the cartons. This unit is designed to be used inside a refrigerated storage room. The fan unit is shown detached to illustrate how the air should flow within the cooler (Figure 2). The warm exhaust air from the fan should be directed toward the return air side the refrigeration coils.

Table 6. Costs (2009) of installing a modified room air conditioner for a produce cold room.

	Cost (USD per m^2)	
Refrigeration capacity	3.5 kW (1 ton)	7 kW (2 tons)
Cold room area*	9.3 – 19 m^2 (100 – 200 ft^2)	19 – 37m^2 (200 – 400 ft^2)
Room air conditioner system*		
Room air conditioner	300	550
Cool-bot controller	300	300
Total for room air conditioner	600	850

*Costs based on published prices for air conditioners and ColdBot controller unit [7].

Table 7. Cost of a panellised cold room installed in the USA.

	Cost (USD per m^2)		
Floor area	10 m^2	20 m^2	40 m^2
Cold room*	9,000**	13,000	23,500
Commercial refrigeration	–	7,000	8,500
Total w/commercial refrigeration	–	20,000	32,000
Room air conditioner w/ Cool-bot	550	600	850
Total w/room air conditioner	9,550	13,600	23,850

*Based on data in [21].
**Extrapolated based on the mean cost per area of insulated panels for 20 and 40 m^2 rooms.

General rules for packing and packaging to accommodate FA pre-cooling [2, 3, 21, 24, 25]

- The width of the centre air return tunnel should be a minimum of 20 cm when four full-sized pallet loads are placed on the cooler, and a minimum of 30 cm when six pallets are placed on the cooler.
- Because air is forced through the produce packages by the difference in air pressure between the cold room and the inside of the cooling tunnel, stack them in such a way as to minimise voids and openings between boxes.
- Openings between containers allow the air to bypass the produce, reducing cooling efficiency. Barriers such as fibreboard pieces or wooden boards may be positioned over unavoidable openings (such as pallet openings under the load) to direct the air into the vents, holes and through the containers of produce.
- Internal packaging materials should be selected to minimise airflow restriction. Produce packed in consumer bags will cool more slowly because the bags prevent the cold air from directly contacting the product. Internal plastic-film box liners dramatically increase cooling time because the liner is often forced against the vent openings and slows or prevents airflow into the box.
- Stacking pallets two deep should be avoided because this slows cooling and causes increased difference in temperature between product in the cool and warm sides of a pallet load.
- The recommended size and pattern of vents for cartons used to hold produce is 5% of the total surface area, and located 5 to 7.5 cm (2 to 3 inches) away from the corners. A few large vents (1.3 cm = 0.5 inch wide or more) are better than many small vents.

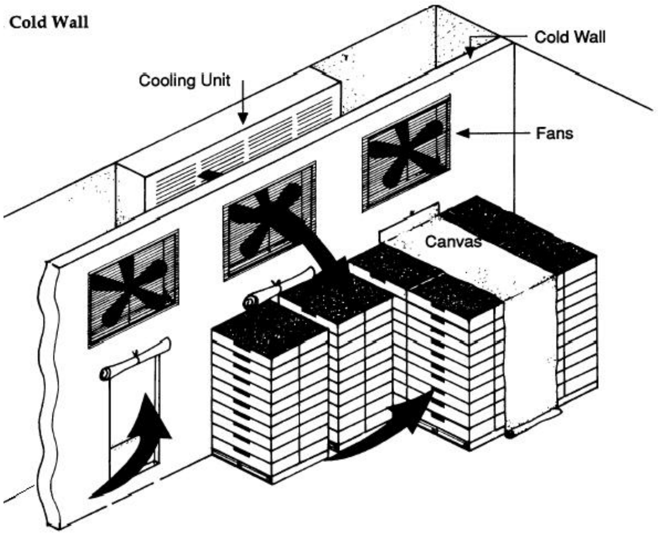
Portable forced-air cooling units

Two types of portable pre-coolers currently exist and both have been tested extensively [19, 26, 27]. They can be self-constructed at relatively low cost, and complete plans are available on the internet on the NCSU website http://www.bae.ncsu.edu/programs/extension/publicat/postharv/ag-414-7/index.html and the ATTRA website (http://www.attra.ncat.org).

The USDA Porta-cooler can be carried on traditional small-scale transport vehicles [27]. A small insulated box (3.5 m^3), holding approximately 700 kg of produce, fitted with a room-sized air conditioner (2.9 to 3.5 kW) and diesel-powered generator (2 kW) can be pulled as a trailer or set into a pick-up truck bed. These units can be operated successfully at temperatures of 10°C or above with good results, making them most useful for transporting tropical and sub-tropical horticultural crops. At temperatures below 10°C, however, ice will build up on the coils, and the air conditioner will not work as designed. Room air conditioners are designed to produce low relative humidity air that can cause unacceptably high water loss during cooling of fruits and vegetables. Water loss can be reduced by using plastic liners in containers.

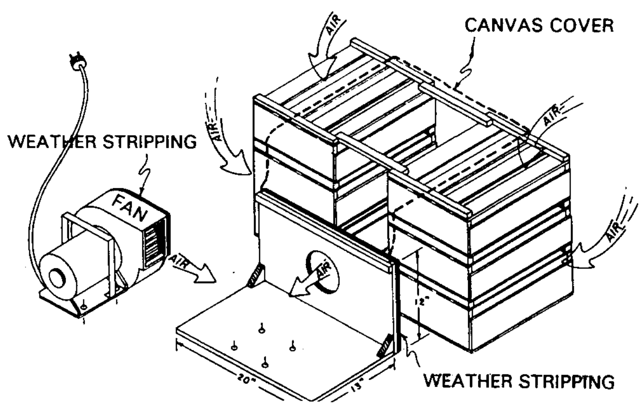
The original Porta-cooler (Figure 3) was built by a team at USDA, Beltsville, Maryland, to pre-cool highly perishable berries and other air cooled produce. It uses a 12,000 BTU/h (3.5 kW) 110 volt room or window air conditioner to cool air inside the insulated box. The cool air inside the front of the box is forced through the produce by a pressure fan in a second wall inside. The return air passes under a false floor to the front of the box. The approximate cost is $US 1,200, but the cost can be considerably lower if it is built using a used air conditioning unit. The original plans required rewiring the air conditioner unit so it can achieve a temperature below 15°C, but currently it is possible to purchase a ready-made CoolBot control system and not void the warranty. The CoolBot system has not been tested to determine its effect on rela-

Figure 1. Tunnel-type forced air cooling using the cold wall system.



Source: Gast and Flores [22].

Figure 2. A portable forced-air cooling unit.



Source: Parsons and Kasmire [15].

tive humidity, but the unit is designed to defrost the coils using cold room air and has little potential of removing moisture from the room air.

Mobile forced-air cooling systems

Depending on the commodity and packaging, the usual configuration for mobile forced-air pre-cooling systems is to pre-cool 10 pallets per cycle in a custom 48-foot container with a stainless steel interior and a stainless steel plate floor. A standard 40-foot container can pre-cool about 8 pallets per cycle. These containers are readily available from companies in China, but refrigeration and airflow capacities vary widely. Generally the fans and refrigeration coil occupy about 7 feet in the nose and are connected to a refrigeration unit via piping. Some companies add more insulation, improving energy efficiency but decreasing the volume that can be cooled in a batch load.

Another mobile pre-cooling system involves the use of a docking module which houses the electrical, refrigeration, and air handlers on a skid or trailer. A container or van is loaded with warm produce and with the rear doors left open, it is backed against the cooling module where it is sealed against a cushion and the cooling unit is started. This system is used for melons in the Southwest USA and Mexico and typically the docking system has up to three cooling modules on a 48-foot equipment trailer. This system requires no modification to the shipping vehicle. Cooling times are about 3–10 hours depending on packaging and product [28]. The configurations possible inside these standard containers make it difficult for successful pre-cooling of fresh produce in a 20- or -40 ft refrigerated highway trailer because of limited floor area for supply and return air channels, and inadequate refrigeration capacity.

Researchers at the University of Florida's Center for Food Distribution and Retailing (cfdr.ifas.ufl.edu) have recently been working with Thermo King (www.thermoking.com) and helped to convert its standard Magnum marine container into a forced-air pre-cooler capable of 7/8ths cooling of a small volume of fresh produce (1.5 MT) in about 2 hours [29].

CoolForce Co. (USA) markets a three-port mobile forced-air pre-cooler mounted on 53' x 102" trailer with strong steel frames, air ride suspension and extra, permanently mounted, front and rear stabiliser legs [18]. The Mobile Pre-cooler is designed to pre-cool one to three trailer loads of fresh fruits or vegetables, which may be too large for most small-scale operations. A total of 150 tons of refrigeration is available through a patented high humidity air handler. Each port delivers up to 37,000 CFM of chilled air at nearly 100% relative humidity at a static pressure of 3.8 cm (1.5 in) of water column. Each port can be operated independently. The pre-cooler can easily be relocated, without escort, using a standard semi-tractor truck.

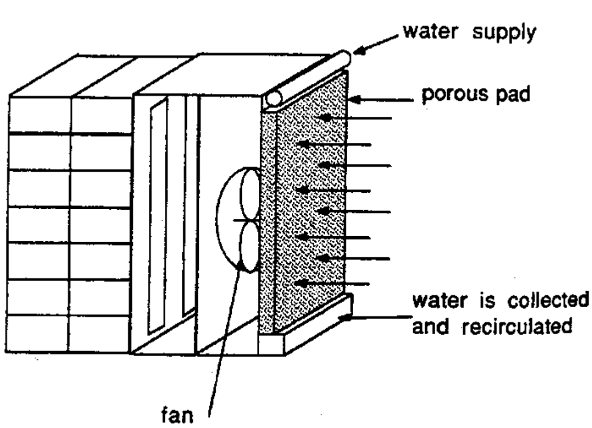
RINAC (India)

For pre-cooling of horticultural produce at the farm-level Rinac has designed a special range of mobile and stationary pre-coolers that are well equipped with power back-ups, storage facilities and multi-method pre-cooling options [18]. Batch sizes from 1,500 kg to 5 MT are reported to reach target temperatures in 1.5 to 4 hours.

There are no published evaluations of any of the above commercial systems to date. They are designed to be leased from

Figure 3. USDA Porta-cooler.

Figure 4. Evaporative forced-air cooler [3].



the supplier on an as needed basis, and fees will vary based upon distance to site, length of lease and time of year.

Evaporative cooling for room cooling or forced-air pre-cooling systems

Evaporative cooling units, sometimes called "swamp coolers," or "desert coolers", use the evaporation of water to produce cool air. Evaporative coolers have a low initial cost, and use much less electricity than mechanical refrigeration systems.

For desert or semi-arid climates, an evaporative cooling unit can be substituted for a mechanical refrigeration unit, requiring only 12 volt or 24 volt power to run a small water pump and a fan. Cooling to a few degrees above the wet bulb temperature is possible. Evaporative cooling is more energy efficient at lower fan speeds and colder air temperatures at lower ambient relative humidity levels.

When low air temperatures are not needed, an evaporative cooler will be a less expensive and better performing option for the porta-cooler. The evaporative cooling unit can replace the air conditioner in the design, and a deep cycle battery can supply the power to run a small water pump (1 L/min, requiring 10 watts or less) and a 100 to 200 watt fan for moving air through the wet pad of the cooler. The interior of these cool boxes is 3.5 to 7.0 m^3, and the fan needs to be able to provide one air exchange per minute and move the air against a static pressure of 0.6 cm w.c. (approximately 64 to 128 cfm). An exit vent must be provided at the back of the load to allow the evaporatively-cooled air to move completely through the load and exit the cooled volume. If the unit is on a truck, it can be fitted with an air scoop above the cab to force air through the unit when the truck is moving so the fan power is required only when the unit is stationary.

In a direct evaporative cooler, a blower forces air through a permeable, water-soaked pad. The pads can be made of straw, wood shavings or other materials that absorb and hold moisture while resisting mildew. Aspen fibre pads, also called excelsior, need to be replaced every season or two, and generally cost $20 to $40 for a set of two [21]. As the air passes through the pad, it is filtered, cooled, and humidified. Evaporative coolers are sized based on airflow rates. Airflow for evaporative coolers is typically higher than conventional air conditioning systems. Evaporative coolers with too much airflow waste water and energy. Coolers with two-speed fans are available that can handle varying cooling loads.

Evaporatively-cooled storage rooms require a fan capacity of 0.3 m^3/s per MT of fresh produce (64 cfm/MT) [3, 8]. Assuming the fan operates against a static pressure of 0.6 cm of water column and has 50% efficiency, the system will consume 0.09 kWh of electricity per MT of product storage capacity per day of operation [21]. The fan operates continuously when the outside air temperature is greater than the desired storage temperature. The fan should have the capacity to exchange the air in the room completely once every two minutes. Table 8 provides estimates of cooler size and energy use for storage rooms and small portable cooling units.

For evaporative forced-air cooling, the fan should provide an airflow of 1 L/s-kg against a wide range of static pressures. For example 225 kg of tomatoes can be cooled in about two hours with a 0.1 HP fan, and requires about 0.15 kWh of electricity. Energy use is then about 0.7 kWh per MT [21]. Packaged evaporative coolers located in the peak of a storage structure can cool an entire room of stored produce such as sweet potatoes or other chilling sensitive crops. The vents for

Table 8. Estimated equipment sizing and energy use for selected evaporative coolers [21].

	40 m^2 Cool room (430 ft^2)	20 m^2 Cool room (215 ft^2)	Porta-cooler large (6 m^2 or 64 ft^2)	Porta-cooler small (3 m^2 or 32 ft^2)
Capacity (MT)	10 to 13	5 to 6	0.8 to 1.0	0.4 to 0.5
Cubic meters	100	50	7.0	3.5
Cubic feet	3,500	1,765	256	128
Fan capacity (cfm)	1,664	768	128	64
kWh/day	0.9 to 1.2	0.45 to 0.54	0.07 to 0.09	0.04 to 0.05

outside air should be located at the base of the building so that cool air is circulated throughout the room before it exits. In California this design is used to store sweet potatoes at 13°C during the fall, winter and spring storage seasons [8].

Two-stage evaporative coolers have been developed that pre-cool air before it goes through the moistened pad. According to Dieckmann *et al.* [30] these new "indirect-direct" coolers are reported to be as effective as mechanical air conditioning and can reduce energy consumption by 60–75% over conventional air conditioning systems. They can cool successfully to near 10°C where tested in California and the Southwest USA, but their initial cost is high – about $5,000 for a 3 ton system, approximately the same cost as air conditioning units of similar size (2009 prices).

An evaporative cooler can be combined with a forced-air cooler for small lots of produce that require pre-cooling to temperatures in the range from 2 to 3°C above the wet bulb temperature (Figure 4). The fan must be able to provide airflow of 1 L/s-kg against a wide range of static pressures. Doubling the airflow will speed cooling somewhat but the cost will rise considerably because the fan would need to have approximately six times greater horsepower to accomplish the same work, although electrical energy consumption may go up by only a factor of four because cooling time is decreased [2, 3, 21, 31–33].

Passive evaporative cooling storage systems

In Nigeria, a recent example of the "clay in clay" style cooler was described by Anyanwu [9]. A small clay storage box with a total storage volume of 0.014 m^3, consisting of a box-shaped porous clay container located inside another clay container, created a moist, cool environment for tropical vegetable crops.

In the Philippines, an evaporative cooler equipped with a vortex wind machine has been used to cool vegetables [5, 11]. Chicken wire was used to construct two thin boxes on opposite sides of the cooler that hold wet chunks of charcoal or straw. Water is dripped onto the charcoal or straw, and the wind turns the turbine, sucking moist, cool air through the load of produce in the cooler. This cooler produces temperatures 3 to 5°C (6 to 10°F) below ambient air temperature, when ambient relative humidity is about 85%.

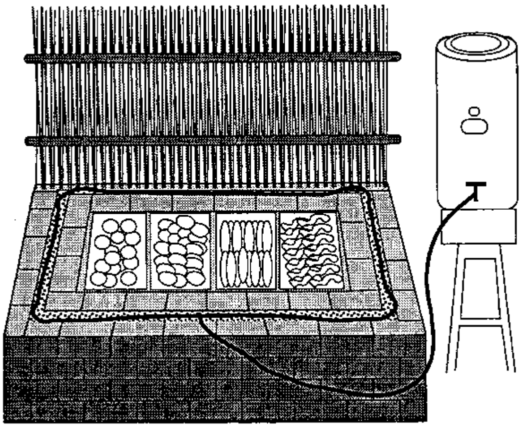
A second type of cooler stands in a galvanised iron (GI) pan of water, and has a pan of water on top [5, 12]. The sides and top are covered with jute sacks kept wet by dipping their top and bottom edges into the pans of water. Also in the Philippines, a cooler has been constructed with the inner side walls made from plain GI sheet with fine holes (spaced at 5 x 5 cm) while the outer walls are made of fine mesh (0.32 cm) wire [5, 13–14]. The 1.5 cm space between the inner and outer walls is filled with rice hulls, kept wet by contact with a cloth that wicks water from pan placed on top of the cooler.

Produce stored in these passive evaporative coolers has a longer shelf life than produce kept at ambient conditions. Tomatoes and peppers lost less weight and ripened more slowly, and could be kept for as long as they typically can be stored under refrigeration (about 3 weeks). Decay can be a problem, but can be controlled by washing produce in chlorinated water prior to cooling. Mustard greens lost much less weight and showed little wilting for up to 5 days compared with not being cooled.

A low cost pre-cooling chamber named a "zero energy cool chamber" (ZECC) is constructed from stacked bricks. A cavity between double walls is filled with sand and the bricks and sand are kept saturated with water. Fruits and vegetables are loaded inside, and the entire chamber is covered with a rush mat, which is also kept moist. Since a relatively large amount of materials are required to construct this cool storage chamber, it may be useful only when handling high value products.

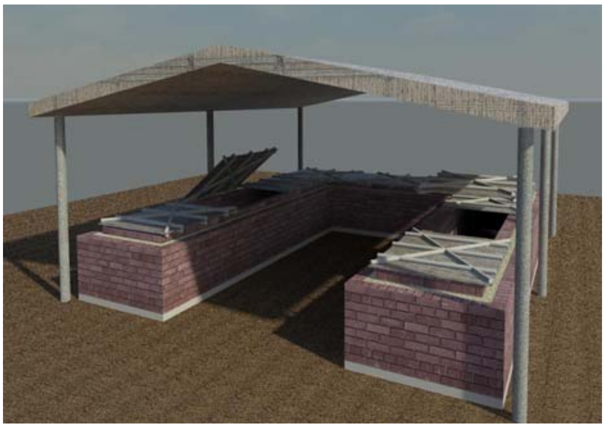
During the hot summer months in India, this chamber is reported to maintain an inside temperature between 15 and 18°C (59 and 65°F) and a relative humidity of about 95% [5, 6, 10, 34]. A variety of different sized models (Figures 5 and 6) were tested in a series of field trials conducted during 2009 as part of the WFLO "Appropriate Postharvest Technology" planning project, and soon to be published results indicate that the ZECCs from 100 kg capacity to 1000 kg capacity

Figure 5. Improved zero-energy cool chamber.



Source: Roy [10]; Illustration from [6].

Figure 6. The most recent design for the "walk-along" model of the ZECC was developed by SK Roy and colleagues at Amity University in India in 2009 [34, 35].



performed equally well in reducing postharvest losses and maintaining quality [34].

Hydro-cooling

Hydro-cooling provides fast, uniform cooling for some commodities. The commodity as well its packaging materials must be tolerant of wetting, chlorine (used to sanitise the hydro-cooling water), and must not be susceptible to water beating damage [33].

Hydro-coolers cause no moisture loss in cooling, and can rehydrate slightly wilted product. Hydro-cooler water will spread decay organisms, so it must be obtained from a clean source and chlorinated (usually with hypochlorous acid from sodium hypochlorite or gaseous chlorine) to minimise the levels of decay organisms in the water during pre-cooling [2]. Calculations of hydro-cooler size, refrigeration capacity, water flow needs and typical product cooling times can be found in Thompson *et al.* [2]. Hydro-coolers can be fairly energy efficient and are among the least expensive cooling methods to purchase [3].

Immersion hydro-coolers are large, shallow, rectangular tanks that hold moving chilled water. Crates or boxes of warm produce are loaded into one end of the tank and moved by hand or on a submerged conveyor to the other end where they are removed. Crushed ice or a mechanical refrigeration system keeps the water cold, and a pump keeps the water in motion. Most produce is only slightly buoyant so the individual produce items tend to stay submerged. The length of time the produce remains in the water varies with the initial product temperature and minimum product diameter [3].

A shower-type cooler distributes icy water over produce placed in the cooler. Water is collected under the product, cooled again and recirculated back to the top of the cooler. A batch-type hydro-cooler can be constructed to hold small quantities in wooden or plastic crates or entire pallet-loads of produce [3, 36] can be added to help control the time produce stays in contact with the cold water. Water is cooled using ice or mechanical refrigeration. Water is a better heat-transfer medium than air, so hydro-coolers cool produce much more quickly than forced-air coolers. In well-designed shower type hydro-coolers, small diameter produce such as cherries will cool in less than 10 minutes, while large diameter products such as melons will cool in 45 to 60 minutes [3].

Refrigeration capacity requirements will depend upon the amount of produce to be cooled per hour, the incoming temperature of the produce, final temperature of the produce, and the amount of external heat that enters the hydro-cooler water through air infiltrating into the cooler and conducted across the walls of the cooler. The refrigeration capacity for a common hydro-cooler employing no special energy conservation measures is twice the heat to be removed from the product. An energy efficient unit would need only 50% capacity above what is needed for product temperature drop. To cool 500 kg of produce per hour, 1.4 kW of refrigeration capacity is needed to achieve an 11°C temperature drop; 2.8 kW for a 24°C drop; or 5.3 kW for a 39°C drop. A hydro-cooler installed in a cold room will require about 30% less refrigeration capacity than an insulated hydro-cooler installed outdoors [2, 3].
A small-scale cabinet type hydro-cooler used for pre-cooling 15 to 20 kg batches of produce was recently tested in Hawaii [37]. Sixteen rows of spray nozzles, pressurised with a two-

stage booster pump, were enclosed in an insulated chamber. The reservoir holds 40 L of ice-chilled water and the loading door is closed during operation to reduce heat infiltration and water losses. Cucumbers and lychee fruits were successfully hydro-cooled without injury. Cucumbers required 40 min and lychee required 12 min to obtain a core temperature of 15°C and 5°C, respectively.

A small-scale shower type hydro-cooler was designed to cool a 50 kg-batch of horticultural produce, developed, and evaluated at Punjab Agricultural University in India [38]. The model hydro-cooler cooled 200 L of water from 31.7 to 8.5°C in 1 hour. During 1 hour of hydro-cooling mangoes the pulp temperature dropped from 31.5 to 14°C, which is within the recommended storage range of 13–15°C. The energy requirement for hydro-cooling one batch was estimated to be 3.5 kWh (the equivalent of 70 kWh/MT).

A 2008 California Energy Commission study [40] indicated an electricity use of 107 kWh/ton for asparagus hydro-cooling, including refrigerated short-term storage. Only 37% of the heat input to the facilities was from the product, indicating product cooling required only 40 kWh/ton. Typically asparagus requires only a 9°C temperature drop since it is harvested during cool, early spring mornings when temperatures are relatively low, while the mangoes in India were cooled by 23°C. The electricity use would increase by 2.5 to account for the greater temperature drop. The expected equivalent energy use would be 110 kWh/MT. Laboratory tests with short runs of product are often less energy efficient than actual commercial operations.

Use of ice

Ice can be used either directly as package ice, to cool water for use in a hydro-cooler, or as an ice bank for a small forced-air or room cooling system. Ice can be manufactured using simple solar PV systems, where flat plate solar collectors are used to generate power to make ice, which is then used to cool produce [41].

Package ice

Crushed or flaked ice for package icing can be applied directly or as a slurry in water [3]. Although the use of ice may cause some initial water loss from the produce as water transpiring from warm produce will condense on the ice, the residual unmelted ice and melt water provides a high relative humidity environment around the product, which will slow any further water losses. Package ice can be used only with water tolerant, non-chilling sensitive products and with water tolerant packages (waxed fibreboard, plastic or wood).

Ice banks or ice bunkers

A small-scale ice-based pre-cooling unit has been designed for use by small-scale horticultural marketers in Canada [41]. It is designed to be mounted on a pick-up truck, but can be modified to mount on a trailer if desired. The unit consists of a storage chamber divided into produce, ice bin and engine/fan compartments. A fan forces air down through a bed of ice, along a plenum on the floor, up through containers of produce in the produce compartment and back through the fan. Air exits the ice bed at or below 2°C. The horizontal ice bin system unit is designed to handle a maximum of 317 kg of product. This amount of fresh produce requires about 168 kg of ice to lower the temperature by 28°C. Complete plans are available online at http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex7471.

Cooling with transported ice allows a central ice making plant to provide cooling to locations where electricity and mechanical refrigeration are not available. This was the original basis for the development of the long distance perishables business in the USA. However, cooling using ice is relatively inefficient because only about half the cooling effect is actually used to cool the produce. The rest is lost to heat exchange with the warm environment [43]. In addition there can be significant loss of ice as it melts in transit from the central refrigeration plant to the cooling facility. Making ice is an energy intensive process and can be expensive [21]. Most ice machines produce between 5 and 12.5 kg of ice per kWh. One of the most energy efficient ice makers available, Crytec's Bubble Slurry™ Ice machine Model CR-004, produces 18.5 kg of ice per kWh and has a capacity of 146 kg of ice per hour, but it is very expensive. Since 330 kg of ice would be required to cool one MT of fresh produce by 28°C, requiring up to 66 kWh for the least efficient ice making machine, the cost of making ice for this purpose can often be prohibitive [44].

Solar chiller

Prototypes of this ice-based cool box are available via a United Nations program, using a solar powered 3 x 60 W PV array and ice as the energy storage medium (rather than batteries which tend to have a short life in hot climates and create environmental hazards if not recycled properly). Cost is estimated at less than $2,000 for a unit that has a storage capacity of 50–100 L. These units would be best used for pre-cooling and temporary storage of highly perishable high value crops such as fresh cut fruits or vegetables, strawberries, bean sprouts or mushrooms [18].

Alternative methods of refrigeration and shade

A variety of simple methods exist for cooling produce where electricity is unavailable or too expensive to use mechanical refrigeration systems. Examples of alternative systems include the use of shade [45], night air ventilation, radiant cooling, underground (root cellars, field clamps, caves) or high altitude storage [3].

Use of shade

Rickard and Coursey [45] measured pulp temperatures in horticultural produce exposed to the sun of 3° to 10°C higher than that of the ambient air temperature. Tomatoes and eggplant left in the sun for 1 hour after harvest will be at least 15°C (25°F) hotter than fruit held in the shade [3, 34]. Pro-

Table 9. Characteristics and relative costs of selected pre-cooling systems

Cooling technology	Purchase Price (USD)	Crops suited to the pre-cooling system	Typical size or capacity	Energy Use per MT (kWh)	Cost per MT at an electricity rate of $0.20/kWh
Evaporative forced-air cooling (0.1 HP fan) to 13°C	$400	Tropical fruits and vegetables	0.5 MT	0.7	$0.14
Evaporative forced-air cooling (0.5 HP fan) to 13°C	$1,300	Tropical fruits and vegetables, potatoes	1 to 2 MT	0.7	$0.14
Ice put into packages (330 kg required to cool 1 MT by 28°C)	$6,000 to $10,000	Broccoli Sweet corn Radishes Carrots with tops Green onions	5 to 12.5 kg ice/kWh	27 to 67 (Actual = 54 to 134 since half of the ice is lost before cooling)	$5.40 to 13.40 (Actual = $10.80 to 26.80)
Hydro-cooling – shower type to 0 to 2°C	Varies	Carrots Peaches Asparagus	3 MT cooled in less than 1 hour	80 to 110	$16.00 to 22.00
Hydro-cooling – immersion type to 0 to 2°C	Varies	Cherries	3 MT cooled in 1 hour	110 to 150	$22.00 to 30.00
Hydro-cooling – shower type to 7°C	Varies	Potatoes Melons	3 MT cooled in half hour	35 to 100	$7.00 to 20.00
Portable forced-air cooling (1 HP) fan in existing cold room to 2°C	$1,600	All crops	3 MT cooled in 4 to 6 hours	55	$11.00
Portable forced-air cooling (1 HP) fan in existing cool room to 13°C	$1,600	All crops	3 MT cooled in 2 to 4 hours	35	$7.00
Room cooling to 0 to 2°C	Varies	Apples Pears Onions Garlic	Cooling requires 24 hours or more	55	$11.00
Room cooling to 13°C	Varies	Citrus crops Mangoes Sweet potatoes	Cooling requires 24 hours or more	35	$7.00

duce left at ambient, dry conditions will lose moisture up to 100 times faster than produce that is moved into a cold room [2, 46]. Covering fresh produce and protecting it from direct sunlight is a low-cost way to reduce heat gain. Using roofing or cloth tenting for providing deep shade over all assembly points and working areas is recommended. A deep overhanging roof extension (at least one meter) can provide shade for windows or doorways [47] and a light coloured or reflective roof can reduce surface temperatures and temperatures under the shelter by up to 20°C.

Night air ventilation

Storage structures can be cooled using night air if the difference in day and night temperature is relatively large [3]. The storage facility should be well insulated and air vents should be located at ground level. Vents can be opened at night, and fans located high in the building can be used to move cool air through the storeroom. The structure will best maintain cool temperatures during the heat of the day if it is well insulated and vents are closed early in the morning. As a rule night ventilation effectively maintains a given product temperature when the outside air temperature is below the given product temperature for 5 to 7 hours per night.

Radiant cooling

Radiant cooling can be used in dry climates with clear night skies to lower the temperature of ambient air. By using a solar collector at night, air will cool as the collector surfaces radiate heat to the cold night sky. Temperatures inside the structure of 4°C (about 8°F) less than night air temperature can be achieved [3, 48].

Use of well water

Well water is often much cooler than air temperature in most

Table 10. Relative costs and benefits of investments in small-scale pre-cooling systems

Postharvest cooling technology	Location and crops for field tests	Initial cost including improved containers	Profit potential (additional profit compared to current practice of no pre-cooling)	Payback period at zero interest
ZECC 1MT size	India, tomato	$1,150	$140 / 1,000 kg	8.2 uses (8 weeks)
ZECC 1MT size	India, summer vegetables	$1,250	$390 / 1,000 kg	3.2 uses (about 3 weeks)
ZECC 100 kg size	India, summer vegetables	$125	$40 / 100 kg	3.1 uses (about 3 weeks)
CoolBot equipped cold room (6 MT)	India, potatoes stored for 3 months	$4,864	$1,296 / 6MT	1 year (4 uses)
CoolBot equipped cold room (6 MT)	Northern Ghana, onions stored for 4 months	$4,880	$8,790 / 6MT	Less than 1 year (2 uses)

Source: Kitinoja [34].

regions of the world. The water temperature of a deep well is approximately equal to the average annual air temperature of the same locality. Well water of 12 to 15°C can be used directly for hydro-cooling chilling sensitive crops.

High altitude storage

Typically air temperatures decrease by 10°C (18°F) for every 1 km increase in altitude. If handlers have an option to pack or store commodities at higher altitude, pre-cooling costs could be reduced, since pre-cooling and storage facilities operated at high altitude would require less energy than those at sea level for the same results. In California when temperatures in the Central Valley reach 38°C (100°F), the temperatures in the high Sierra mountains, only about 50 miles away, are likely to be only 21 to 24°C (70 to 75°F).

Energy use for small-scale pre-cooling systems

Information on the costs of various pre-cooling methods and cooling operation technologies was recently compiled by Kitinoja and Thompson for USAID [21]. The costs of forced-air cooling and room cooling are approximately the same per MT, since forced-air cooling uses more power but requires less time, while room cooling uses less power but takes a long time. Energy costs per MT increase whenever cooling equipment or facilities are not utilised to their full capacity.

An electricity use survey of produce coolers conducted for the California Energy Commission [40], indicates that typical commercial forced-air cooling has a seasonal average energy use of 59 kWh/MT, with a range from 22 to 167 kWh/MT. This includes some short-term storage prior to shipment. Product throughput affects energy efficiency, measured as kWh consumed per box, more than any other factor in an operation.

Cooling technology characteristics and costs

Table 9 provides the available information on the costs of various pre-cooling systems and cooling operation technologies [20, 21, 26]. Energy use costs for operation of a pre-cooling system will depend upon the local cost of electricity, but estimates range from a low of $0.14 /MT for evaporative cooling to 13°C (if electricity costs 20 cents/kWh) to $30/MT for immersion hydro-cooling to 0°C. Room and forced-air cooling fall between these two extremes, costing from $7 to $11/MT depending upon the target temperature.

Conservative estimates of the financial benefits from pre-cooling range widely but estimates of weight and decay related losses for highly perishable crops such as berries, leafy greens and delicate vegetables such as okra or green beans can be 20 to 30% within a few hours. Losses of crops intended for storage can be just as high if crops are not cooled before storage, even if losses tend to take place over a longer period of time. Whenever the value gained by reduced physical waste and improved market value is higher than the cost of pre-cooling the load of produce there are obvious financial benefits to be obtained from pre-cooling. For example, using a locally constructed portable forced air pre-cooling unit inside an existing under-utilised walk-in cold room at Big Tree Farm’s packinghouse in Bali, Indonesia, 0.8 MT strawberries can be cooled in less than 2 hours. Energy use to pre-cool the berries from 35°C to 2°C is estimated at 40 to 50 kWh per MT and postharvest losses decreased from 30% to 5% during one day of marketing [21]. A few more examples of costs and potential benefits are provided in Table 10, from a recent study on identifying appropriate postharvest technology for Sub-Saharan Africa and South Asia [34].

Conclusions

Small-scale producers can select from a wide range of pre-cooling systems, including those that utilise mechanical refrigeration, electric-based or passive evaporative cooling, ice and alternative sources of cooling. Selection of the most appropriate pre-cooling system should be based upon their costs, efficacy and safety for the type of produce to be cooled, and upon expected financial benefits. Efforts to utilise management practices that conserve energy should be undertaken in order to further improve financial benefits.

References

Papers of interest have been highlighted as:
*Marginal importance
**Essential reading

1 Brosnan T and Da-Wen Sun. Precooling techniques and applications for horticultural products — a review. International Journal of Refrigeration, 2001: 24: 2: 154–170.

2 Thompson JF, Mitchell FG, Rumsey TR, Kasmire RF and Crisosto CC. Commercial cooling of fruits, vegetables, and flowers. University of California, DANR Publication 21567; 2008.

**The authors of this manual provide the formulae for determining pre-cooler sizes and discuss energy efficiency and management issues.

3 Thompson JF, Mitchell FG and Kasmire RF. Cooling horticultural commodities. In Postharvest technology of horticultural crops, Third edition, Kader AA (Tech. Ed). University of California, Division of Agriculture and Natural Resources, Publication 3311. 2002: 97– 112.

4 Thompson JF. In: The commercial storage of fruits, vegetables, and florist and nursery stocks. USDA Agriculture Handbook Number 66. 2004. Accessed online March 2010. http://www.ba.ars.usda.gov/hb66/011precooling.pdf

5 Kitinoja L and Gorny JR. Small-scale postharvest technology: economic opportunities, quality and food safety. Postharvest Horticulture Series No.21, Department of Pomology, University of California, Davis; 1999.

6 Kitinoja L and AA Kader. Small-scale postharvest handling practices: a manual for horticultural crops (4th Edition). University of California at Davis. Post-harvest Horticulture Series No. 8E July 2002, slightly revised in November 2003.

7 CoolBot unit: www.storeitcold.com

8 Thompson JF and Scheuerman RW. Curing and storing California sweetpotatoes. Merced County Cooperative Extension, Merced, California 95340; 1993.

9 Anyanwu EE. Design and measured performance of a porous evaporative cooler for preservation of fruits and vegetables. Energy Conversion and Management 2004:45 :13–14: 2187–2195.

10 Roy SK. Postharvest technology of vegetable crops in India. Indian Horticulture 1989: Jan-June: 76, 78.

11 Redulla CA *et al*. Temperature and relative humidity in two types of evaporative coolers. Postharvest Research Notes 1984: 1(1): 25–28.

12 Redulla CA *et al*. Keeping perishables without refrigeration: use of a drip cooler. Appropriate Postharvest Technology 1984: 1(2): 13–15.

13 Acedo AL. Storage life of vegetables in simple evaporative coolers. Tropical Science 1997: 37: 169–175.

14 Acedo A. Ripening and disease control during evaporative cooling storage of tomatoes. Tropical Science 1997: 37: 209–213.

15 Parsons RA and Kasmire RF. Forced-air unit to rapidly cool small lots of packaged produce. University of California Cooperative Extension, OSA #272; 1974.

16 Rij R *et al*. Handling precooling and temperature management of cut flower crops for truck transportation. USDA Science and Education Administration, AAT-W-5, UC Leaflet 21058; 1979.

17 Talbot MT and Fletcher JH. Design and development of a portable forced-air cooler. Proceedings of the Florida State Horticultural Society 1993:106:249–255.

18 Examples of commercially available small-scale pre-cooling systems include: Retro-fitted refrigerated vans: www.cold-box.com; CoolBot: www.storeitcold.com; Portable FA coolers: www.coolforce.com; www.rinac.com/precoolers.htm ; http://www.brancato.it/pages/tornado_news.htm; Mobile 3-bay FA coolers, hydro-coolers: www.millenniumcooling.com; Solar chiller: www.solarchill.org

19 Boyette MD. Cool and Ship: A low cost, portable forced air cooling unit. NCSU Extension Publication AG-414-7. No date. http://www.bae.ncsu.edu/programs/extension/publicat/postharv/ag-414-7/index.html

20 Thompson JF and Spinoglio M. Small-scale cold rooms for perishable commodities. University of California, DANR Publication 21449; 1996.

21 Winrock International. Empowering agriculture: energy solutions for horticulture. USAID Office of Infrastructure and Engineering and the Office of Agriculture; 2009: 79p.

22 Gast KLB and Flores R. Precooling produce. Kansas State University Cooperative Extension, Manhattan, Kansas; 1991.

23 Baird CD, Gaffney JJ and Talbot MT. Design criteria of efficient and cost-effective forced-air cooling systems for fruits and vegetables. ASHRAE Transactions 1988: 94(1): 1434–1454.

24 Guillou R. Coolers for fruits and vegetables. California Agricultural Experimental Station Bulletin 1960:773.

25 Mitchell FG *et al*. Commercial cooling of fruits and vegetables. California Agricultural Experiment Station Extension Service Manual 43; 1972.

26 Boyette MD and Rohrbach RP. A low-cost, portable, forced-air pallet cooling system. Applied Engineering in Agriculture 1993: 9(1):97–104.

27 USDA Transportation Tip: The PortaCooler; 1993 http://www.ams.usda.gov/tmd/MSB/PDFpubList/portacooler.pdf

More details on the USDA PortaCooler Cooling System are available from David S. Ross, Extension Agricultural Engineer, University of Maryland http://www.bre.umd.edu/portacooler2.htm

28 Personal communication with R Crabb (USA); 2007.

29 Brecht J, Ritenour M and Sargent S. "Keeping Cool". American Vegetable Grower. August 2007. Accessed online March 2010 http://www.growingproduce.com/americanvegetablegrower/?storyid=719

30 Dieckmann J, McKenney K and Brodrick J. Going "back to the future" of evaporative cooling. ASHRAE Journal May 2009: 87–90.

31 Thompson JF and Kasmire RF. Evaporative cooling of chilling sensitive vegetable crops. ASAE 1979: 79–6516.

32 Thompson JF and Kasmire RF. An evaporative cooler for vegetable crops. California Agriculture 1981: March-April: 20–21.

33 Mitchell G. In: Postharvest technology of horticultural crops, Kader AA (Ed). University of California, Division of Agriculture and Natural Resources, Publication 3311. 296 pp; 1992.

34 Kitinoja L. Identification of appropriate postharvest technologies for Improving market access and incomes for small horticultural farmers in Sub-Saharan Africa and South Asia. Final Report. Alexandria VA: WFLO; 2010.

35 Personal communication with Roy SK; 2009.

36 Boyette MD, Estes EA and Rubin AR. "Hydrocooling." Postharvest Technology Series. AG-414-4. North Carolina Cooperative Extension Service. 1992. www.bae.ncsu.edu/programs/extension/publicat/postharv/ag-414-4/index.html.

37 Tsang Marcel and Furutani S. A low cost hydro-cooling unit for horticultural commodities. Journal of Hawaii and Pacific Agriculture, An E-Journal of Agricultural Research 2007: 14. Accessed online February 2010. http://www.uhh.hawaii.edu/academics/cafnrm/research/documents/Alowcosthydro-coolerforvegetables.pdf

38 Ghuman BS and Dhatt AS. Design, development and evaluation of a small scale hydro-cooler. Journal of Research, Punjab Agricultural University. http://www.cababstractsplus.org/abstracts/Abstract.aspx?AcNo=20043056655.

39 Becker BR and Fricke BA. "Hydrocooling time estimation methods." International Communications in Heat and Mass Transfer 2002: 29 (2):165– 174.

40 Thompson JF and Singh RP. Status of energy use and conservation technologies used in fruit and vegetable cooling operations in California. California Energy Commission, PIER Program. CEC-400-1999-005. 2008.

41 Umar B. The use of solar cooling to minimize postharvest losses in the tropics. Tropical Science 1998: 38: 74–77.

42 Government of Alberta. Fresh fruit and vegetable pre-cooling for market gardeners in Alberta: build your own ice-based cooling system; 2004. Accessed online March 2010. http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex7471.

43 Thompson JF and Chen YL. Energy use in hydrocooling stone fruit. Applied Engineering in Agriculture 1989: 5(4): 568-572. Accessed online March 2010. http://postharvest.ucdavis.edu/datastorefiles/234-1056.PDF

44 Crytec Bubble slurry ice machines. http://www.crytec.biz/pdfs/about_ice_machines.pdf

45 Rickard JE and Coursey DG. The value of shading perishable produce after harvest. Appropriate Technology 1979: 6(2):18–19.

46 UN FAO. Improvement of postharvest fresh fruit and vegetable handling-a manual. Bangkok: RAPA/FAO/AFMA; 1986.

47 Walker DJ. World food programme food storage manual. Chatham, UK: Natural Resources Institute; 1992.

48 Kamaruddin A, T Wilujeng and MS Mahendra. Radiative cooling for storage of vegetables in the tropics. World Renewable Energy Congress VI, 2000: 702–705.

© 2010 Published by Stewart Postharvest Solutions (UK) Ltd.
All rights reserved. www.stewartpostharvest.com