Postharvest management of vegetables

Australian supply chain handbook

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Postharvest management of vegetables

Australian supply chain handbook

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Abbreviations

BCDMH	1-Bromo-3-chloro-5,5-dimethylhydrantoin
Δt	change in temperature
C_2H_4	ethylene
CA	controlled atmosphere
CMYK	cyan, magenta, yellow, black
CO_2	carbon dioxide
CO_2TR	carbon dioxide transmission rate
EDN	ethane dinitrile
ELISA	enzyme-linked-immunosorbent assay
FSANZ	Food Standards Australia New Zealand
GI	glycaemic index
GPS	global positioning system
Gy	gray (derived unit of ionizing radiation dose)
HDPE	high density polyethylene
HOCl	hypochlorous acid
ICA	interstate certification assurance
KPa	kilopascals
LD50	lethal dose that kills 50% of the population
LDPE	low density polyethylene
MAP	modified atmosphere packaging
MB	methyl bromide
Medfly	Mediterranean fruit fly
MJ	megajoule
µg	microgram
µl	microlitre
mmol	millimole
MW	megawatt
N_2	nitrogen
O_2	oxygen
O_3	ozone
OTR	oxygen transmission rate
PAA	peryoxacetic acid
PCN	potato cyst nematode
PET	polyethylene terephthalate
PP	polypropylene
ppm	parts per million
Q10	temperature quotient
Qfly	Queensland fruit fly
RGB	red-green-blue
RH	relative humidity
UV	ultraviolet
VPD	vapour pressure deficit
WVTR	water vapour transmission rate

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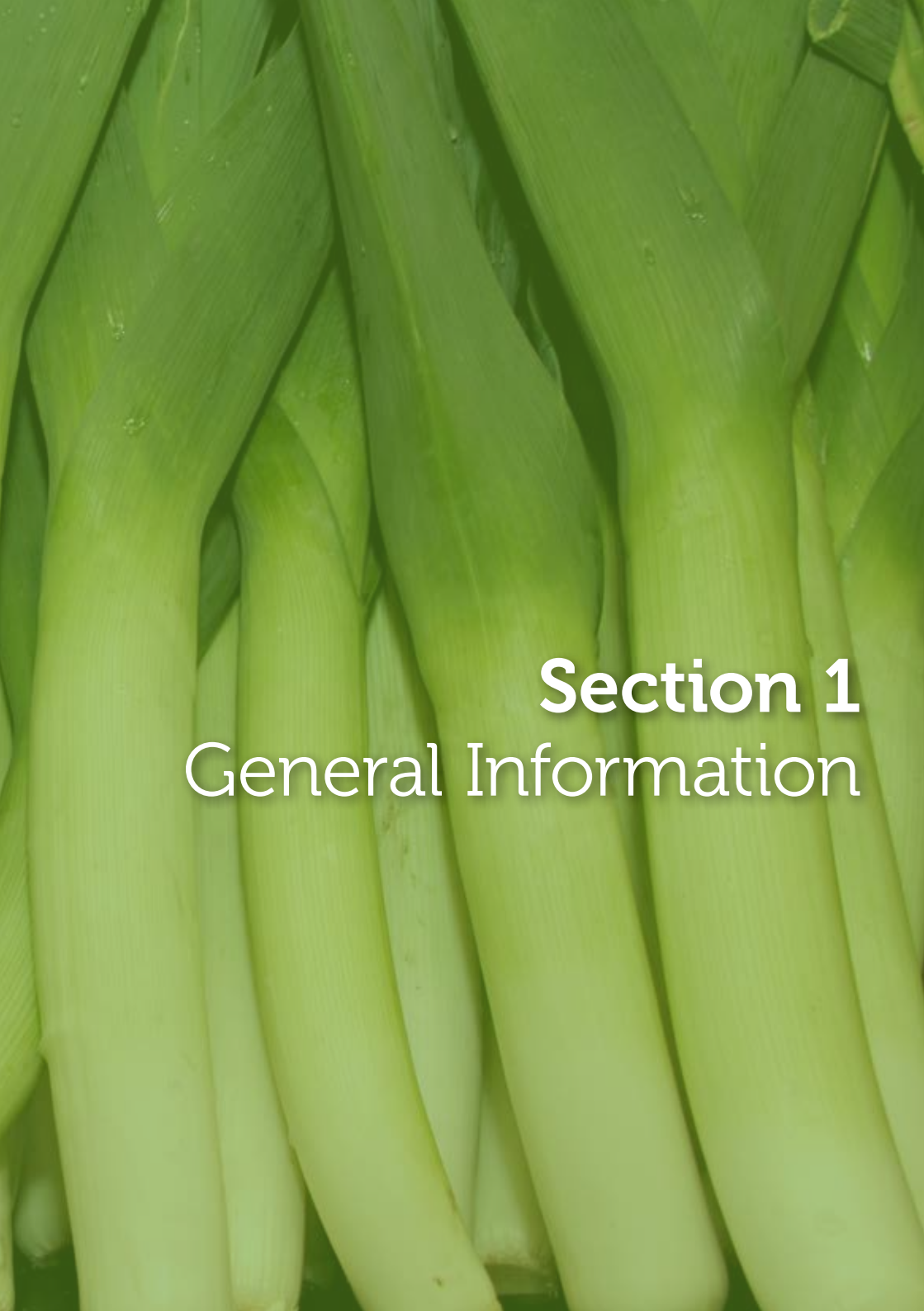


Section 1
General Information

1 Introduction

We could not survive without the nutrients naturally contained in fruit and vegetables. Vegetables especially are important sources of carotenoids, anthocyanins, dietary fibre and many other plant compounds demonstrated to have major benefits for health.

According to data from the Australian Bureau of Statistics, Australia produced close to 3 million tonnes of vegetables in 2013–2014 with a value of approximately $3.8 billion. The majority is destined for the local market. Most Australians are therefore fortunate to have an abundant quantity, quality and range of fresh vegetables available virtually seven days a week, 365 days a year. The result is a highly competitive market where quality and price are keys to success.

Vegetables are parts of living plants. Harvest cuts them off from their source of water and nutrients, setting them on the path to deterioration and death. How quickly death occurs depends in part on the water and energy reserves they have accumulated during growth, and how quickly these are used or lost after harvest.

Good postharvest management extends the time vegetables stay fresh and alive by avoiding damage, limiting water loss and reducing metabolic activity. Poor postharvest management leads to premature deterioration, and therefore waste. Around 20% of vegetables produced—even up to 50%—are wasted before they reach the consumer.

The importance of reducing waste increases as fresh vegetables move through the supply chain. This is because the costs of harvesting, cooling and packing are often higher than the cost of growing the product in the first place. So, a head of broccoli worth a few cents while growing in the field may be worth $1 at wholesale, $2 at retail or $10 when it is served in a restaurant. Every step of the supply chain adds value to the product. Conversely, the total loss resulting from a product thrown away at retail is far greater than if that product was discarded before harvest.

Proper postharvest management is essential to avoid waste and, therefore, loss within supply chains.

However, optimised postharvest management is not just about quality. Cost is also important. Having the best quality product is no victory if it loses the business money.

There are many techniques and technologies that can be used to keep produce at its optimal freshness. However, only those that are cost-effective will be useful in vegetable supply chains. Selecting—and implementing—the right practices for each product is the fundamental challenge for all those involved in vegetable supply chains.

1.1 Temperature

It is sometimes said that the three most important factors in good postharvest management are temperature, temperature and temperature! Cooling slows down the loss of water and energy from vegetables and reduces growth of rots. Without cooling, many vegetables would not last long enough to reach the consumer. In effect, cooling is value-adding with electricity.

However, cooling is also a major cost within supply chains. Determining the most efficient way to cool a product, and how much cooling is necessary to meet quality and price objectives, is an important part of postharvest management.

Colder is not always better, and not just because of cost. Vegetables originally from warm climates, such as cucumbers and eggplants, can be damaged by low temperatures. However, the appearance of damage is a factor of time as well as temperature. Most chilling sensitive products can withstand a short period below recommended storage temperatures, although this can range from days to hours.

Understanding the effects of temperature on vegetables, both high and low, can help supply chain members know where they can be flexible, and where temperature control is critical.

1.2 Moisture

After temperature, preventing dehydration is also critical to postharvest quality management. Vegetables are essentially water in fancy packaging – only 5 to 15% of their content is dry matter such as carbohydrates and fibre. Moisture keeps vegetables fresh, crisp and good to eat.

Most products are sold by weight, so keeping them hydrated is not only essential for maintaining quality but also directly relates to returns. Increasing

relative humidity (RH) around vegetables can reduce moisture loss. Plastic packaging, ice, misting and cold room settings can all be used to increase RH.

However high RH, especially if combined with temperature fluctuations, increases the likelihood of condensation. Free water can cause splitting, cracking, discolouration and rots. If human pathogens are present, the presence of free water may help them to survive. Balancing the risks associated with external water with those of moisture loss is another challenge to the postharvest practitioner.

1.3 Atmosphere

A third way of maintaining vegetable quality is by changing the composition of the storage atmosphere. Fresh produce is alive, so continues to respire after harvest. This means that oxygen is consumed and carbon dioxide is released. Limiting oxygen and/or increasing carbon dioxide can slow down respiration and potentially increase storage life. Modified atmosphere packaging (MAP) or controlled atmosphere storage environments help with this. However, temperature control is usually critical, and such technologies can be expensive.

1.4 This publication

This publication aims to provide information on not only the BEST ways of handling vegetables, but also the most cost-effective. It is split into three main sections:

1. **Introduction to the principles of postharvest**
   This section outlines general postharvest principles as they apply to vegetable crops. These include physiology and biochemistry, the effects of temperature, moisture loss and humidity, the storage atmosphere and evaluation and management of quality.
2. **Crop specific information**
   Best practice guides are included for a number of important vegetable lines. These include basic information on harvest, cooling, expected storage life and significant disorders or diseases affecting the crop. More detailed information on each crop is also available on Fact Sheets, downloadable from **postharvest.net.au**.
3. **Reference tables and charts**
   A series of tables summarises information on storage conditions, storage life, physiology, composition and retail display. This is essentially a quick reference for basic information.

2 Vegetable physiology

2.1 Structure and composition

What is a vegetable?

Vegetables can be from any part of the plant. Their origin as a root, shoot, leaf, flower bud, fruit or other part affects how easily they can be handled and stored.

Unlike fruit, which are derived from flowers, vegetables cannot easily be defined. Vegetables are derived from many different parts of plants. Some are actually fruit; others are buds, leaves, stems, roots or storage organs. Where the vegetable comes from on the plant affects how well it stores and many of its sensory qualities.

Vegetables can generally be grouped into three categories:

1. Bulbs, roots and tubers
2. Flowers, buds, stems and leaves
3. Fruit, seeds and pods

The origin of vegetables affects how they are best handled after harvest. For example, vegetables from above the ground are more likely to have waxy skins to protect them from water loss. Roots and tubers do not have such protection, so may require high humidity to limit dehydration.
Seeds necessarily contain stored energy in the form of sugars or carbohydrates. Buds and shoots generally have few stored reserves and are developing rapidly, so need careful handling to preserve them after harvest.

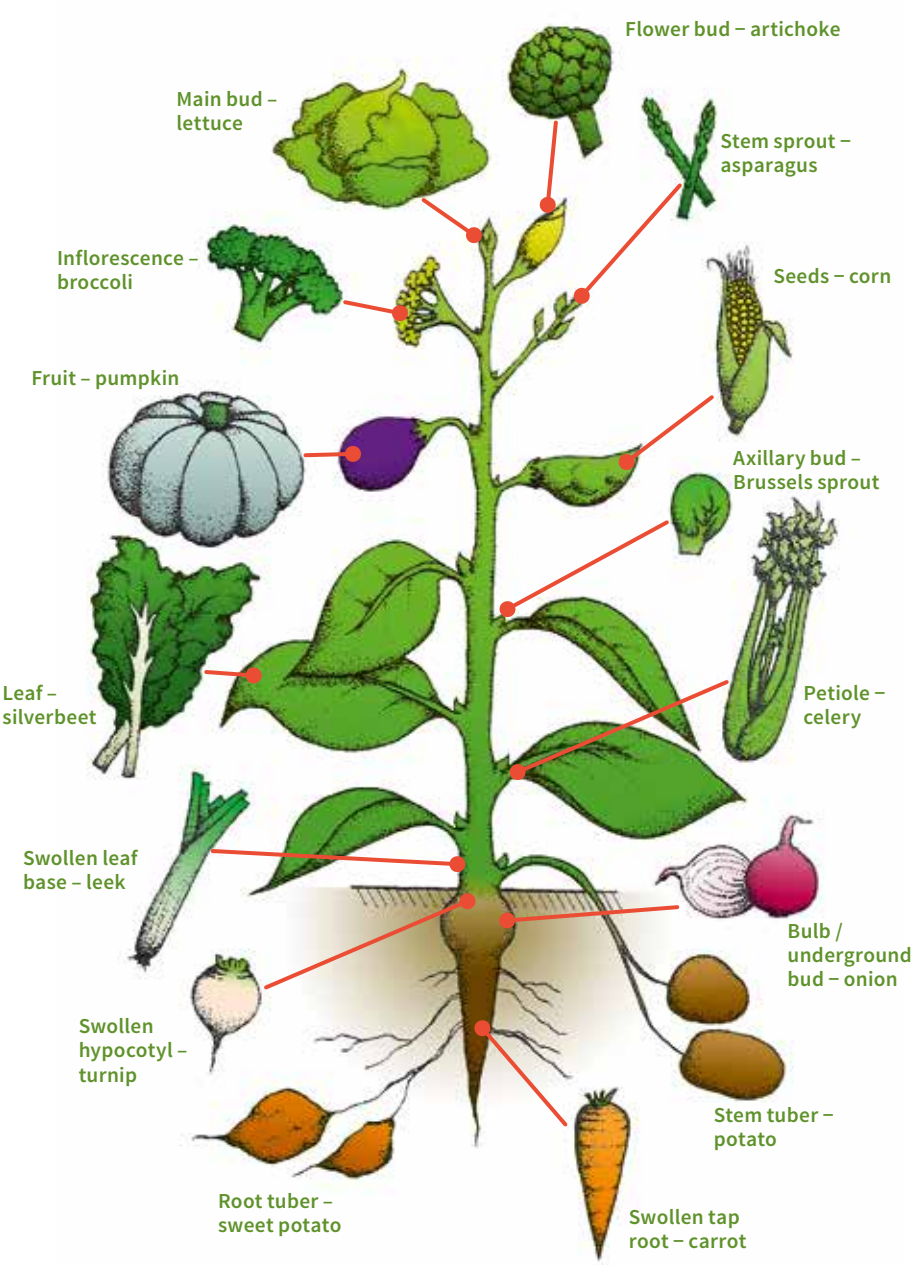


Figure 1 – Origins of vegetables from different plant parts

Changes at harvest

Harvested vegetables are still alive. However they have been removed from their sources of water and nutrients, so are living on stored reserves. How quickly these reserves are depleted can determine storage life.

When a fruit is harvested, it could be seen as continuing its natural 'purpose'. That is, fruits are produced by plants in order to be eaten, and will eventually detach by themselves if not actively harvested.

Unlike fruit, most vegetables are not adapted to exist apart from the whole plant. Once harvested, vegetables are cut off from their source of water and nutrients. Without sunlight, they are unable to photosynthesise and are usually removed from the protection of soil or foliage. Many fruiting vegetables – such as cucumber and eggplant – are harvested while immature. These 'baby fruits' lack the sugar reserves and/or protective skins of fruit such as apples or bananas.

With the exception of vegetables which are mature fruit, bulbs or storage organs (pumpkin, onions, sweetpotato, etc.), most vegetables are on the path to senescence and death from the moment they are harvested.

The role of postharvest management is to delay deterioration, maintaining freshness, nutrition, flavour and texture until vegetables reach the end consumer.

Plant cells

The water pressure inside plant cells is what keeps vegetables firm and crisp. Damage to cell membranes allows compounds kept separately inside the cell to combine and the cell contents to leak out. This results in brown, soft and/or water-soaked areas.

Like other living things, vegetables are made up of cells. There are many different types of cells within even a simple vegetable, and each has different functions within the plant.

Plant cells have a fairly rigid cell wall, composed mainly of cellulose, lignins and some proteins. Calcium is critical in the formation of cell walls. If calcium is deficient (due to low soil levels or growth faster than the rate of transport within the plant) the growing tips of fruiting vegetables such as zucchini and eggplants will lack structural integrity and can break down. This is the cause of blossom end rot.

The cell wall is permeable to water and solutes. Inside the cell wall is the plasmalemma, which acts like a liner. The plasmalemma helps maintain pressure inside the cell, keeping it turgid. It is this turgidity that keeps vegetables firm and crisp.

Adjacent cells are glued together by a layer of pectins. A series of channels (plasmodesmata) allows exchange of various substances between cells.

The cell contains a liquid 'soup' called cytoplasm. Within the cytoplasm float various structures and organelles, each of which has a specific purpose. These include:

- The nucleus, which contains the cell's DNA and acts as the control centre.
- One or more vacuoles. These are reservoirs of liquid containing sugars, acids and other materials. Some plant products (such as phenols) are stored inside the vacuoles to keep them apart from enzymes with which they would otherwise react.
- Mitochondria, which are the cell's powerplant, converting breakdown products from sugars into energy the cell can use.
- Chloroplasts are found in green parts of the plants. They contain chlorophyll and are responsible for photosynthesis.
- Chromoplasts develop from chloroplasts once chlorophyll breaks down. They contain the red and yellow pigments (carotenoids) that give some vegetables their colour.
- Amyloplasts, that contain grains of starch.

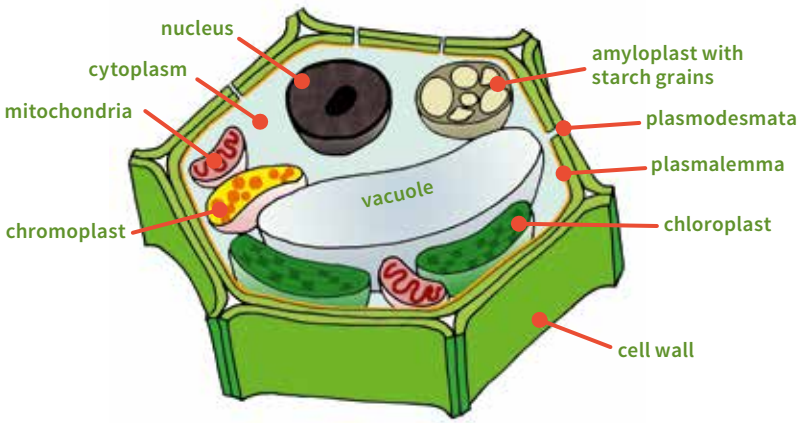


Figure 2 – A plant cell showing some of the organelles and structures.

If the cell walls are broken—by freezing or physical injury—then the turgidity of the cells is lost and the contents leak out, resulting in soft, water-soaked tissue.

Breaking or crushing cells also allows compounds normally held in separate parts of the cell to mix. For example, phenols held in the vacuole mix with oxidising enzymes in the cytoplasm, turning them brown. This is what causes the brown colour in bruises and on cut surfaces. Lowering the pH (with citric acid, for example) inhibits this reaction on cut surfaces, reducing browning. Reducing oxygen (O_2) to a very low level can also reduce browning reactions.

Plant cellular structure

There are many types of plant cells and they perform different functions for the plant. How the plant cells are arranged and whether the vegetable has a thick epidermis and/or waxy cuticle strongly affects 'keeping' quality and water loss.

Plant tissues contain many different types of cell, as well as air spaces. These include:

- Veins, consisting of:
  - Xylem vessels – which transport water and minerals from the roots to the leaves.
  - Phloem vessels – which transport sugars from leaves to the roots.
- Stomata and lenticels – openings that allow gas exchange between the inside and outside of the plant tissues.
  - Stomata are actively controlled by 'guard' cells; these open to allow gas exchange or close to reduce water loss. They usually close at harvest in response to a small drop in water pressure inside the cells. Leaves can have large numbers of stomata spread across their surface.
  - Lenticels are sunken openings that cannot be closed. They are typical of storage organs such as sweetpotato as well as cucumbers and other fruit vegetables.
- Epidermal cells – the plant's skin. These can develop a waxy cuticle, protecting the underlying tissue against water loss. In some storage organs, such as potatoes, several layers of epidermal cells form a corky layer protecting the underlying cells.
- Parenchyma cells – non-specialised cells that carry out functions such as photosynthesis and form most of the internal tissue (mesophyll).
- Collenchyma cells – stretchable cells rich in pectin and cellulose that help give the plant strength, e.g. celery strings are mainly collenchyma.

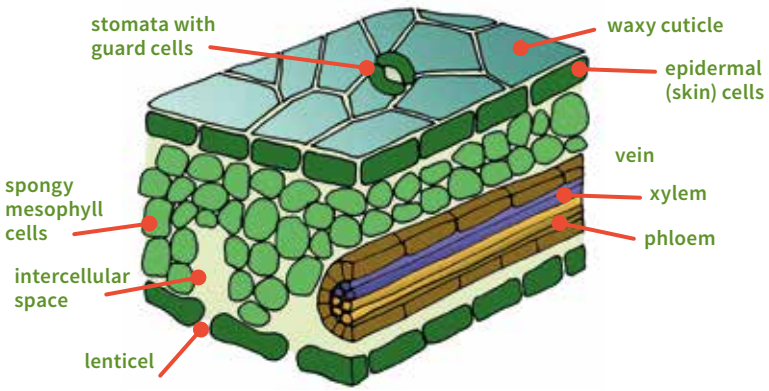


Figure 3 – Cross section of a leaf, showing some of the cells that can be present.

The structure of the epidermis and the number of lenticels and stomata govern how quickly a vegetable will lose water. For example, solanaceous fruiting vegetables (eggplant, capsicum, tomato, etc.) do not have lenticels or stomata. This reduces the rate of water loss from the fruit. Cucumbers have numerous lenticels, while many leafy vegetables have large numbers of stomata across their surface, so both lose water rapidly. The thin epidermis of a zucchini presents little barrier to water loss compared to the thick epidermal layer and waxy cuticle of a pumpkin.

The veins (vascular bundles) that transport water and nutrients can also conduct diseases. Browning of the vascular system due to bacteria or fungus can result in stripes or spots. Brown striping of celery stems, or reddish brown streaks inside a cut-open eggplant, show where the veins have been infected.

Chemical composition

Vegetables are mostly water. They also contain carbohydrates, dietary fibre, protein and many vitamins and nutrients that are important for human health.

Water

Vegetables are mostly made of water. Lettuce, cucumbers and leafy vegetables contain about 95% water, so only 5% of their mass is dry matter. Hard vegetables like carrots and pumpkins have around 12–15% dry matter, sweetpotato are close to 20% dry matter, and cassava is one of the highest at 35–45% dry matter.

Harvesting when water content is highest is an obvious way to both increase yield and ensure products have firm texture.

Carbohydrate

After water, the next most important component in vegetables is carbohydrate. Carbohydrates can be present as starch, sugars and dietary fibre.

Starch is mainly found in storage organs, such as potatoes and sweetpotato. Starch is used by the plant as a concentrated, 'long-term' fuel source. It needs to be broken down into sugars in order to provide energy to cells (See section 3.2 for more on this).

The main sugars that are present are glucose, sucrose and fructose, although not every product contains all three. Although more usually associated with fruit, sugars are an important component of flavour in vegetables such as carrots, sweet corn and peas.

Dietary fibre compounds include cellulose, lignin, pectins and other substances. Dietary fibre may be soluble or insoluble, with soluble dietary fibre now believed to have particular benefits for health[1]. Dietary fibre cannot be readily broken down by the digestive system, and most is simply excreted. However, consumption of dietary fibre is now considered an important health marker and is actively promoted by many health professionals.

Carbohydrates can be used as fuel by humans, as well as by plants. The speed at which carbohydrates are absorbed by the body is defined by the glycaemic index (GI). A low GI indicates that the carbohydrates are absorbed slowly, so these foods tend to be satisfying for longer. Most starchy vegetables are low to medium GI (score 50 – 55). This is less than many grain based starch sources eg bread or white rice (score ~70 and ~85 respectively).

Other components

Protein is also found in vegetables, although in small amounts. Brassica vegetables and legumes (peas and beans) are generally the best protein sources, containing around 3–5% protein.

Other components include vitamins, minerals, phenolic compounds, volatiles and anti-oxidants. Although also present in relatively small quantities, these compounds are likely involved in many of the health benefits demonstrated for diets rich in vegetables. For example, beta-carotene (found in carrots but also sweetpotato, pumpkin and many leafy greens) converts to vitamin A in the body and has benefits in terms of healthy skin, eye health and improved immune system. The sulphur compounds found in brassicas and onions have been associated with reduced risks of certain cancers, as has lycopene, responsible for the red colour of tomatoes.

1 Slavin J. 2013. *Health aspects of dietary fibre*. In 'Fibre-rich and wholegrain foods: improving quality' Eds. JA Delcour, K Poutanen. Woodhead Publishing Cambridge.

2.2 Respiration

Just as we need oxygen to stay alive, so do vegetables. Respiration is a process common to all living cells, whether plant, animal or fungi. It is the process by which oxygen (O_2) breaks down carbohydrates or organic acids. This process produces energy, as well as carbon dioxide (CO_2) and water. Some energy is released as heat, but most is used to maintain the integrity of the plant cells and keep them alive. Respiration processes can be summarised as;

$$\text{Carbohydrates} + O_2 \Rightarrow CO_2 + H_2O + \text{Energy}$$

Storage life

Respiration rate is often linked with storage life as it indicates metabolic activity. Reduced respiration is a key benefit from cooling vegetables after harvest.

The rate at which harvested vegetables deteriorate often appears to be related to respiration rate. For example, cool temperatures, modified atmospheres and waxy coatings all reduce respiration rate and extend storage life. Conversely, treatments that speed up respiration—such as high temperatures, stress and wounding—all decrease storage life.

As respiration indicates metabolic activity it seems logical that it can also be a guide to the rate at which product deteriorates. Products such as asparagus and beans, which have high respiration rates, tend to be highly perishable. Conversely, products such as cabbage and pumpkin have slow respiration rates and can be stored for longer.

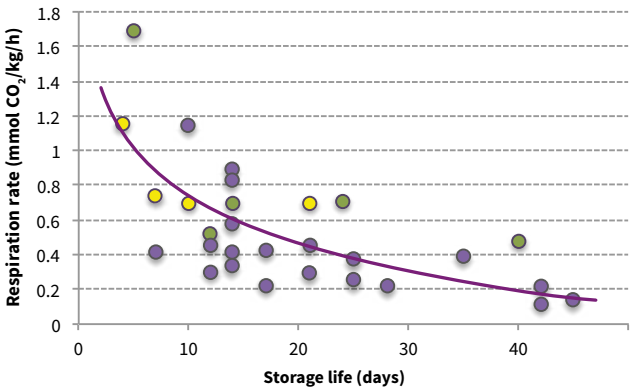


Figure 4 – Respiration rate and storage life of broccoli, sweet corn, and a number of other different vegetables (data extracted from Thompson 1996, AUF Manual, 1980, UC Davis www.ucdavis.edu)

Reducing respiration is certainly one of the key benefits from cooling products after harvest. Measuring the effect of cooling on respiration can be used to estimate the effects on storage life and quality, at least for some products. In the case of broccoli, respiration rate is a good predictor of storage life at temperatures between 5 and 20°C; at lower temperatures storage life is often determined by development of rots. Respiration rate also relates closely to storage life of shoots, such as asparagus, but is less accurate for leafy vegetables.

Flavour and quality

Some of the energy produced by respiration is released as heat. If this is not removed then products can warm up. This reduces quality and burns up the sugars and acids that help give vegetables their flavour.

Respiration can use up the stored sugars and acids that give vegetables flavour. As vegetables generally contain low quantities of sugars and acids to start with, even small losses can impact quality. For example, respiration of broccoli florets during storage for three weeks at 4°C can use up half to two-thirds of their stored sugars, a change closely related to yellowing and flavour loss.

Respiration not only powers plant cells, it produces heat. If vegetables are stored without effective cooling or ventilation, then respiration causes them to warm up. This can be a particular problem for product that has not been properly cooled and is then stored in unvented boxes or lined containers. Heating further increases respiration rate, which then further increases heating, a circular process inevitably leading to deterioration and decay.

3 Temperature

Temperature is the single biggest factor in postharvest quality of vegetables. The temperature of produce drives water loss, changes in metabolic activity, loss of flavour, texture and nutrients and the development of rots.

Temperature effects are often divided into three main classes:

- Low temperature effects, such as chilling injury or freezing damage
- Mid-range temperature effects
- High temperature damage

3.1 Low temperature effects

Freezing damage

Most vegetables freeze at just below 0°C. Freezing damages cells, allowing the contents to leak out. Tissue that has been frozen can have a water-soaked or dehydrated appearance.

The temperature at which products freeze is a function of the concentration of dissolved solutes—such as sugar—within the cells. Pure water freezes at 0°C. A product such as lettuce, which is mostly water, will freeze at approximately –0.2°C. In contrast, the high sugar content (up to 10% at harvest) of products such as carrots and sweetpotato, means they may not freeze until temperature falls to –1.8°C.

When products freeze, water forms into ice crystals within and between cells, resulting in dehydration of the cells themselves. Expanding ice crystals can also pierce the cell walls. When the product thaws the cells collapse, resulting in the water-soaked appearance and loss of structural integrity typical of freezing injury. Freezing can effectively 'kill' the product, which is unable to resume its normal metabolic activity. Damage is most likely when the vegetable

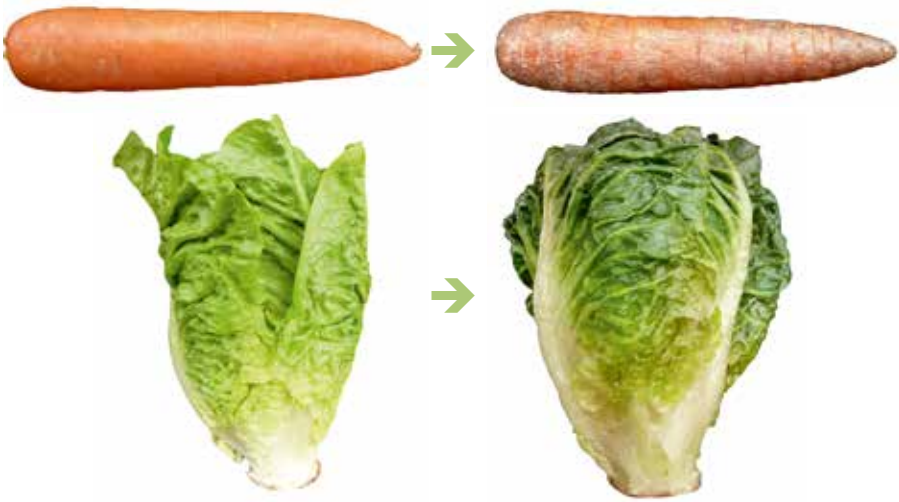


Figure 5 - Fresh (left) and frozen carrots and lettuce, showing the dehydration and water-soaking symptoms that are typical of freezing injury.

freezes slowly, resulting in the formation of larger ice crystals. Food processing facilities producing frozen vegetables rely on rapid blast freezers to limit the size of ice crystals and maintain the integrity of the frozen product.

A few vegetables, such as cabbage, have some tolerance to freezing and can recover if defrosted slowly.

Chilling injury

Chilling injury can occur when warm climate vegetables are held at low temperatures. Symptoms include pitting, water loss and rots. Damage may not be obvious in storage, but appears when the product returns to warmer conditions.

Chilling injury is most commonly a problem for fruit and root vegetables that originate in tropical or warm temperate regions. It occurs when these products are held above their freezing point but below a temperature at which physiological damage occurs. The reasons why chilling injury occurs are still not well understood, however, it appears to relate to malfunction of cellular membranes and disruption of normal processes within the cells.

Injury is not simply an issue of temperature, but also of exposure time. Most chilling sensitive products can withstand limited exposure to temperatures below their normal temperature threshold, but as storage time increases damage becomes more likely.

Symptoms of chilling injury may not be obvious during storage, but develop after products are returned to warmer temperatures. Common symptoms include the development of sunken, pitted areas, water-soaked lesions, internal browning, and accelerated development of surface rots and decay. Fruiting vegetables can fail to ripen normally, as well as develop off flavours and odours. Weight loss is often rapid, with products deteriorating quickly once on retail display.

Preventing or reducing chilling injury

Susceptibility to chilling injury can be affected by growing conditions, variety and maturity as well as postharvest treatments such as delayed cooling or short exposures to heat.

Vegetables vary in their susceptibility to chilling injury according to variety, growing conditions and maturity. Chilling sensitivity can be unpredictable; an environment or treatment that reduces chilling injury in one product may increase it in another. There are a number of ways susceptibility to chilling injury can be reduced:

- Growing a healthy plant. For example, greenhouse cucumbers grown under optimal temperature and humidity were less susceptible to chilling injury than those grown with fewer environmental controls[2].
- Harvest maturity. Mature, fully red capsicums and chillies are less sensitive to chilling temperatures than green fruit.
- Plastic packaging. Increasing the RH around the product appears to have some effect. If the packaging also modifies the atmosphere—by increasing CO_2 and reducing O_2—then this can further reduce chilling sensitivity[3].
- Heat treatments such as hot water dips or showers[4]. Short exposures to high temperatures can induce heat shock proteins in the product. The effect is somewhat similar to a vaccination, providing protection against later exposure to cold temperatures. For example, a postharvest treatment of 30 seconds under a shower of 55°C water delayed the onset of chilling injury in green capsicums stored at 2°C by 4 – 6 weeks.

2 Ekman JH et al. 2010. Growing conditions affect postharvest quality of greenhouse cucumbers. ActaHort. 877:181-186.

3 Wang CY 2013. Managing chilling injury in vegetables. ActaHort. 1012:1081-1085.

4 Fallik E et al. 1999. A unique rapid hot water treatment to improve storage quality of sweet pepper. Postharvest Biol. Technol. 15:25-32.

Figure 6 – Mature red capsicums are less susceptible to chilling injury than green fruit. Photo shows effect of storage for 3 weeks at 0°C, 2°C, 4°C or 6°C on capsicum quality. Green fruit at 0°C and 2°C are showing light pitting, an early symptom of chilling damage.

Figure 7 – Hot water treatments can delay the onset of chilling damage. Capsicums were treated under a shower of 20°C (left) or 55°C (right) water for 30 seconds before storage at 2°C for 6 weeks. Zucchini were treated with 20°C (left) or 55°C (right) water for 30 seconds before storage at 5°C for four weeks.

- Low temperature conditioning. Reducing temperature gradually after harvest can effectively acclimatise the vegetable to low temperatures. For example, one day at 18°C or two days at 10°C both delayed the appearance of chilling injury symptoms in zucchini stored at 5°C[5].
- Intermittent warming. Raising the temperature briefly appears to allow the plant tissues to recover, metabolising damaging compounds produced during chilling and replenishing reserves[6].
- Irradiation with ultraviolet (UV) light[7]. Like heat treatments, irradiation with UV light can also produce defence compounds in vegetables. It may also reduce symptoms by killing microorganisms on the vegetable skin.
- Treatment with plant growth regulators or antioxidants. Products that may reduce chilling injury include abscisic acid, polyamines, methyl jasmonate, gibberellins and salicylic acid.

For chilling sensitive products, selecting the best storage temperature is a balance between the development of low temperature damage and the rots, yellowing and water loss that can occur at warmer temperatures. For some vegetables, storage life is longer at temperatures that can cause chilling damage than at 'safe' temperatures, where rots, yellowing and water loss become major problems. Capsicums are an example of this, with storage life maximised at close to 0–2°C in spite of their chilling sensitivity.

3.2 Mid-range temperature effects

For non-chilling sensitive products, quality is usually best maintained when vegetables are held just above the temperature at which they freeze. Such temperatures are often used as recommended optimums for transport and storage. This is often 0°C ±0.5°C.

In reality, it is very difficult to maintain products at close to freezing point. In order to keep products cool, the delivery air temperature inside a cool room must necessarily be lower than the temperature at which the room is set. Depending on how the room has been designed, the difference may be 1, 2 or even 3°C. For example, in a room set at 5°C the delivery air needs to be 2–4°C in order to cool the room contents. A room can only be maintained at 0°C if the delivery air is below zero. Products placed directly in the delivery airflow are therefore at risk of freezing.

5 Ekman JH Pristijono P. 2010. Evaluation of new shipping technologies for Australian vegetables. HAL Final Report VG06045.

6 Biswas P et al. 2016. Intermittent warming in alleviating chilling injury – a potential technique with commercial constraint. Food Bioprocess Eng. 9:1-15.

7 Promyou S, Supapvanich S. 2013. Chilling injury alleviation in 'Golden Bell' sweet pepper caused by UV-C treatment. ActaHort. 1011:357-362.

In addition, evaporation of water from products further cools them, especially if humidity is low. So, evaporation from leaves in a cold room running at exactly 0°C can potentially reduce the product temperature to -0.3°C— low enough to result in freezing injury.

For many products, the risks posed by freezing outweigh the potential benefits to storage life of such low storage temperatures. For this reason, products such as leafy vegetables and lettuce are often stored at 2°C or higher.

Storage life

Temperature affects metabolic activity and storage life, with small changes usually having most effect when temperatures are low.

There are usually significant benefits in keeping products as cool as possible. Good temperature control is important during cold storage, as the effects of temperature on quality and storage life are not constant. So, a reduction of 5°C will have little effect when products are over 20°C, but a major effect on quality if products are below 10°C.

The reason changes in temperature are so important is due to metabolic activity. The rate of physiological reactions within plant tissue increase exponentially with rises in temperature. This relationship is described using the 'temperature quotient' or Q10. The Q10 was proposed by the Dutch chemist Jacobus Henricus van't Hoff, who determined that the rate of chemical reactions approximately doubles for each 10°C rise in temperature:

$$\mathbf{Q10 = (Rate2 / Rate1)^{10/(temperature2 - temperature1)} = Constant\ (about\ 2)}$$

For many biological processes the Q10 actually varies considerably, and is highest between 1 and 10°C. This is important, as high Q10 values can indicate that small changes in temperature will have major effects on quality.

For example, in the case of broccoli:

Temperature	0°C	2°C	3°C	5°C	7°C	10°C	20°
Storage life	80	60	45	24	11	9	2
Deterioration/day	0.012	0.017	0.022	0.042	0.09	0.11	0.5
Value Q10	\ 4 /	\ 18 /	\ 23 /	\ 49 /	\ 2 /	\ 4 /	

The Q_{10} values shown above suggest that reducing temperature has the greatest benefit between 2 and 7°C. Reducing the temperature from 2 to 0°C or from 20

to 10°C has less effect on storage life. Instead, it could be argued that the most efficient storage temperature is between 2 and 5°C, as it is within this range that cooling has the greatest benefit in terms of increased storage life.

Rots and mould

Low temperatures reduce growth of microorganisms, helping to reduce disease in stored products.

Just as low temperature reduces the rate of deterioration of fresh vegetables, it also reduces growth of microorganisms. Most postharvest pathogens grow optimally from 15 to 25°C. A few, notably grey mould (*Botrytis cinerea*), can continue to grow at 0°C. Although most bacteria and fungi can survive exposure to low temperatures, their growth rate is only a fraction of that under ambient conditions (Figure 8).

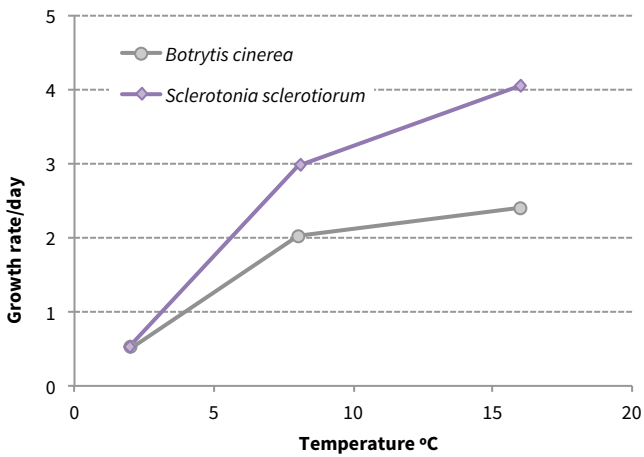


Figure 8 – Effect of temperature on growth rates of grey mould (*Botrytis cinerea*) and white mould (*Sclerotinia sclerotiorum*) on carrots (from Liew & Prange, 1994).[8]

8 Liew CL, Prange RK. 1994. Effect of ozone and storage temperature on postharvest diseases and physiology of carrots (Daucus carota L.). J. Amer. Soc. Hort. Sci. 119:563-567.

Flavour

Storage temperature affects flavour. Low temperature is critical for preserving sweetness in products such as sweet corn and peas, but can cause undesirable sweetening in potatoes.

Many vegetables contain sugars, such as fructose and glucose, and starch. Plants can convert convert sugars into starch, or vice versa, in order to store energy for later use (as starch) or fuel metabolic activity (with sugars). These compounds therefore exist in equilibrium:

Photosynthesis → Energy → Sugars ←→ Starch ←→ Sugars → Energy → CO_2

Storage temperature can alter the balance between starch and sugar in vegetables such as potato, sweetpotato, peas and sweet corn.

For root and tuber vegetables, such as potato and sweetpotato, storage at low temperature tends to increase conversion of starch into sugar. This affects colour and flavour, and can mean fried products brown more quickly due to caramelisation. Conversion of starch into sugar increases below around 10°C for potatoes and 15°C for sweetpotato, depending on variety. This has negative effects on quality (particularly for potatoes), but usually reverses after a period at warmer temperatures.

In contrast, high sugar is strongly preferred for products such as peas and sweet corn. It is important to cool these products as quickly as possible after harvest to prevent sugars being either converted to starch or lost through respiration. For example, sweet corn can lose 60% of the sugars that give it flavour within 24 hours of harvest if it is kept at 30°C, partly due to loss in respiration but also due to conversion of sugars into starch.

3.3 High temperature effects

As well as increasing weight loss and disease, high temperatures can limit the development of colour and ripening in some fruit vegetables. Short periods of high temperatures can benefit long storing root and bulb crops by increasing wound healing.

Vegetables may be accidentally exposed to high temperatures if left in the sun after harvest or due to a malfunction in the normal cool chain. They may also be heat treated to reduce chilling sensitivity, kill microbes or as a quarantine treatment against insects.

Temperatures over 30°C can destroy the enzymes in vegetables that are responsible for colour changes and maturation. For example, capsicums and tomatoes held at over 30°C may fail to develop normal red colour. High temperatures can stimulate breakdown of chlorophyll, resulting in premature yellowing, and cause rapid softening, wilting and dehydration.

A few vegetables can benefit from exposure to high temperatures during curing. Curing is used to allow the vegetable to heal over injuries inflicted during harvest, such as breaks, cuts or scratches. Products such as sweetpotatoes, pumpkins and onions, may benefit from 7 – 10 days at temperatures between 22 and 30°C, particularly if they have been damaged during harvest and extended storage is planned.

4 Water

Vegetables are essentially water in fancy packages. Most vegetables are over 80% water; some are close to 95% water. It costs money to put the water in, and it is a direct loss in yield and monetary return if that water comes out.

Moisture loss results in wilting, texture changes, poor flavour and spoiled appearance. However, too much water can also be a bad thing, increasing rots and disease, causing splitting and discolouration in some products, and generally degrading quality.

Getting the right balance between avoiding moisture loss by keeping humidity high while also avoiding products getting wet is one of the challenges of postharvest management.

4.1 Relative humidity and condensation

Relative humidity is the percentage saturation of the air. Temperature changes/fluctuations can cause water vapour to condense out of the air, wetting cartons and produce and increasing fungal growth.

Humidity refers to the amount of water vapour that is held in the air. This varies according to temperature, with warm air able to hold far more water vapour than cold air. So for example, at 30°C a cubic metre of air can hold a maximum of 31g of water as vapour. At 0°C that same cubic metre will hold less than 5g of water as vapour.

Relative humidity refers to the amount of water vapour in the air compared to the maximum it can hold at that temperature. So a cubic metre of air at 30°C, which contains 20g of water as vapour is approximately 64% of the maximum amount, ie 64% RH.

As temperature drops, air is less able to hold water vapour. The vapour will therefore condense out as liquid water. This has implications for packaging and transport.

For example, if sealed cartons of warm vegetables are placed in a cool room, the air inside the cartons will lose moisture as it cools, resulting in condensation on the product and the inside of the carton. Conversely, when cold cartons are moved into ambient conditions they cool the surrounding air. Depending on the RH, water vapour from the cooled air will then condense on the outside of the cartons.

Temperature fluctuations therefore almost inevitably result in condensation. This can weaken packaging materials and increase water loss from packed product. Condensation can encourage development of rots and increase the chance of products splitting.

Relative humidity is particularly implicated in fungal infection and growth. Dry conditions prevent spores from germinating, and even if germination is successful the exposed tissue may be too dry to permit infection. Most fungi cannot grow if RH is below 85-90%. However, humidity this low is not suitable for products susceptible to moisture loss, such as leafy vegetables and carrots, both of which should ideally be held at >95% RH.

4.2 Osmosis and vapour pressure

Osmosis

Water moves into and between cells through permeable membranes. This process is driven by differences in solute concentration (sugars, acids, etc.) inside and outside the cell. This process— osmosis— creates turgor pressure and is what keeps vegetables firm and crisp. However, too much water can lead to splitting.

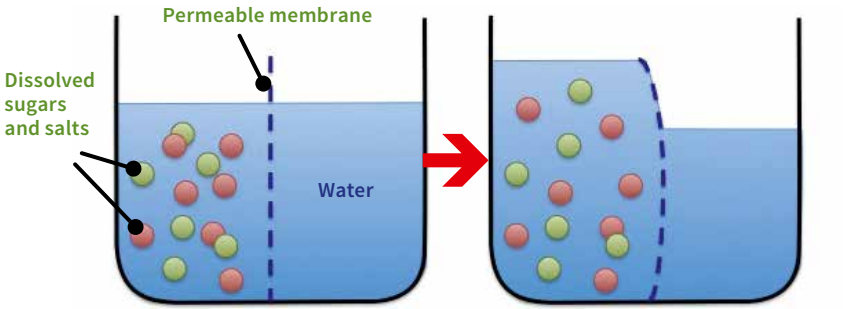


Figure 9 – Osmosis is the process by which water moves through a permeable membrane from areas of low concentration of solutes (e.g. sugars and acids) into areas of higher concentration. This creates turgor pressure.

Vegetables stay crisp and firm because water inside the cells is under pressure and pushes out against the cell walls and membranes. Water is drawn into the plant cells by osmosis, which ensures they stay turgid.

Osmosis is the process by which water will move through a permeable membrane (e.g. the plasmalemma inside the cell wall) from areas of low concentration of solutes to areas of higher concentration. Solutes can include dissolved sugars, acids, minerals and salts. The resulting increase in the volume of water inside the cell creates turgor pressure (Figure 9).

When a product with a semi-permeable skin and high concentrations of solutes is placed in water, osmosis will result in it absorbing water. This can result in weight gain and improved turgidity. However, if the process goes too far, the result is swelling and cracking, as occurs with broccoli stems left in melt-water.

Vapour pressure

Vapour pressure is the amount of water vapour held in the air. Differences in vapour pressure due to RH and temperature are termed the vapour pressure deficit (VPD).

At any temperature and humidity, water molecules constantly change between the liquid phase—water, and the gas phase—vapour. At 50% RH water will tend to move from the liquid phase into vapour, while at 100% RH a product with high osmotic potential (eg a carrot) can absorb moisture from the air, effectively changing vapour back into liquid water. At 95–100% RH, the water vapour

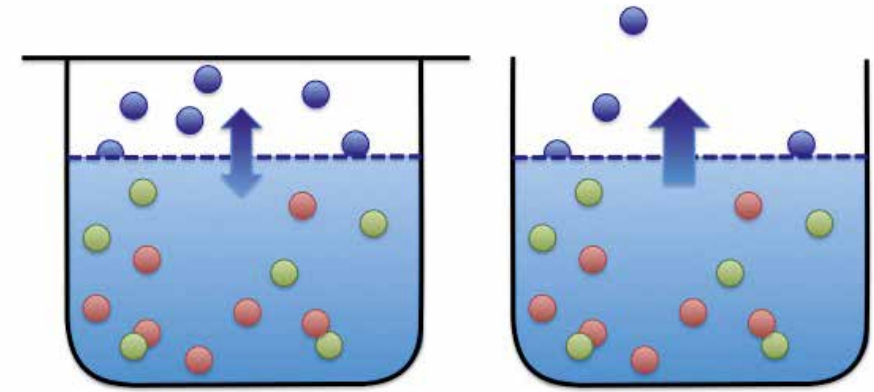


Figure 10 – Water constantly moves between the liquid and vapour phase. At 100% RH the liquid and the gas phase exist in a dynamic equilibrium (left). However, at lower RH, water will move out of the liquid phase and into the gas phase (right).

outside most products will be in equilibrium with the water vapour inside the product, which in turn is in equilibrium with the liquid water contained in the cells. Under these conditions changes between liquid and vapour will be the same in both directions.

As vegetables are mostly water, the air spaces inside them are normally saturated with water vapour. While this means the internal air spaces are effectively at 100% RH, the actual amount of water held as vapour will be affected by temperature. The amount of water vapour in the air can be expressed as vapour pressure, with units in kilopascals (KPa).

The difference in vapour pressure between this environment and the air outside the product is the vapour pressure deficit (VPD).

Calculating the vapour pressure deficit

The VPD in KPa can be calculated from information on temperature and humidity. Large VPD values drive moisture loss, and are likely to occur when warm produce is placed in a cool room. Cooling vegetables quickly is essential to avoiding moisture loss.

One of the easiest ways to determine vapour pressure in KPa at different combinations of temperature and humidity is by using a psychrometric chart

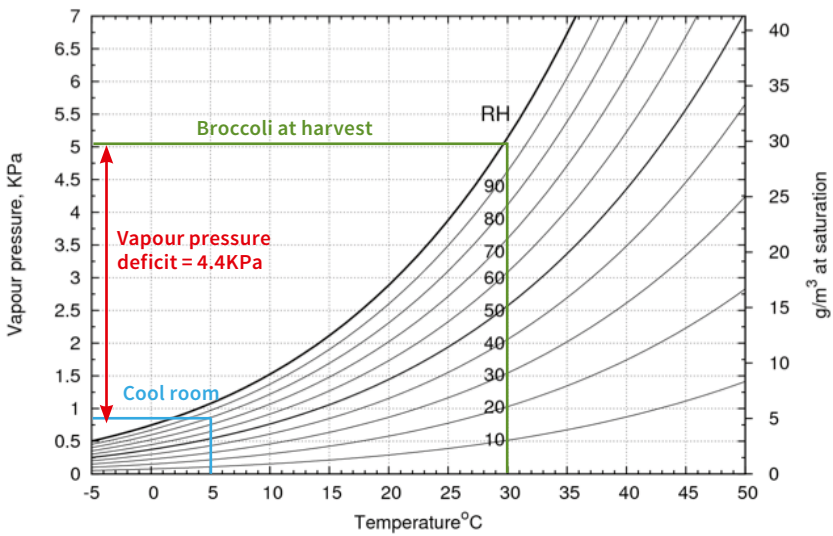


Figure 11 – Using the psychrometric chart to calculate vapour pressure deficit. An example is shown for freshly harvested broccoli at 30°C which has been placed into a cool room running at 5°C and 80% RH. The vapour pressure deficit is approximately 4.4KPa.

(Figure 11). This shows how quickly the amount of water vapour air can hold increases as temperature rises.

While vegetables are warm, they are almost certainly losing moisture. This is because their internal vapour pressure will be much higher than the vapour pressure inside the cool room, even if both are close to 100% RH. The difference between the vapour pressure inside the product and that in the surrounding air is termed the vapour pressure deficit (VPD).

The example shown in Figure 11 shows the VPD for broccoli freshly harvested at 30°C (internal RH = 100%) placed into a cool room running at 5°C and 80% RH. The vapour pressure inside the broccoli is approximately 5.2KPa, whereas that in the cool room is only 0.8KPa. The resulting vapour pressure deficit is around 4.4KPa. This difference in water vapour pressure between the inside and outside of the product has the potential to drive significant moisture loss as water moves from the broccoli into the cool room air.

If broccoli harvested at 10°C is placed into the same cool room, the vapour pressure deficit would only be around 0.7KPa (1.5KPa – 0.8KPa). Under these conditions moisture loss will be more than six times slower than in the first example.

The speed of cooling is therefore critical to reduce loss of moisture from products, even if the cool room is running at close to saturated humidity.

4.3 Reducing water loss

Cool room design

Relative humidity can be maximised in cool rooms by ensuring the delivery air is close to the desired temperature, reducing temperature fluctuations due to defrost cycles, avoiding opening and closing the room, and adding humidifying vapour if necessary.

The main method of reducing the VPD, thereby also reducing moisture loss, is to increase RH in the cool room air. Humidifying storage rooms is relatively simple, as all that is required is to add water, usually as a fine mist. However, adding mist can also lead to soft, damp packaging, floor puddles and increased disease if products become wet. Moreover, adding free water at rooms close to zero increases frosting on the refrigeration coils, leading to longer and more frequent defrost cycles.

One of the best ways to increase RH in the storage environment is to design the cooling system so that the delivery air is only slightly colder than the

setpoint for the room. This minimises the difference in temperature between the coils and the produce, and so avoids excess condensation and/or drying of the air. Using large coils with a high surface area for heat exchange can help achieve this.

Rooms that are poorly sealed, frequently opened or vary significantly in temperature will have lower and more variable humidity than those that are more accurately controlled. In the example shown in Figure 12, both rooms have been set at 1.5°C and fluctuate by approximately ±0.5°C overall. However, the larger and more frequent temperature changes in room 2 result in lower and more variable RH inside the room, potentially causing condensation on and/or dehydration of the produce.

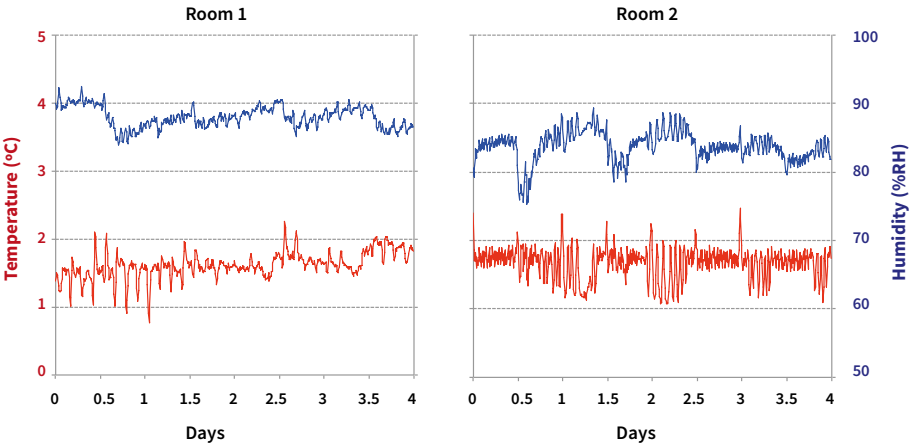


Figure 12 – Temperature (—) and humidity (—) in two different cool rooms both set at 1.5C. In room 1 (left), temperature is relatively stable, so RH remains at 85-90%. In room 2 (right), more frequent and larger temperature fluctuations results in room RH varying from 76 to 90%. (Data recorded at 10-minute intervals in both cases.)

Product characteristics

Product characteristics such as size, shape, number of natural openings and skin features affect how easily the product will lose moisture.

As well as the magnitude of the VPD, many other factors will affect how quickly a vegetable will lose moisture. These include:

- The surface area to volume ratio. All other factors being equal, a leafy vegetable such as spinach will lose water more quickly than a more solid product such as a sweetpotato or eggplant.
- The characteristics of the plant skin. A thick skin and/or a waxy surface, such as that of a pumpkin, can present a significant barrier to moisture loss.
- The presence of open stomata or lenticels.
  - Stomata in leaves usually close at harvest or in darkness, reducing moisture loss.
  - Stomata may remain open during rapid cooling or following chilling damage.
  - Lenticels are open pores, but may be blocked with soil or waxes. For example, washing treatments can spread natural waxes in the skin more evenly over the surface, helping to block lenticels.
  - The skins of solanaceous fruit vegetables (eggplant, chilli) don't have stomata or lenticels; most gas diffusion is through the calyx area. Leaving tomato fruit attached to the stem (as normal practice for hydroponics) or waxing the calyx scar, can both reduce postharvest water loss.
- Mechanical injury, including bruising or abrasion. Moisture loss increases as the integrity of the skin is destroyed.

Air movement

Air movement around vegetables should be minimised to avoid excess moisture loss.

The surface of produce has a thin layer of stationary air around it—the 'boundary layer'. Within this layer the vapour pressures of the air and the product will be in equilibrium. The boundary layer is thickest for products with hairy skins, such as the Asian gourd 'chi qua' or 'hairy melon'. Uneven surfaces, such as found on bitter melon (fu qua) also increase the boundary layer.

Increased air movement disrupts and reduces the boundary layer. Rapid air movement can help cool produce and air movement during storage is needed to remove heat generated by respiration. However, reducing air movement around fully cooled vegetables will avoid disrupting the boundary layer and reduce moisture loss.

Packaging materials

Plastic packaging can be an effective barrier to moisture loss, but it is important to avoid condensation on the products. Natural packaging such as wood and cardboard can absorb moisture from the product or storage environment.

Packaging has a clear role in increasing the RH around a product, thereby reducing the VPD. Packaging holds products together, restricting air movement around individual items. This increases the boundary layer and so reduces water loss. Even a mesh bag may reduce dehydration, simply by interfering with air movement.

Plastic films are very effective barriers to water loss. However, it is important to avoid condensation inside the package that can increase rots and diseases. Films made of ultra-thin, plasticised materials or which have anti-fog coatings or microperforations have reduced risk of internal condensation while still protecting against moisture loss.

Waxes and other fruit coatings can have a somewhat similar effect to packaging materials, especially if the material blocks openings in the vegetable skin. In this case there is no issue with condensation.

Shrink wrap, which is commonly used to package telegraph cucumbers, can also provide RH control without significant condensation. In this case the plastic is in close contact with the produce skin. Condensation does not occur inside the wrapping because the film and the product are at the same

temperature. Shrink wrapping has been shown to be effective for a number of different products, however, cost and consumer resistance are barriers to use.

Some types of packaging can also have the opposite effect on water loss in produce. Wooden bins or boxes, paper and cardboard can all absorb significant amounts of moisture even before they appear damp. For example:

- Wooden bins can gain 6-10% weight in a moist environment. This would represent up to 5kg water absorbed by one half-tonne bin.
- Cardboard can gain up to 17% additional weight. For example, 128g of moisture could be absorbed from 5kg of vegetables by a 750g cardboard carton, a direct weight loss of 2.5% due to the carton alone.

Storing in a high RH environment can reduce moisture absorption by bins, although this is not always feasible. Waxed, varnished or plastic-coated cardboard is less moisture absorbent than raw cardboard.

Even if the atmosphere around a product is close to saturation, some moisture loss will still occur due to metabolic activity and respiration.

5 Atmosphere

Vegetables are alive, they respire and they interact with the atmosphere around them. Normal air contains approximately 400ppm carbon dioxide (CO_2), or 0.04%. Air also contains approximately 21% oxygen (O_2), with 78% Nitrogen (N_2) forming the bulk of the remainder, along with traces of water vapour and other gases — argon, helium, hydrogen, etc. Manipulating the gas concentrations in the atmosphere around fresh products can maintain quality and extend storage life.

Vegetables generate many volatile compounds, of which ethylene is the most important. Ethylene can have many different effects, most of which are undesirable for vegetable storage life and quality.

5.1 Oxygen and carbon dioxide

Altering the concentrations of oxygen and carbon dioxide around products can inhibit respiration and increase storage life due to reduced yellowing, decay and softening.

Section 2 discussed the principles of respiration. Respiration follows the equation:

$$\text{Carbohydrates} + O_2 \rightarrow CO_2 + H_2O + \text{Energy}$$

As products respire they use O_2 and release CO_2. This suggests that reducing the concentration of O_2 and/or increasing the concentration of CO_2 can inhibit respiration and extend storage life.

In fact, responses to altered atmospheres vary widely between different vegetables. In many cases respiration may be less affected than other factors that impact on storage life. Potential effects include:

- Reduced production of ethylene.
- Reduced sensitivity to ethylene, effectively slowing down colour change and ripening in fruit vegetables.

- Improved retention of green colour due to reduced breakdown of chlorophyll.
- Reduced softening due to retention of the pectins that hold cell walls together.
- Less breakdown due to rots and diseases; growth of some fungal diseases is reduced when CO_2 is 10% or more.

Altering the atmosphere around products can also have negative effects. If O_2 falls too low then products can turn anaerobic. Anaerobic respiration induces undesirable changes in texture and flavour. It also results in storage reserves (sugars and carbohydrates) being used up many times faster than during normal aerobic respiration. Depletion of reserves can affect flavour and reduce storage life.

Anaerobic conditions can also allow the growth of some human pathogenic bacteria. These may not spoil the product, but pose a significant danger to human health.

5.2 Modifying the atmosphere

Controlled atmosphere storage

Controlled atmosphere (CA) storage involves active control of O_2 and CO_2 concentrations in the storage atmosphere. While this can maximise potential storage life, CA systems are costly and may not fit with normal vegetable supply chain practices.

Controlled atmospheres (CA) involve active control of the storage atmosphere to maximise the benefits of reduced O_2 and/or increased CO_2. This technology is widely used for long-term storage of apples, which can be maintained in good condition using atmospheres of 1 to 3% O_2 and 2 to 5% CO_2.

The advantage of CA is that it is fully controlled. However, this also increases costs. Specialised equipment is needed to generate the atmosphere as well as monitor it to ensure critical limits for O_2 and CO_2 are not exceeded. It can take several days to create a stable atmosphere inside an apple store. The store then usually stays closed for many months before it is unpacked.

Such long storage periods are not necessarily suitable for vegetables, which tend to be less seasonal and stored for shorter intervals.

One possible use of CA is during sea freight. Nitrogen can be used to reduce both O_2 and CO_2 inside a sealed shipping container. During transport, the container

can be vented with air in response to an O_2 sensor inside the unit, ensuring O_2 does not fall too low. While these containers have been used effectively for some fresh products, disadvantages include cost and container availability.

Modified atmosphere packaging

Modified atmosphere packaging uses the respiration of the product to alter the storage atmosphere inside a sealed package. The equilibrium atmosphere that develops is a factor of respiration, temperature, film permeability and film area relative to product weight.

Modified atmosphere storage uses the respiration of the produce itself to reduce O_2 and increase CO_2. The atmosphere that develops will be determined by the respiration rate of the product as well as the area and permeability of the film. The aim is to produce a stable atmosphere, where the rate of gas movement through the plastic film equals the rate at which O_2 is consumed and CO_2 is produced.

Designing a MAP system for any product requires understanding of storage conditions and the range of normal respiration rates under those conditions. It is also important to know what atmospheres may be beneficial to the product, and what atmospheres may cause damage. Many products are damaged by high CO_2 concentrations. For some products, a CO_2 increase of only 2 or 3% can

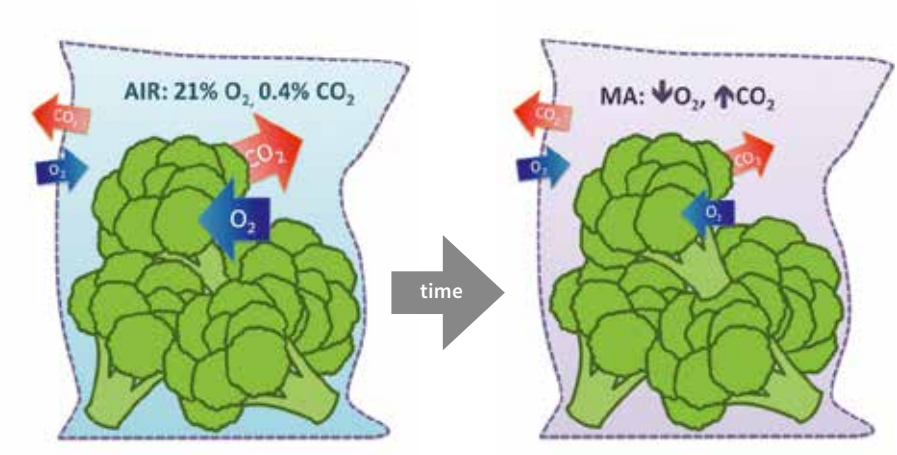


Figure 13 – MAP of broccoli. Initially, the rate of respiration of the broccoli is greater than the rate of gas permeation through the film. After the package is sealed, respiration reduces O_2 and increases CO_2 inside the bag. This inhibits respiration, until the rate at which gases diffuse through the plastic film equals the rate of CO_2 production/O_2 consumption by the broccoli.

result in internal breakdown. Such products are unlikely to benefit from MAP, no matter how permeable the film.

Even if appearance is good, taste and texture can be affected. For example, broccoli stored in MAP has reduced yellowing compared to product stored in air. However, it can develop strong off odours. Although these odours disappear after a time in air, they detract from what otherwise appears a good quality product.

Another consideration is that although some products can look good while still in MAP, they deteriorate extremely fast afterwards. This can be an issue where packages will be opened before retail sale.

Modified atmosphere packaging films

Integral plastic films are usually 3–4 times more permeable to CO_2 than to O_2 whereas microperforated films are equally permeable to both gases. Film selection and degree of microperforation can be manipulated to ensure the atmosphere that develops inside a MAP is beneficial to the product.

Most plastic films are more permeable to CO_2 than to O_2. This is because gas moves through plastic film by dissolving into the plastic then reforming on the other side of the barrier (Figure 14a). This process is driven by differences in gas concentration on either side of the film – a process equivalent to osmosis with liquids through a membrane (Section 3).

The CO_2 molecule is composed of three atoms and has a slightly polar electrical charge, whereas O_2, with two equal atoms, does not. This allows CO_2 to more easily dissolve into the plastic film than O_2. Nitrogen (N_2) is even less able to dissolve through a membrane than O_2.

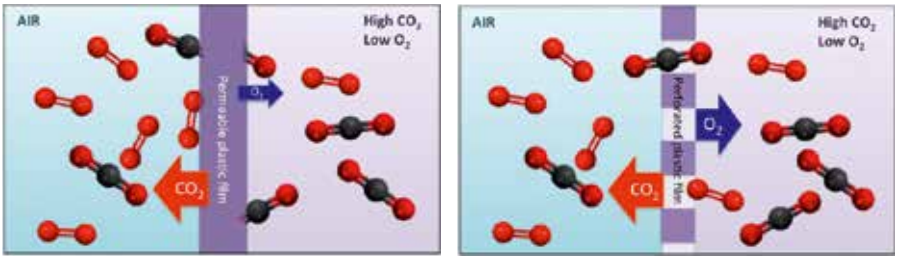


Figure 14a – Diffusion of O_2 (red molecule) and CO_2 (red and black molecule) through a barrier film. Individual gas molecules dissolve into the film itself, then reform on the other side, a process driven by differences in concentration either side of the barrier.

Figure 14b - Diffusion of O_2 and CO_2 through a perforated film. Gas molecules move directly through tiny holes. Unlike permeable materials, perforated films are equally permeable to all gases.

Film permeability is usually expressed as oxygen transmission rate (OTR) and/or carbon dioxide transmission rate (CO_2TR). Water vapour transmission rates (WVTR) may also be noted. The rate of permeation of gases is described as cm^3/m^2/day/KPa. In other words, the volume of gas transfer per m^2 of film, expressed per day and per bar of pressure.

Package permeability varies considerably depending on the type and thickness of plastic, manufacturing technique and surface area. Most plastics are 3–4 times more permeable to O_2 than to N_2, and 10–20 times more permeable to CO_2 than to N_2 (Table 5.1). So, for example, the stable CO_2 concentration inside a package made of nylon-based film will be lower than the stable CO_2 concentration inside a package made of LDPE film, even though the O_2 concentration may be similar. In all such films, increases in CO_2 inside the package will be significantly less than decreases in O_2 (Figure 15).

Table 5.1 - Relative permeability to O_2 and CO_2 of different types of plastic film, in comparison to their permeability to N_2

Polymer	N_2	O_2	CO_2
Low density polyethylene (LDPE)	1	3.1	10.7
High density polyethylene (HDPE)	1	3.2	11.9
Polypropylene (PP)	1	4.3	13.6
Nylon 6	1	3.4	18.4
Polyethylene terephthalate (PET)	1	3.6	17.8

(Data from V. Siracusa. 2012. Food packaging permeability behaviour: A report. Int. J. Polymer Sci. 302029.)

Perforated films are different. In this case gas exchange is through holes, so permeability to O_2 and CO_2 is the same(Figure 14b). While there can be some contribution to gas movement by diffusion through the film barrier, this is usually insignificant compared to the much faster gas transmission through the holes. In packages made of microperforated films, decreases in O_2 will be matched by increases in CO_2 (Figure 15).

Once the optimum concentrations needed to extend storage life are known, films can be selected to achieve this result at the anticipated storage temperature. For example, storage life of spinach can be extended in an atmosphere of 10% O_2 + 10% CO_2 — a combination which may be achieved using a microperforated bag. In contrast, cauliflower is best stored in 2–5% O_2 + 2–5% CO_2: a nylon film bag could (theoretically) develop an atmosphere of 3% O_2 + 3.3% CO_2, making it a suitable material for this product.

One advantage of micro-perforated films is that their permeability is determined by the number of holes created during manufacture. This means packaging materials can be readily tailored for specific products and purposes.

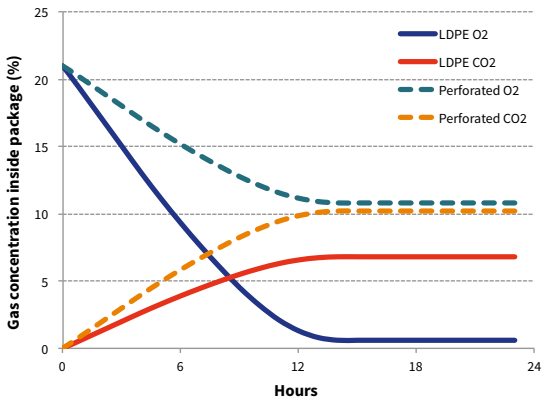


Figure 15 – Concentrations of O_2 and CO_2 inside a theoretical package made of either LDPE or a microperforated film. After 15 hours both packages have reached equilibrium. That is, where respiration rate is equivalent to the rate of gas diffusion through the film. However, both O_2 and CO_2 are higher in the microperforated film compared to one made of LDPE.

Modified atmospheres and temperature

If temperature rises, the resulting increase in product respiration rate is usually greater than the accompanying increase in film permeability. This means high temperatures can cause MAPs to become anaerobic.

One of the major difficulties with MAP is that the permeability of films to O_2 and CO_2 generally increase only slightly in response to temperature, whereas respiration rates increase a lot more. Polyethylene films can double in permeability with a 20°C increase in temperature. However, over the same temperature interval respiration may increase tenfold or even more.

If conditions are warmer than those for which the package was designed, O_2 used for respiration will be greater than O_2 transmission through the film and the package will run out of oxygen (become anaerobic). However, if packages are designed to provide a suitable atmosphere when being 'temperature abused' they are unlikely to provide significant benefits (in terms of low O_2 and/or high CO_2) during normal cold storage.

Package designers have attempted to overcome this limitation by adding patches of materials that are more responsive to temperature, or which increase in permeability when saturated with water. Despite this, MAP remains best suited to applications where temperature can be closely controlled.

5.3 Ethylene

Ethylene is a gas released by fruit and vegetables due to injury, decay or during ripening. Exposing vegetables to ethylene can result in yellowing, shortened shelf life and increased disease. Ethylene can be removed using scrubbing systems, venting or ozone. The effects of ethylene are reduced at temperatures below 5°C.

Ethylene (C_2H_4) is a gas produced naturally by plants. It is particularly associated with ripening of fruit such as bananas, mangoes and tomatoes. These fruit are known as 'climacteric' due to the large amounts of ethylene, and marked increase in respiration, that occurs during ripening. Ripening of climacteric fruit can be trigged by treating with ethylene during storage. This technique has wide commercial application, particularly for bananas and avocados.

Ethylene is also released in response to injury, and during rotting/composting of vegetation. It is additionally given off in the exhaust fumes from cars and trucks. Acetylene has a similar chemical structure to ethylene, and produces the same reactions in plants. Acetylene is used during welding, or released from calcium carbide.

Vegetables in mixed storage rooms may be exposed to ethylene if fruit are also present. For example, apples continue to release significant amounts of ethylene even when stored at close to 0°C.

While different vegetables vary in their sensitivity to ethylene, all the effects of ethylene on vegetables are negative. Ethylene exposure increases breakdown of chlorophyll (causing yellowing), reduces storage life, increases sensitivity to chilling injury and can help spread decay. A concentration of 0.1ml/L (0.0001%) can be enough to cause undesirable changes in products such as leafy vegetables.

Ethylene is used commercially to increase ripening and improve colour consistency of mature green tomatoes. Capsicum are non-climacteric, so do not respond in the same way. Trials have shown that some capsicum and chilli varieties do have faster red colour development when ethylene is present, but only if they were already changing at harvest. Even in this case, ethylene exposure is likely to shorten storage life, so costs may still outweigh benefits.

The effects of ethylene on vegetables can be avoided or reduced by:

- Low temperature storage. Below 5°C the effects of ethylene are greatly reduced.
- Keeping the storage area ventilated to avoid accumulation of ethylene inside.
- Removing ethylene from storage rooms by reacting it with potassium permanganate.
- Oxidising ethylene by reacting it with ozone (O_3).

6 Cooling and storage

Refrigeration and the cool room are both Australian inventions. The world's first ice-making plant was built in Geelong, Victoria, in 1851 by James Harrison. Cooling was achieved by 'evaporation of volatile liquids in vacuo', the basic technique which is still used today. Refrigerated cold stores, first for the storage of meat, but shortly afterwards for apples and pears, were in operation by the 1880s—an Australian first.

6.1 Cool rooms

Refrigeration systems

Refrigeration systems work by compressing a refrigerant, then allowing it to expand. The expansion of the gas absorbs energy, cooling the evaporator coils and, indirectly, the air passed over them. This delivery air must be colder than the room setpoint in order to cool the room and the products it contains.

All cool room refrigeration systems have five main components:

1. The compressor, which compresses the refrigerant gas
2. The condenser, in which the hot gas is cooled to a liquid
3. An expansion valve, which controls flow of the liquefied gas and where liquid gas expands to vapour
4. Evaporator coils, where the liquid gas expands and boils. This process absorbs energy, cooling the coils
5. Fan or fans, to circulate air over the cold evaporator coils, thereby cooling the cool room. Air may also be circulated over pipes containing some type of liquid antifreeze, which have themselves been cooled using the evaporator. Fans also circulate air around the cool room to ensure even distribution of the cold air and reduce temperature variations within the room.

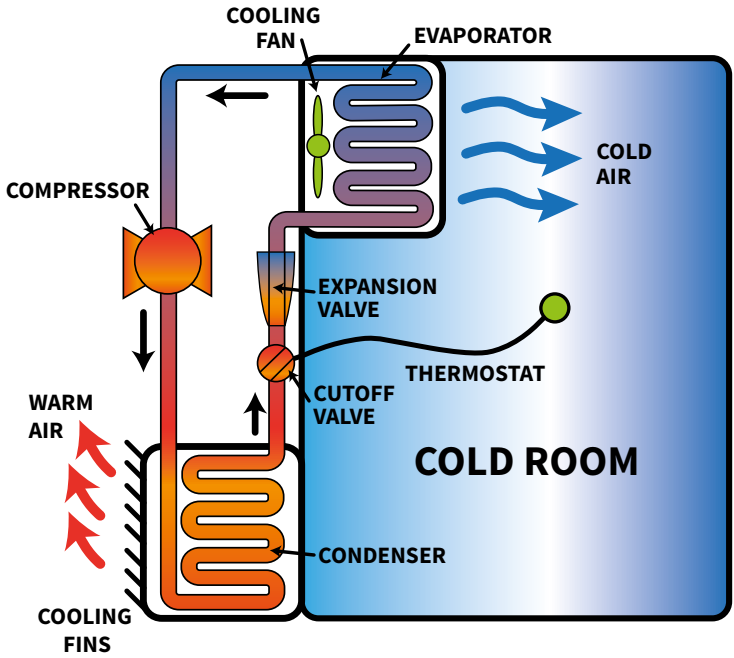


Figure 16 – Refrigeration systems all contain the key elements of a compressor, a condenser, an expansion valve, evaporator coils and circulation fans.

The temperature of air leaving the coils must necessarily be lower than the cool room setpoint, in order to remove heat generated inside the room. The RH inside the room is affected by:

- The magnitude of the difference between the room setpoint and the coils.
- The amount of temperature variation allowed before the system switches on or off (eg 2°C ± 2°C means the room can increase to 4°C before the fan unit turns on).

Smaller temperature differentials maximise RH, as discussed in Section 3.

Insulation

Insulation must be kept dry to be effective. Good insulation of floors, walls and ceiling improves temperature control and greatly reduces running costs.

Cool room panelling relies on trapping air, usually in a foam or polystyrene matrix, to prevent transfer of heat from the outside environment into the cool room inside. However, it is vitally important to keep this material dry. If the inside of the panelling becomes wet due to condensation and/or entry of humid air from the room then it will become ineffective. Seals around all cool room panels must be intact and waterproof enough to repel water used for cleaning (eg jet washing).

Concrete floors should include layers of insulating materials, and be thoroughly sealed against water from floor puddles or washing. Many commercial cool rooms do not have well insulated floors, even though good floor insulation can greatly reduce temperature leakage.

Cool room design and construction

There are many factors to consider in cool room design. It is important to have a clear plan of how the room will be used to ensure it has sufficient cooling capacity, appropriate temperature range and accurate enough control of temperature, humidity and air circulation to operate effectively.

A cool store is essentially a large, insulated box with a refrigeration system and a door. Temperature will vary in different areas inside the room depending on airflow, the way produce has been loaded inside, and the amount of heat contained within that produce.

The design of cool rooms needs to take into account a number of criteria:

- Temperature range. Systems which need to achieve temperatures below zero are usually more expensive than those which have a minimum temperature of 2°C or greater.
- Accuracy of control. A room which seeks to control temperature within ±0.2°C, for example, will be more costly than one which allows larger fluctuations.

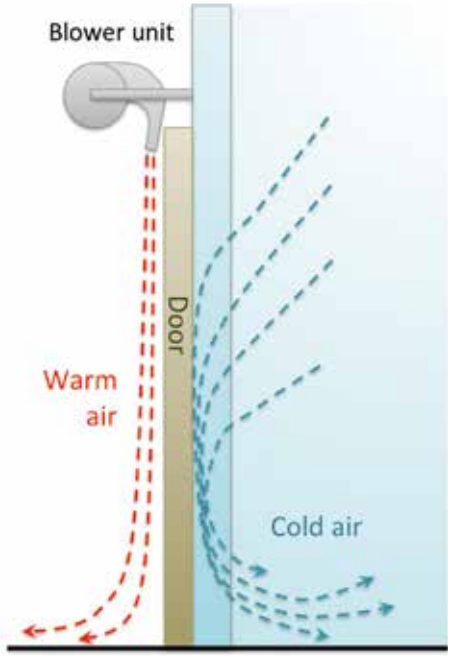


Figure 17 - An air curtain uses a narrow jet of air as a barrier between the cold room and the outside atmosphere.

- Degree of spatial variation within the room. All rooms have warmer areas, often by the door, or in the back corners. The coldest zone is almost always in front of the delivery air. Minimising spatial variation requires increased air circulation and volume, adding cost to equipment and materials.
- Cooling capacity. For example, a room might need to have sufficient cooling capacity to reduce the temperature of 20 harvested bins of broccoli (equivalent to 20% of the total room capacity) from 25°C (harvest temperature) to 5°C within 12 hours.
- Heat load from the outside environment. This will affect the thickness and quality of insulation materials chosen for the walls and floor. Using heat reflective paints and materials as well as roof shading can significantly reduce heat load on the room.
- How the room will be loaded and produce stacked. Air circulation should ideally be consistent with the normal orientation of pallet skids.

- How often the door needs to be open for incoming and outgoing product. Frequent door opening, particularly if ambient temperatures are high, greatly increases the load on the refrigeration system. Having a small door for foot access, in addition to a roller door for forklifts, may reduce loss of cold air. These can be further enhanced with flexible curtaining materials, fast automatic roller doors, or double door systems. An air curtain (Figure 17) can also be used to reduce entry of warm air into the cold room.
- Running costs. Electricity is a major cost for packing and storage facilities. Spending more on better insulation and door seals may be highly cost effective if it reduces power costs. If temperature control is not critical and rooms are left closed during the day, it can be possible to use mainly off peak electricity. Product is cooled overnight and allowed to slowly increase during the day.
- With water-cooled systems, off-peak electricity can be used to cool a chilled water tank ('heat sink'), which can then be used during the day.
- Sanitation. Rooms need to be kept clean, so using materials that are easily washed and including provision for drains will make this easier.

Cool room loading

Produce must be loaded into cool rooms with consideration of airflow. Blocking airflow will prevent the room operating effectively and can lead to warm areas developing in packed pallets.

For the cool room to operate correctly, air must be able to circulate around the produce inside, whether it is already cool or not.

Produce should therefore never be stacked against the cool room wall. It is recommended to leave a gap of at least 10cm for air to circulate. A larger gap (10–15cm) should be left if the wall is exposed to the sun. These gaps will allow any heat transferring from the outside environment to be carried away in the room air before it can warm the product.

Likewise, a clear air space of 25cm or more should be left between the fan unit and the top of stacked pallets or bins. This will allow the cold air to move over the top of the store contents, rather than being blocked by products nearest to the refrigeration unit.

Stacking products on pallets allows air circulation between the floor and the packed products. Aligning the pallet skids to run parallel to the direction of the cooling air (ie towards the refrigeration system) will create a more efficient air circulation.

6.2 Cooling rates

Einstein wrote "*Energy cannot be created or destroyed, it can only be changed from one form to another.*"

Heat is simply thermal energy. Energy will always naturally move from high areas (hot) to low areas (cool). Cooling involves speeding up this process, actively moving thermal energy from a product into a cooling medium and then away into the broader environment.

The speed at which this occurs is governed by:

- The volumetric flow and type of cooling medium
- Surface area
- Thermal conductivity
- The difference in temperature between the product and the cooling medium

The cooling medium

Cooling can occur by conduction, convection or radiation. Air and water move heat energy away from products by a mixture of conduction and convection. Water is many times more efficient at removing heat than air.

Transfer of heat energy can occur by three mechanisms:

- Conduction
- Convection
- Radiation

Conduction occurs when heat transfer occurs without any flow of materials. If cartons of hot product are placed together with cartons of cold product, conduction will eventually even out the temperatures. That is, the cold product will warm, and the warm product will cool, until all are the same temperature.

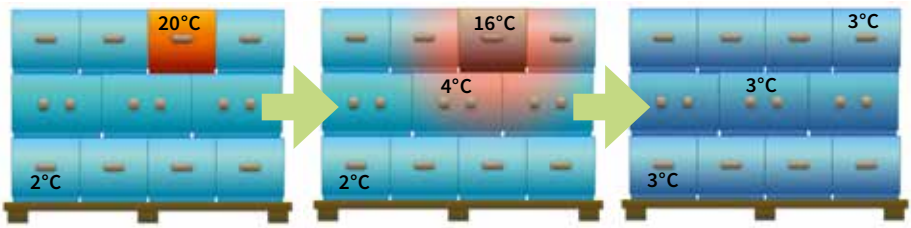


Figure 18 – If a hot carton is stacked among cold cartons, conduction will eventually even out the temperatures in the stack. The hot carton will be cooled, but the cold cartons will be slightly warmed.

Convection involves transfer of heat by the movement of air or water. Movement carries the energy from a high temperature location to a low temperature location. Forced air and hydrocooling systems use convection to move heat out of vegetables and into the refrigeration system, where the energy is absorbed.

Radiation is transfer of heat by electromagnetic waves. This is the mechanism by which heat is transferred from the sun to the earth, from a toaster into a slice of bread, and from cool room lights into stored products.

When warm product is cooled, the energy first moves through the surface by a process of conduction into air, water, packaging or neighbouring vegetables. It is then carried away from the product by convection.

Air is a poor conductor of heat. In fact it is considered a thermal insulator. A feather-filled sleeping bag is both light and incredibly warm because it traps the internal air, keeping it immobile between the layers of feathers and material. This stops heat from transferring from the body inside to the outside air.

Water is a better conductor of heat. Even without warm clothes it is possible to survive and be active at 0°C or less. However a person in 0°C water is likely to become unconscious within about 15 minutes and survive less than one hour.

Cold water can remove heat more than 20 times faster than air. In effect, this means that a much larger volume of air is needed to achieve the same amount of cooling as a quantity of cold water.

Surface area

Transfer of heat energy into the cooling medium occurs through the surface. Objects which have a large surface area compared to their volume cool fastest. For packed product, forced air and hydrocooling systems increase the effective surface area from the outside of the carton or pallet to that of the product contained.

Thermal energy—heat—can only be transferred at the point of contact between the cooling medium and the product.

For a single vegetable surrounded by cold air or water, surface area relative to volume will be large, even for a round product such as a pumpkin.

However, if product has been packed into a carton, or is still in the harvest bin, the effective surface area is the outside of the container, not the product skin. The surface area of a bin relative to its volume is very small, resulting in a slow cooling rate.

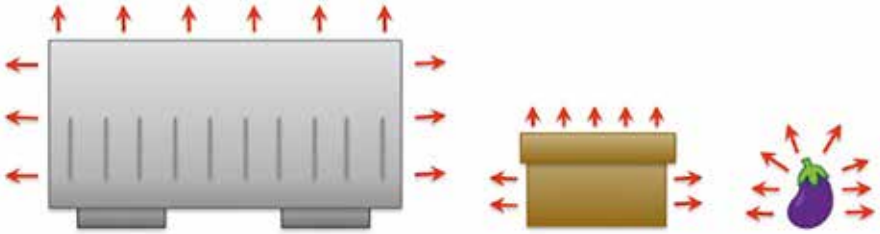


Figure 19 – Heat transfer occurs through the surface that is in contact with the cooling medium. For a single product in air that is its skin, whereas for product in a bin or packed into a carton, the surface area is that of the container.

It is possible to increase the effective surface area for product in bins or cartons by forcing air (or water) through the container. This allows heat to be removed directly from the surface of the product. Forced air-cooling effectively does this, pulling air through the container across the surface of the products contained. Hydrocooling also allows direct contact between the product and the cooling medium, greatly increasing the rate of cooling even if product is still inside the harvest bin.

Thermal conductivity

Thermal conductivity determines how quickly heat can be removed from a specific vegetable. This is affected by its structure and other physical properties.

Thermal conductivity refers to how easily heat can be removed from a specific vegetable. This is affected by shape, skin structure and composition.

Layers of air trapped between overwrapping leaves, such as a cabbage or lettuce, reduce thermal conductivity. This means they are slower to cool, especially when compared to a solid vegetable of similar size and shape such as a pumpkin.

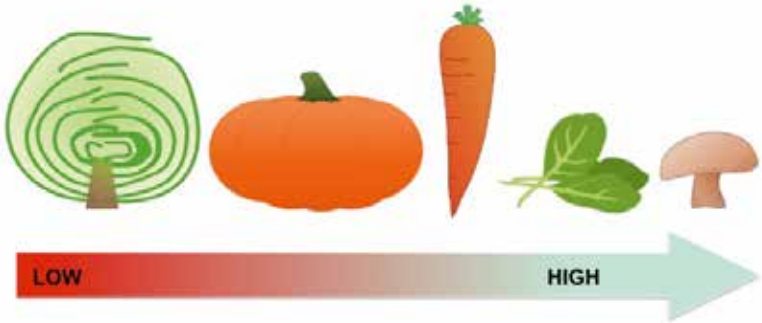


Figure 20 – Thermal conductivity of different vegetables, ranked from low to high.

Thin skins, such as a carrot, and large surface area, such as leafy greens, also increase thermal conductivity. Mushrooms lack a skin and are 90% moisture, so their thermal conductivity is highest of all fresh products (Figure 20).

Temperature differential and cooling times

Vegetables cool fastest when there is a large temperature difference between them and the cooling medium. As they approach the setpoint they cool slowly. Cooling times are therefore not the time taken to reach the setpoint, but the time taken to decline by ⅞ or ¾ of the original temperature differential.

The difference in temperature between the product and a cooling medium is another driver for temperature changes. A large differential results in rapid cooling. However, as the temperature of the product approaches that of the surrounding air or water, temperature changes more slowly.

It can take hours or days for product to reach the same temperature as the delivery air. In some cases it never reaches this point, as the heat produced by respiration keeps the product fractionally warmer than its surroundings.

For this reason cooling rates are usually expressed in terms of the time taken for product to become '¾ cooled' or '⅞ cooled'. This is calculated as the time for ¾ or ⅞ of the initial difference in temperature between the product and the cooling medium to be removed.

For example, a head of broccoli that is 25°C at harvest, placed into a cool room running at 5°C would be ¾ cooled when it cooled to 10°C and ⅞ cooled when it reached 7.5°C. For broccoli initially at 30°C placed in a cool room running at 2°C, ¾ and ⅞ cooled would be reached at 9°C and 5.5°C respectively (Figure 21).

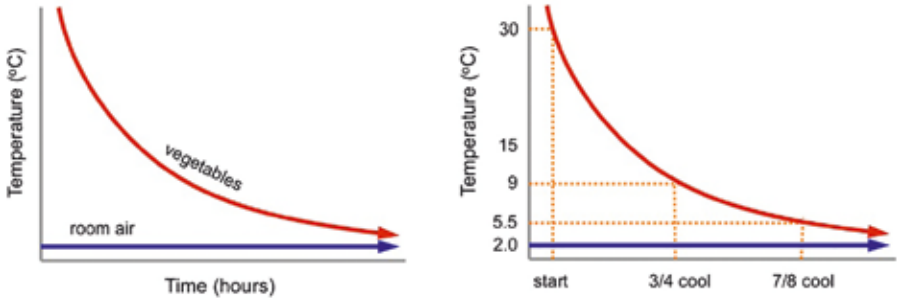


Figure 21 – Vegetables placed in a cool room initially cool rapidly. However, cooling slows as they approach the temperature of the room air (left). For this reason, cooling rates are usually expressed as the time taken for products to be ¾ or ⅞ cooled (right).

6.3 Cooling methods

Room cooling

Room cooling is when produce cools passively inside a cool room. Temperatures can take hours or days to approach the room setpoint, depending on air circulation and container venting. Room cooling minimises re-handling. However, slow cooling rates can increase weight loss and cause condensation.

Room cooling is where a bin or carton of produce is simply placed inside a cool room. Unless there is rapid air movement, most cooling will occur by conduction—heat energy moving out of the product into the surrounding environment.

While cost and labour are minimised, this method can result in quite slow cooling rates. The centre of a half-tonne bin, for example, can take several days to cool from an initial temperature of over 20°C to below 5°C. This can be problematic if products have been harvested while hot, are susceptible to moisture loss and/or have a fungal or bacterial infection. Moreover, as warm, saturated air from the centre of the bin cools, condensation on the product is likely.

Room cooling rates will be affected by the amount of air moving across and through the package. It is recommended that air velocities around packages should be >1m/second. However, whether this is sufficient will depend on the

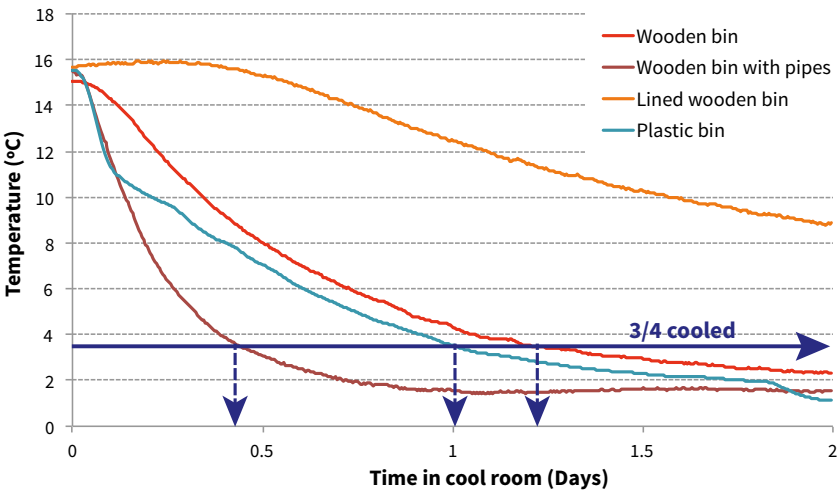


Figure 22 – Temperatures of produce at the centres of half tonne bins during room cooling. The wooden bin, wooden bin with pipes and plastic bin were ¾ cool in approximately 1.3 days, 0.5 days and 1 day respectively. The lined wooden bin failed to reach ¾ cool during the trial.

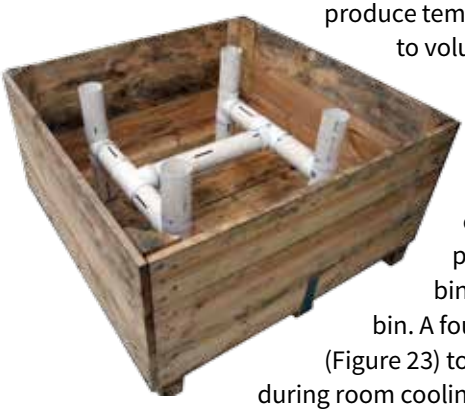


Figure 23 – Wooden bin fitted with ventilation pipes to increase air circulation during room cooling

produce temperature, type and surface area relative to volume. The surface area of a packed pallet or half-tonne bin is relatively small, so it will be slow to cool. For example, Figure 22 shows the internal temperatures of freshly harvested chestnuts at the centre of half-tonne bins placed in a cool room. Wooden and plastic bins were tested, as well as a lined wooden bin. A fourth bin was fitted with ventilation pipes (Figure 23) to increase air circulation through the core during room cooling.

In this case the plastic bin cooled slightly faster than the wooden bin, likely due to the increased air vents on the bin floor and sides. The bin with ventilation pipes cooled fastest, although fruit at the top and base of this bin cooled at the same rate as the standard wooden bin. The lined bin was extremely slow to cool due to prevention of air circulation through the fruit.

As products must be widely spaced to allow airflow, room cooling is also space inefficient. It can also increase the load on the refrigeration system if warm products are constantly being added to the room.

Forced air-cooling

During forced air-cooling, air is pulled rapidly through bins or cartons of vegetables. This increases the effective surface area from that of the bin or carton to that of the produce inside. This increases the rate of cooling and avoids condensation.

Forced air or 'pressure cooling' effectively increases the surface area being cooled from that of the package to that of the produce inside. Forced air-cooling can reduce cooling times by 10 times or more, compared to room cooling.

Forced air systems pull cold air through vented packages at rates varying from 0.1 to 2.0L/second/kg. A general guide to fan strength is that there should be enough pressure to hold a piece of A4 paper against one of the carton vents.

Most forced air systems are designed for two rows of stacked pallets (or bins) to be placed against a central plenum (Figure 25). A tarpaulin is draped over the top to block the gaps between the pallets, forcing air through the carton

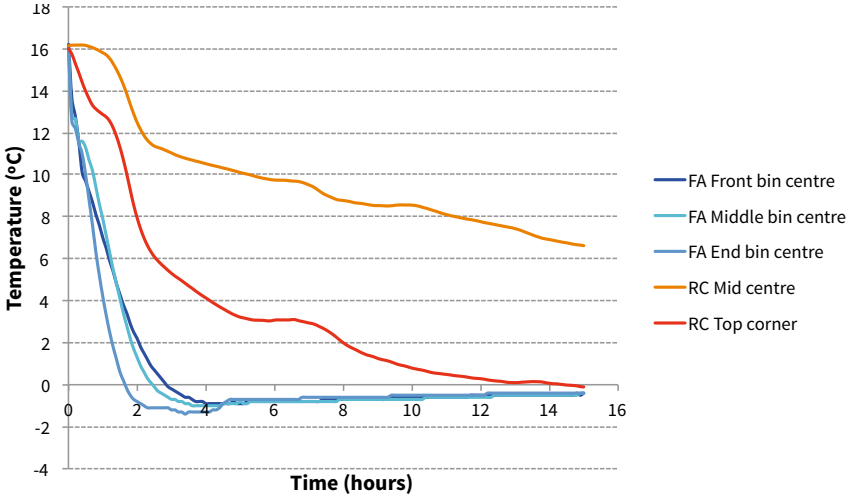


Figure 24 – Temperatures of vegetables in the centre of bins, which were forced air-cooled (blue lines), or in the centre and top corner of bins that were room-cooled (red lines). All bins were inside the same cool room. In the forced-air system air warms as it moves through the bins, so the end bin cools slightly faster than the front bin.

side vents. The fan inside the plenum pulls air through the cartons, removing heat from the packed produce. The air may be exhausted directly back into the room or passed through a cooling system first.

For forced air-cooling to be efficient, cartons should have vents covering at least 5% of their surface area at the air entry and exit points. The vents must line up between cartons, even if pallets are cross-stacked. Note that one or two large holes allow more air movement than many small holes, even if the total area is the same, due to the edge effect around vents.

For smaller quantities of product, a simple bin cooling system may be used (Figure 26). A fan enclosed in housing is simply placed on the top of one or more vented half-tonne bins. Vents on the side of the bins are blocked (with plastic wrap or tarpaulin material), forcing air to move only through the base. Air is pulled through the bins and exhausted directly into the room. This system can work well for smaller volumes of products, especially if cool room space is limited.

Moisture loss is not usually a problem during forced air-cooling as the process is quite fast. However, high-humidity systems are available if this is an issue.

Unlike room cooling, condensation does not occur with forced air systems. Condensation can increase disease and reduce strength of cardboard packaging. Without positive air movement, water vapour transpired by warm

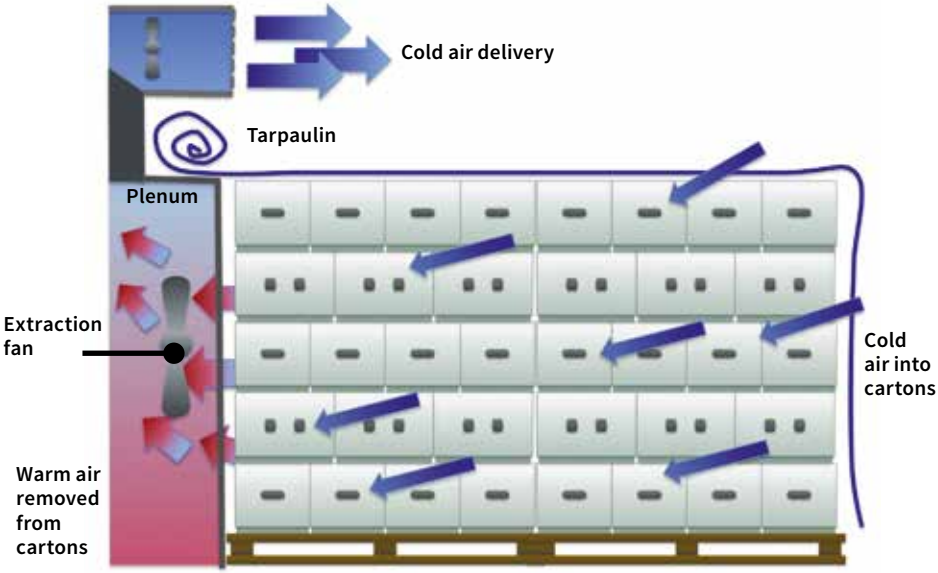


Figure 25 – Forced air-cooling system for large volumes of packed cartons or bins.

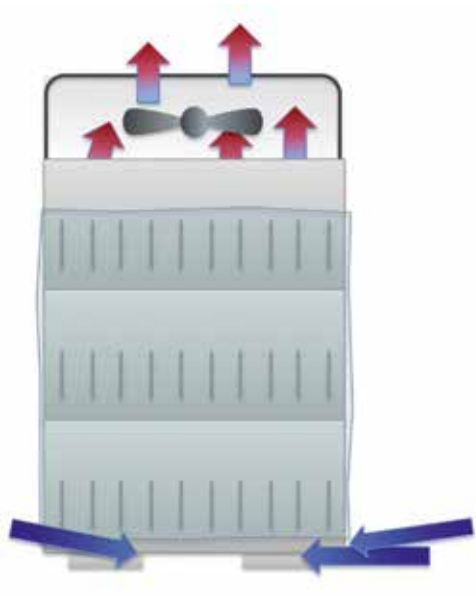


Figure 26 – Forced air-cooling system for small volumes of bins.

produce can condense on the cold product or packaging closer to the air delivery system. With forced air systems, the air warms as it moves through the produce, increasing its capacity to hold and remove water vapour thus avoiding condensation occurring.

The energy efficiency of forced air systems varies widely. In some cases rooms used for forced air are also used for storage. This can reduce overall efficiency, especially if the fans are left on in between cooling cycles to keep the room cool. Efficiency of fans can also be a source of variability.

Hydrocooling

Water is a better conductor of heat than air, so hydrocooling can provide fast cooling so long as the water chiller has enough capacity to remove the heat from the dip or drench water. It is not suitable for all products, and it is important to include a sanitiser to avoid spreading human or plant pathogens.

Water is much better at conducting heat than air, so hydrocooling can provide very rapid cooling of produce. Hydrocooling systems can be either continuous feed on a conveyor, or a batch treatment. Product may be immersed in a dip tank of cold water or drenched by a shower or spray to extract heat from the product. Drenching systems often use a pan with holes to distribute the water, as this requires less energy than generating pressure and spraying through nozzles.

To be effective, the cooling system for the water must have sufficient capacity to remove the heat absorbed from the produce by the treatment water. Also, treatment times have to be long enough to thoroughly cool the product's core temperature; a brief shower or immersion treatment may cool the outer skin, but fail to significantly reduce core temperatures.

Hydrocooling systems generally recirculate water, making it important to include a sanitiser to avoid spreading human or plant pathogens. This is particularly important for fleshy products or those containing internal air spaces, such as capsicums or pumpkins. As the warm air inside the product cools, it contracts, creating negative pressure. This can draw water into the

Figure 27 – Broccoli is often packed with ice. However, ice can cause freezing damage to the florets (left). If the ice melts, broccoli in liquid water is likely to split and develop rots (right).

flesh or cavity. If the water contains fungi or bacteria, this can provide them with an ideal environment in which to grow.

In addition, not all products tolerate being wet. Soft rots and other diseases are more likely on wet products, especially if they are not dried before packing.

One advantage of hydrocooling is that the product loses no moisture, and some may even be gained.

Ice

Packing products with ice can provide 'insurance' against poor cold-chain practices and may be expected by customers for certain products. However, ice can also cause freezing injury when it is applied, and increase rots and disease if it melts. Using ice is an inefficient method of cooling vegetables.

Before refrigerated trucks and the common availability of cool rooms, ice was used for cooling produce. Ice is still used occasionally during transport, notably for broccoli and Brussels sprouts. The main reasons for using ice are that it keeps product cold and hydrated, it looks good when the carton is opened, and (most importantly) the customer expects it.

The freezers that make ice may lower the temperature to well below 0°C; even a simple domestic freezer operates at close to minus 20°C. The temperature of the ice itself may therefore be below the freezing point of the product. Even tolerant products such as broccoli and Brussels sprouts may suffer freezing injury as a result of contact with such cold ice.

As water changes from solid (ice) into liquid state (melts), it absorbs energy from the surroundings. Apart from the heat absorbed directly through conduction, ice mainly cools produce if it is melting. If the ice is still solid when the carton is opened then it was not needed.

If the ice has melted, thereby cooling the product, then the vegetable will inevitably be wet, and often sitting in water. This can cause splitting, discolouration and increased rots and disease.

Water used for icing must be of a high microbial standard. It must not contain human pathogens, and should also be free of fungi and bacteria that can cause plant disease. Making ice uses considerable energy and the process of top icing adds an extra step during packing, all of which increase costs. Adding ice to cartons also adds weight and increases volume, thereby increasing transport costs.

Vacuum cooling

Vacuum cooling involves reducing pressure inside a sealed chamber. Water inside the vegetables turns to vapour, absorbing heat energy. Vacuum cooling works best for products that lose water easily, such as lettuce and babyleaf crops. Hydro-vacuum coolers add a misting system to avoid moisture loss from the product. Vacuum cooling is fast and energy efficient.

Vacuum cooling removes heat from vegetables by boiling off some of the water they contain.

Produce is loaded into a sealed container and the air is pumped out. This reduces the pressure from normal air (approximately 100 KPa) to a virtual vacuum (<1KPa). Under these conditions water boils at <7°C. As water inside

Figure 28 – Hydro-vacuum cooler loaded with bins of broccoli.

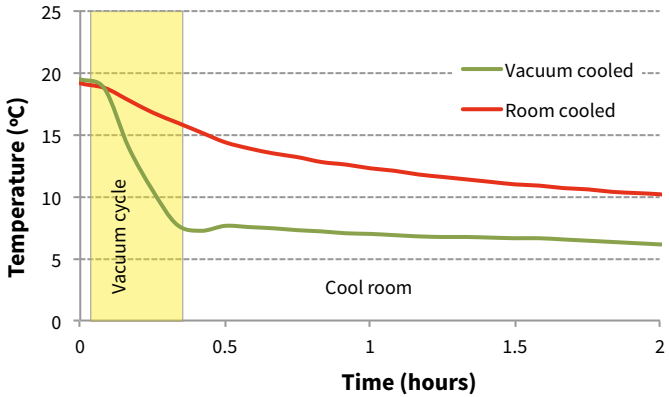


Figure 29 – Temperatures of broccoli vacuum cooled then transferred to the cool room or simply placed in a plastic crate in the cool room. The vacuum cooler reduced the temperature of broccoli from 18.8°C to 7.8°C in 15 minutes.

the vegetables changes from liquid into gas it absorbs heat energy from the product, cooling it. This vapour is removed by drawing it past refrigeration coils, which condenses it back into liquid water.

For vacuum cooling to cool vegetables quickly, they must be able to lose moisture easily. For this reason vacuum cooling is very well suited to leafy products, such as lettuces, Asian greens and silverbeet. Products such as broccoli, celery and sweet corn can also be cooled effectively using this method. Vacuum cooling is not suitable for products with waxy skins, or low surface area compared to their volume, e.g. carrots, potatoes or zucchini.

For every 5°C reduction in temperature, approximately 1% of the produce weight needs to be turned into water vapour. However, modern hydro-vacuum coolers address this issue by spraying water over the produce during the vacuum process. This can reduce moisture loss to negligible levels.

For suitable products, vacuum cooling is the fastest of all cooling methods. Typically, only 20 – 40 minutes is needed to reduce temperature of leafy products from 30°C to 4°C. In the example shown in Figure 29, vacuum cooling reduced the temperature of harvested broccoli by 11°C in 15 minutes. Large vacuum coolers can cool many pallets or bins of product simultaneously, reducing demand on cool room systems. The process can even be used on packed cartons, so long as there is sufficient venting to allow air and water vapour to escape quickly.

Vacuum cooling is also the most energy efficient form of cooling, as nearly all the electricity used reduces the temperature of the product. There are no lights, forklifts or workers inside a vacuum cooler that can increase the temperature. The unit is sealed during operation so there is no issue with infiltration during cooling.

Hydro-vacuum coolers will be slightly less efficient as the water is also cooled. It has been estimated that 570L of cold water are lost from the system for each 400 carton load—water which must be replaced and re-cooled. Also, cold water on the sides of the unit cool the walls, potentially allowing heat transfer into the unit. However, such losses are relatively minor compared to those in most cool rooms.

6.4 Cost of cooling – a case study with broccoli

Under the assumptions used in this study, vacuum cooling proved the most energy efficient and cheapest cooling method for broccoli, followed by forced air-cooling then hydrocooling. Room cooling was slow and inefficient, with top icing by far the most expensive method of cooling broccoli. Choosing the best method of cooling will depend on equipment efficiency, equipment costs and product volumes.

As cooling is 'value adding with electricity', it is important to use that energy efficiently.

The following case study for broccoli estimates the energy required to cool 1 tonne of broccoli from 20°C to 4°C ($\Delta T = 16$) using the different methods available. The rate of cooling will vary between the leaves, florets and stalk, and be affected by the surface area of the broccoli relative to its volume. These calculations assume an average thickness of 1.73cm, a surface area of 1.515cm^2/g and a density of 0.385g/cm^3 (values calculated from measurements of six heads).

Various cooling methods could be used, each of which has advantages and disadvantages.

The energy removal that is required to reduce the temperature of broccoli to the target is referred to as 'sensible heat'. This is calculated as:

mass x change in temperature x heat capacity

The time taken to get broccoli to the target temperature is a key factor in the energy used, as losses occur during this cooling period.

In theory, 64MJ/tonne is needed to extract the sensible heat from broccoli, reducing temperature from 20°C to 4°C. Actual energy requirements will be higher than this figure.

Room cooling – broccoli

Broccoli placed in a cool room will cool relatively slowly. Based on experimental data, broccoli inside a harvest bin can take three days to reach 4°C with passive room cooling alone. Investigations in 2014 indicated that most cool store floors are not insulated, although this could markedly increase energy efficiency. Energy efficiency within the cool store is estimated at 17%, mainly due to losses through the floor. Total energy needed is estimated at 233MJ/tonne, giving this method an overall efficiency of 27%.

Forced air cooling – broccoli

Forced air systems can reduce the time required to cool broccoli from three days to 6–10 hours or even less. However, forced air systems do suffer the same losses as occur during room cooling, through heat conduction with structures as well as external heat sources such as fans and forklift motors. Total losses will depend on construction, throughput and operating temperatures. Forced air systems reduce the energy required for cooling in air from 233MJ/tonne to 90MJ/tonne, resulting in an overall efficiency of 71%.

Hydrocooling – broccoli

Hydrocooling systems for broccoli typically involve chilled water used as a drenching shower over harvested bins of broccoli. The water extracts heat from the broccoli, so its temperature increases as it flows through the product as well as through the connecting pipes and reservoirs. The energy costs of pumping water are also significant.

Around 30 minutes are typically needed to cool broccoli, although this will depend on the rate at which water flows across the broccoli surface. As the heat capacity of water is three orders of magnitude greater than for the same volume of air, a much smaller amount of water is needed to cool the broccoli.

Although hydrocooling has the advantages of being fast and keeping broccoli hydrated, the inevitable losses in the system are significant. Its energy efficiency is therefore relatively low at 47%, with 136MJ/tonne energy required.

Vacuum cooling – broccoli

Vacuum cooling cools broccoli through the latent heat of vaporisation — that is, the heat absorbed by liquid water when it turns into vapour. To cool one tonne of broccoli from 20°C to 4°C, 26kg of liquid water needs to turn into vapour, assuming other materials do not add heat to the system. In this case there is no need to cool

pipes, reservoirs or any equipment other than the bin the broccoli is contained in. Vacuum cooling is also rapid, typically taking 30–50 minutes for a cycle.

Vacuum cooling is the most efficient method of cooling broccoli from 20°C to 4°C, with an estimated energy consumption of 78MJ/tonne and an overall efficiency of 82%.

Top icing – broccoli

In Australia (unlike the USA), ice is not normally used to cool broccoli. Rather, it is used to maintain temperature during storage, transport and distribution. However, the costs associated with ice are included here for comparison.

Ice contact with broccoli is generally poor, leading to uneven cooling. It is also inefficient, as a large amount of energy is needed to remove the sensible heat from water in order to make ice. It is estimated that 1kg of ice is required to chill 3kg of broccoli from 20°C to 4°C, and that this would take approximately one day for a full bin. This would mean 927MJ energy is required to cool one tonne of broccoli, giving this method an overall efficiency of 7%.

Storage costs

While some growers now pack broccoli directly into cartons in the field, the more common practice is to harvest into bins, cool and then pack at a later date. It is then stored for a period before dispatch.

Broccoli may be packed into lined cartons, plastic crates or flow wrap films. Historically, broccoli was packed into polystyrene cartons and top-iced before transport, and many growers still pack broccoli this way. During packing broccoli may warm slightly, so a period of storage before transport can help to bring the temperature back down close to 0°C.

- The total energy cost for room cooling broccoli packed at 4°C to 0°C then storing for two weeks is estimated at approximately 800MJ, or approximately $40/tonne.
- If that same broccoli was packed in ice, over 30,000MJ energy would be required over the two-week period, costing a total of around $1,505/tonne.

In reality, a combination of the two is generally used. However, it is worth noting that ice is a highly inefficient method of cooling, and that large amounts are inevitably wasted.

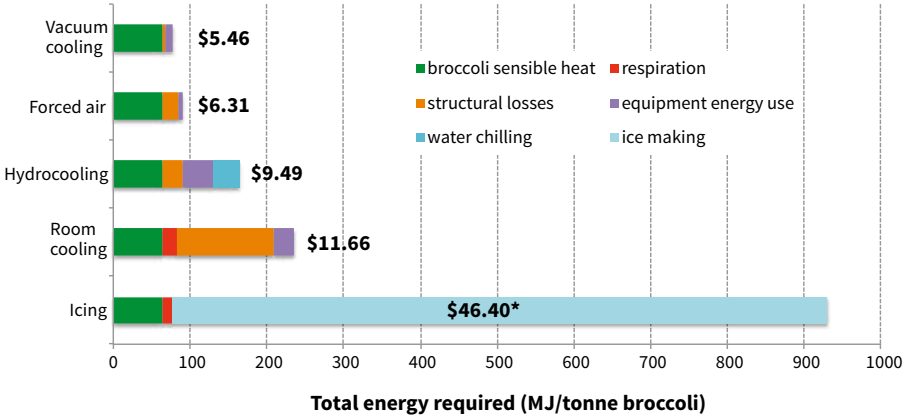


Figure 30 – Estimated energy required and total cost to reduce the temperature of one tonne of broccoli from 20°C to 4°C using different cooling methods. Electricity cost is estimated at $0.07/MW.

* Assumes that off peak electricity is used 50% of the time, and that the cost of off peak electricity is 40% that of normal daily rates.

Summary and conclusions

For broccoli, hydro-vacuum cooling appears to be the most energy efficient method by a considerable margin. Both, the total energy used and estimated approximate cost of each method of cooling, are presented in Figure 30.

However, each business case is different. Previous studies have found large variations in energy efficiency between different systems, even ones using the same method of cooling. This can be related to the capacity of the system; an inefficient vacuum cooler run while only partly full can have lower energy efficiency than an efficiently operated hydrocooler[9]. A recent study of cooling systems used on potato farms found the cool room systems on farms were all operating well below the energy efficiencies that are possible with modern cooling equipment.

Moreover, estimates of cost do not include the capital cost of the equipment. They also do not consider the effects on product quality and, therefore, potential sale price. A vacuum cooler is likely to represent a significant investment. However, the fast cooling times achieved may preserve quality and extend storage life. This is particularly important for products such as baby spinach or lettuce, but may also be critical for broccoli during warm harvest conditions.

9 Thompson JF, Chen YL. Comparative energy use of vacuum, hydro and forced air coolers for fruits and vegetables.

7 Controlling microbes

Human and plant pathogens include bacteria, fungi and viruses. Human and plant pathogens are generally separate groups. With a very few exceptions (eg *Aspergillus*), the microbes that cause postharvest rots and disease do not cause human illness, and vice-versa.

Human pathogens are the most important to manage and control. These include bacteria and viruses that naturally live in the gut of mammals, such as *Eschericia coli*, *Salmonella* spp., *Listeria monocytogenes* and Hepatitis. The recently published *Guidelines on Fresh Produce Food Safety*[10] (Fresh Produce Safety Centre, September 2015) provides detailed guidance on reducing the risk of contamination of fresh vegetables during harvest, packing and other postharvest operations. All vegetable supply chain businesses should have a plan in place (eg Freshcare, SQF2000, GlobalGAP) to ensure that their produce is safe to eat.

Plant pathogens cause postharvest loss of quality and waste. In many cases disease symptoms exhibited during transport and retail are the result of infections that occurred well before harvest. With few chemical controls available for use on vegetables, it is important to understand how infection occurs and how growth may be reduced, if not prevented.

7.1 Spoilage organisms

A range of microbes can cause postharvest disease on vegetables. Some are bacteria but most are fungi.

Many bacteria and fungi can cause postharvest disease on fruit and vegetables. The most important postharvest pathogens of vegetables are the fungi *Alternaria*, *Botrytis*, *Fusarium*, *Rhizopus* and *Sclerotinia*. *Erwinia*, the cause of soft rots, is the main bacteria affecting vegetables. Bacterial rots are more likely to

[10] http://freshproducesafety-anz.com/guidelines/

develop on vegetables than on fruit because they usually have a pH >4.5, which favours bacteria.

Table 2 – Main postharvest pathogens affecting vegetables

Pathogen	Disease	Vegetables affected
Albugo candida	White rust	Asian leafy, broccoli, rocket, spinach
Alternaria alternata, Alternaria spp.	Black rot, Alternaria spot, black spot	Bean, broccoli, cabbage, capsicum, carrot, cauliflower, cucumber, eggplant, onion, pea, squash, sweet corn, sweetpotato, tomato
Aspergillus niger	Black rot	Onion, sweet corn, tomato
Botrytis allii	Neck rot	Onion, shallot
Botrytis cinerea	Grey mould	ANY, but particularly bean, broccoli, cabbage, capsicum, carrot, cauliflower, cucumber, eggplant, lettuce, onion, pea, pumpkin, squash, sweet corn, sweetpotato, tomato
Colletotrichum spp.	Anthracnose	Bean, capsicum, cucumber, eggplant, pumpkin, squash, tomato
Erwinia carotovora, Erwinia spp.	Bacterial soft rot	ANY, but particularly bean, broccoli, cabbage, capsicum, carrot, cauliflower, celery, cucumber, lettuce, onion, pea, potato, pumpkin, spinach, squash, sweetpotato, tomato
Fusarium spp.	Soft rot, pink rot, root rot	Cabbage, capsicum, carrot, celery, eggplant, onion, potato, pumpkin, squash, sweet corn, sweetpotato
Pectobacterium carotovorum	Bacterial soft rot	Asian leafy, lettuce, cabbage, cauliflower
Penicillium spp.	Blue mould	Cucumber, tomato
Pseudomonas syringae, Pseudomonas spp.	Bacterial spot	Asian leafy, bean, broccoli, cabbage, cauliflower, celery, cucumber, lettuce, onion, pea, spinach, squash, tomato
Pythium aphanidermatum	Cottony rot	Bean, beetroot, cucumber
Rhizopus stolonifer	Storage rot, rhizopus rot	Bean, capsicum, carrot, cucumber, eggplant, pea, pumpkin, squash, sweetpotato, tomato
Sclerotinia sclerotiorum	White rot, white mould	Bean, broccoli, cabbage, carrot, cauliflower, celery, cucumber, eggplant, lettuce, onion, pea, pumpkin, squash
Thielaviopsis basicola	Black root rot	Carrot

7.2 How infection occurs

Most organisms that cause postharvest disease are weak pathogens. Only a few fungi (such as *Colletotrichum*) can directly invade through healthy skin. Most fungi enter vegetables through wounds in the skin, or infect products already damaged by unsuitable storage conditions.

Preharvest infection

Infection often occurs before harvest. Some fungi infect product during flowering, while other pathogens may stick to the product skin. Microbes that are relatively dormant during plant growth can develop and cause symptoms after harvest.

Pre-harvest infection can occur by direct penetration of the skin, entry through natural openings (stomata and lenticels), transmission through the parent plant, and through damaged areas. Plant defence responses are able to hold such infections in check while the plant is actively growing. However, once removed from sources of water and nutrient, the disease can take hold.

Infection of some fruiting vegetables (eg internal rots in capsicums) actually occurs during flowering. Fungi such as *Alternaria* and *Botrytis* are able to infect flower petals. However, they only start to develop once the vegetable has matured.

Many plant pathogens are present in the soil or on plant debris. Vegetables that are grown in contact with the soil are likely to be carrying spores or

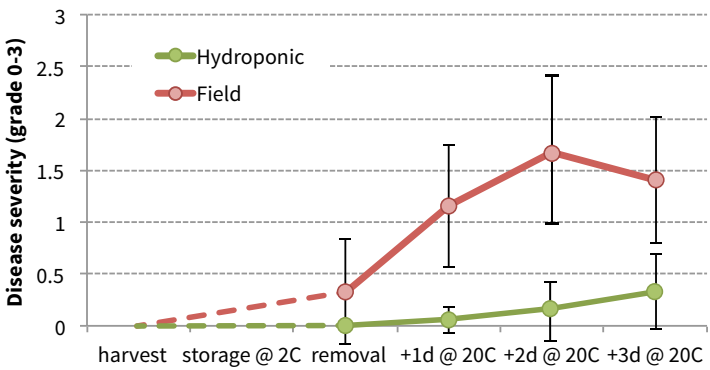


Figure 31 – Postharvest development of leaf diseases in pak choy grown in the soil or hydroponically on run-to-waste benches. Evaluated at harvest, on removal after one week at 2°C, then daily during simulated retail at 20°C. Differences are likely due to the amount of inoculum present at harvest.

mycelium that cause infection, even though these are not apparent at harvest. For example, pak choy grown hydroponically on raised benches appeared similar at harvest to the same product grown in the ground. However, the hydroponic product had consistently longer shelf life, largely because of postharvest development of leaf spots and rots on the field-grown product (Figure 31). The pathogens responsible for these diseases are present in the soil but transfer to the leaves by water splash during rain or irrigation.

Fungal spores are also carried on the wind. Nearby crops infected with fungal pathogens such as white rust (*Albugo candida*), or blue mould (*Penicillium* spp.) release huge numbers of spores, which can land on the intact vegetables. These spores are unable to germinate while the product remains dry. However, condensation during cooling or storage can allow germination, growth and infection.

Postharvest infection

Postharvest infection commonly occurs through injuries or other breaks in the skin, and is increased if products are wet.

Fungal spores are present in the air, on equipment, on containers and even on the hands of harvest workers and packers. However, for those spores to infect the vegetables there must be suitable conditions for spore germination and growth as well as openings that allow them to penetrate the plant tissue.

Moisture is essential for spores to germinate. While most can germinate in pure water, if nutrients are present then germination is increased and growth is more vigorous. For example, studies have found that spores of *Rhizopus* spp. and *Botrytis cinerea* need both water and nutrients to allow spores to germinate and penetrate a host. Bacteria also need water plus nutrients for cells to divide and multiply.

Wounding allows cell contents to leak out. Broken cells provide both water and nutrients, in the form of sugars, acids and other substrates. Wounds therefore provide ideal environments for spores to germinate and bacteria to grow. Moreover, while waxy epidermal (skin) cells represent a significant barrier to infection, the cells underneath are less protected. Once established in a wound site, pathogens can directly attack these cells and spread through the plant tissue.

7.3 Factors affecting postharvest disease development

Temperature, availability of moisture and 'microbial load'—the number of spores or bacteria present at harvest—affect development of disease on vegetables. Low temperatures, keeping vegetables dry, maintaining good pre-harvest hygiene and vigorous postharvest washing and brushing can significantly reduce postharvest disease.

Storage environment

Low temperature storage cannot prevent disease, but can limit the rate at which disease develops. The optimum temperature for spore germination of most fungal pathogens is 20–25°C. Although germination is possible at a much wider range, the further the temperature is from this optimum the slower germination will be. Cold temperatures also delay deterioration of the product, reducing susceptibility to decay.

Fungi differ in their ability to grow at low temperatures. *Aspergillus niger* is unable to grow below 11°C, *Colletotrichum* spp. below 9°C and *Rhizopus stolonifer* below 2°C. However, *Botrytis cinerea* can continue to grow down to –2°C and *Alternaria alternata* still develops at –3°C, making these diseases hard to control in storage.

High RH and free moisture on produce both increase opportunities for disease development. As described in Section 4, dry conditions mean that fungal spores are unable to germinate and grow, and bacteria cannot multiply. Even if fungal germination does occur in a small amount of moisture, if RH is low then further growth will be inhibited. Conversely, wet conditions and high RH allow plant pathogens to spread and multiply.

Microbial load

It is impossible to remove every fungal spore or bacterial cell. However, reducing the number that is present—the microbial load—reduces the chance that infection will occur, even if other conditions are suitable. Reducing the microbial load generally involves pre-harvest hygiene and/or postharvest removal by washing.

Pre-harvest hygiene involves removing sources of inoculum. This may mean removing or rotary hoeing diseased crop residues, using pre-harvest fungicides and ensuring good plant health; healthy, well grown crops are less susceptible to disease infection and development than those grown under more challenging conditions.

Vigorous washing and/or brushing can reduce microbial load by 99% or more. Factors that affect how effectively the washing process removes bacteria and fungal spores include:

- Temperature of the water—high water temperatures can increase the effectiveness of washing. For example, short hot water rinsing and brushing treatments are used commercially to reduce postharvest disease on fruit vegetables such as capsicums and tomatoes. Treatments typically range from 50 to 60°C and last for 10 to 30 seconds. This method has been shown to remove 99.9 to 99.99% of pathogens on the product surface[11].
- Vegetable structure—products with a smooth surface will be easier to clean than those with an irregular surface or complex structure, like cabbage.
- Presence and concentration of a sanitiser and pH of the water.
- Number of washes and amount of agitation—multiple washes are more effective than one.
- Cleanliness of the water—if the water already contains a large amount of organic matter then sanitisers will be ineffective and the washing process may deposit more microbes than it removes.

7.4 Sanitisers and fungicides

There are few or no postharvest fungicides available for vegetable producers. A number of sanitisers can be used which help control pathogens in water and on vegetable surfaces. It is essential to include sanitisers in recirculating water systems.

The ideal postharvest fungicide is water soluble, effective against a wide range of spoilage organisms, has no negative effect on the vegetable, is safe to workers and consumers, remains active over a long period, leaves no visible residues and is cheap. Unfortunately, no such product currently exists.

For many years, chemical fungicides were the main method used to control postharvest fungal diseases, particularly for fruit crops. However, a search of registered fungicides for postharvest application to vegetables reveals only one chemical registered for bulb crops, and two chemicals registered for potatoes. The remaining 'fungicides' are products usually considered sanitisers, but which have broad fungicidal activity.

[11] Fallik E. 2004. 'Prestorage hot water treatments (immersion, rinsing and brushing)'. *Postharvest Biology and Technology 32:125-134.*

Unlike chemical fungicides, not all sanitisers need to be registered for use on vegetables.

- Sanitisers used to ensure food safety by sanitising water or equipment do not need to be registered.
- Sanitisers marketed or supplied specifically for controlling spoilage organisms, such as those in Table 2, do need to be registered.

If wash water is being recycled, or dip-tanks are being used, then it is essential to include a sanitiser to prevent spread of fungi and bacteria in the water during packing processes.

Sanitisers can also help kill fungi and bacteria on the surface of the produce. They will not affect pathogens that are already inside the vegetable flesh or internal air spaces.

There are a number of sanitisers that can be added to water or air, including:

- Chlorine based compounds—calcium hypochlorite, sodium hypochlorite, bromo-chloro compounds, chlorine dioxide
- Peroxyacetic acid
- Iodine
- Ozone

Chlorine compounds

Chlorine is cheap and effective. However, effectiveness depends on pH and chlorine can be rapidly deactivated in dirty water. Chlorine is not permitted by some markets.

The most common sanitiser used is chlorine. Chlorine is cheap, effective and easy to use. A number of chlorine-based compounds are available. The two main ones are calcium and sodium hypochlorite. Calcium hypochlorite is a powder or granule, and is a common active ingredient in swimming pool chlorine products. Sodium hypochlorite is a liquid and the active ingredient in household bleach.

Mixed with water, calcium and sodium hypochlorite generate hypochlorous acid (HOCl). This is the active form of chlorine that oxidises spores and bacteria in the water. However, formation of HOCl is a function of pH. At high pH, the amount of HOCl decreases, with most chlorine in the inactive, oxidised form (OCl^-), which is ineffective ineffective against pathogens.

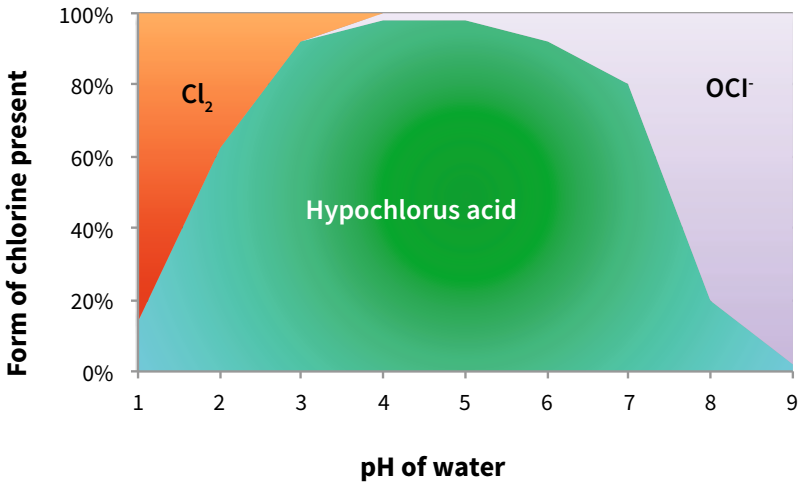


Figure 32 – Effect of chlorine on the amount of hypochlorous acid present in the water. At high pH chlorine is in the inactive form and ineffective against microbes. At low pH poisonous chlorine gas is formed. Chlorine will only be effective against pathogens if pH of the water is 4 – 7.5.

If water is >pH7.5 it must be acidified for chlorine to be effective. Hydrochloric acid is often used to lower pH. However, this must be done carefully because at ≤pH3 poisonous chlorine gas can be given off (Figure 32).

Hypochlorous acid can also be generated on site using electrolysis. The only inputs are electricity and small additions of salt (sodium chloride), or the process may use salts already in the water.

Chlorine not only reacts with fungal spores and bacteria, but with all organic materials. This means that chlorine is deactivated in dirty water. In general, double the amount of chlorine is needed to control pathogens if the water is dirty. It is also deactivated by exposure to light, air and metals.

Typical doses used for sanitation are 50–200ppm of active chlorine (HOCl) in water. However, even much lower concentrations (10ppm) continue to provide some control of microbes.

Bromo-chloro-dimethyl-hydantoin (Tradename Nylate®) is less affected by organic matter than calcium or sodium hypochlorite. It is also less affected by pH, remaining active up to pH 8.5. Lower dose rates are usually needed to control pathogens, with the product usually used as a complete monitoring, filtration and dosing system.

Chlorine dioxide gas is also less affected by pH than the hypochlorite sanitisers. It can be generated on site, is active at very low doses (1–10ppm) and is unaffected by organic matter. However, good ventilation is needed to ensure workers are unaffected, and the gas is explosive at high concentrations.

Peryoxacetic acid

Peryoxacetic acid is less affected by dirty water and pH than chlorine and remains effective at low temperatures.

Peryoxacetic acid (Tradename Tsunami®) also remains active even when organic matter in the water is high. It is effective against a wide range of plant pathogens, and remains effective even at low temperatures, such as in a hydrocooler. High temperatures and high pH will deactivate the product. Dose rates are typically 50–150ppm.

Iodine

Iodine is an effective sanitiser and is not affected by dirty water. Australian diets are somewhat deficient in iodine, so use as a sanitiser has additional potential benefits.

Iodine is not affected by organic material in the water and is effective at a wider pH range than chlorine. Iodine is also an essential element needed for good health; the recommended daily intake for adults is 150µg/day. However, iodine is often lacking in the Australian diet. Using iodine as a sanitiser therefore has potential benefits in addition to its wide activity against fungal spores and bacteria.

Fully automated iodine dosing and recovery systems are commercially available and used by some vegetable producers. The main issues are cost and availability.

Ozone

Ozone gas reacts with fungal spores and bacteria, but also with equipment and workers. It is difficult to monitor, yet the effect on waterborne microbes is highly dependent on contact time and concentration. There are no residual effects on washed products.

Ozone (O_3) is a colourless gas with a distinctive smell. It is produced naturally during thunderstorms as well as by electronic equipment such as photocopiers.

Ozone is highly reactive with organic compounds. These include fungal spores and bacteria, and also soil, equipment, cardboard packaging and workers. Ozone is very effective at killing fungal spores in the air, with ozone generators often marketed as a way of sanitising cool rooms. While this reduces airborne pathogens, unless ozone directly contacts the surface of the vegetables it will have little effect on diseases already present. Ozone has no effect once fungi or bacteria are inside the vegetable. Ozone is also difficult to measure, can cause superficial damage to products at high concentrations and poses significant risks to worker health if not properly controlled.

Ozone can be bubbled through wash water to sanitise it. It reacts rapidly, with effectiveness dependent on contact time and the amount of ozone suspended in the water. As it reacts with soil, ozone is better suited to single use wash water than to recirculating water in dumps and flumes.

Once reacted, ozone has no residual activity. Passing water through an ozone generator will therefore kill pathogens carried in the wash water, but have no impact on microbes still on the surface of the vegetables.

Table 3 – Overview of sanitisers suitable for fresh vegetables

Active ingredient	Sold as…	Monitoring	Key points
Calcium hypochlorite	Swimming pool chlorine Frexus dry chlorine briquettes, Ym-Fab Activ-8	Test strips Chlorine meters	Inexpensive and easy to use Some residual effects on pathogens Important to monitor and control pH (4.0 – 7.5) Quickly rendered ineffective if water is dirty Corrodes metals and packing equipment
Sodium hypochlorite	Household bleach		
Bromo chloro dimethyl hydrantoin (BCDMH)	Nylate®	Automatic analyser	Reasonably inexpensive Some residual effects on pathogens Less corrosive than hypochlorites Less affected by dirty water than hypochlorites Still effective at up to pH 8.5 Reacts to form both hypochlorous acid and hypobromous acid (2 x active ingredients) Must be generated on site
Chlorine dioxide	Vibrex hortiplus®	Redox probe	Effective at low concentrations Some residual effects on pathogens Not affected by dirty water Still effective at up to pH 8.5 Must be generated on site Relatively expensive Requires good ventilation for workers
Peroxyacetic acid (PAA)	Tsunami®	PAA test strips Automated analyser	Less affected by dirty water than hypochlorites Less affected by pH than hypochlorites By-products are biodegradable Effective at low temperature De-activated by high pH or high temperature
Iodine	AIS iodine granules	Automated analyser	Effective at broad pH range Not affected by dirty water May benefit human health Only available as a dosing system Relatively expensive Corrosive to metals
Ozone			Highly effective at killing fungal spores and bacterial pathogens De-activated by dirty water No residual effects on pathogens Not easily monitored and concentrations highly variable Corrosive to metals and equipment

8 Measuring and managing quality

8.1 What is quality?

Quality means very different things to different people. Quality can include external attributes such as size and shape as well as internal attributes such as flavour. Food safety, ethical issues, convenience and price can also be regarded as quality factors.

Quality is very much in the eye of the beholder. Different members within a given supply chain will all have different ideas of what constitutes good quality.

For example, a good quality tomato is:

Grower	The one which maximises returns on investment and, therefore, profitability.
Harvest crew	Large, so that harvest bins or buckets can be filled fast, effectively increasing the hourly pay rate.
Packer	Firm, evenly sized and shaped, and with minimum defects, so they can be processed quickly and with little waste.
Transporter	Hard, so able to be transported without bruising, and compactly packed.
Retailer	Visually appealing and with good shelf life. Possibly packaged so as to increase purchase size and reduce damage caused by consumer 'rummaging'.
Consumer	Looks fresh, well coloured, juicy and full of flavour. Also good value for money and with long shelf life.

Most quality criteria can be divided into external and internal factors. External factors are what generally sells product, as these relate to appearance—size, colour, shape and freedom from defects. Internal factors are what bring customers back—flavour, texture and nutritional value.

Products may also have additional quality attributes such as convenience, food safety, shelf life, value for money and nutritional quality. Such attributes will vary in the order of importance within the context of a supply chain.

Finally, products may have quality factors based on ethics or belief systems. These include:

- Sustainability
- Locally grown
- Country of origin
- Worker welfare
- Organic / biodynamic production
- Absence of artificial genetic modification (currently not applicable in Australia)

Studies have shown that consumers most value vegetables that look fresh, are good value for money, and have no rots or bruises. Their biggest turnoffs are if vegetables are mouldy, bruised or wilted. Some people are negatively disposed by seeing insects on the product, or the fact that the product is imported. However, context is everything—a bunch of beetroot with dirt attached is likely to be perceived negatively in a supermarket, but may be seen as more 'authentic', with local flavour, if it is for sale at a farmers market.

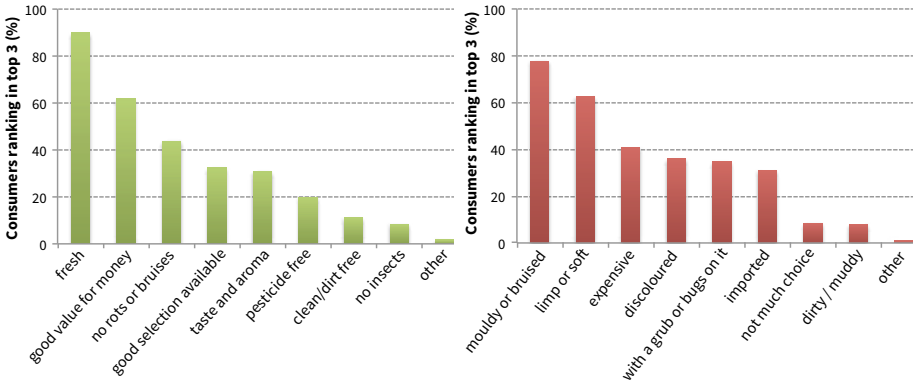


Figure 33 – What consumers value when purchasing fresh vegetables (left) and what the turnoffs are (right). Consumers were asked to rank the potential answers. Column heights indicate the percentage of respondents ranking each attribute in their top 3 (n=1,105). (Data from HAL Final Report VG12084)

8.2 Measuring quality

Quality assessments can be either objective or subjective. Objective measurements involve measuring something, whereas subjective measurements rely on individual judgements.

Objective measurements

Objective quality attributes are those that can be measured. They include size, weight and colour as well as internal quality factors such as sugar and acid content and nutritional value.

The easiest-to-use objective measurements are quantities such as weight, length and diameter. These are commonly used in grading equipment to automatically sort products by size. Colour can also be measured objectively using various devices. Objective measurements also include nutritional content—sugars, acids, fibre, antioxidants and various other compounds that may be beneficial to human health.

Firmness

The firmness of vegetables can also be measured objectively. Penetrometers are usually used for measuring the firmness of relatively homogenous fruit such as apples and stonefruit. They can also be used to provide an objective measurement of the firmness of vegetables such as zucchini, squash, and eggplant but are less useful for a product such as a capsicum or tomato.

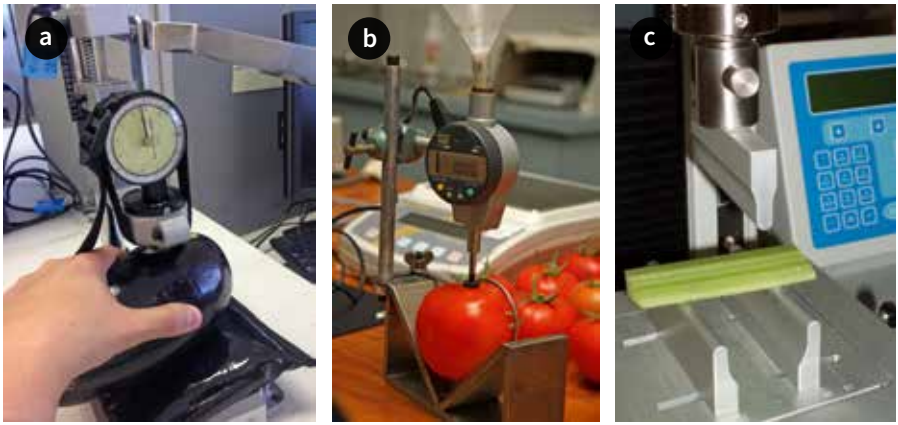


Figure 34 – Different methods of measuring firmness of vegetables. Firmness can be measured using a penetrometer (a), compression meter (b) or texture analyser (c), depending on the product.

Although they can be handheld, better results are obtained when the device is mounted in a drill press or similar (Figure 34a).

For unevenly textured products, different types of equipment may be used. Values are not absolute, but can provide an objective measure of differences in firmness between, for example, packaging methods or storage temperature. Devices range from a fairly simple meter which measures compression (mm) of a vegetable when a standard weight is placed on top (Figure 34b) to sophisticated texture analysers that can test crispness, viscosity or other aspects of product texture (Figure 34c).

Colour

Colour can be measured objectively using a chroma meter. This records the reflected spectrum of light in terms of its hue, lightness and chroma. Research papers often report colour in terms of L*a*b*. This is the CIE Lab colour scale, where 'L' indicates lightness (0 – 100), 'a' indicates red through to green and 'b' indicates yellow through to blue. It is often measured with a Minolta chroma meter, which is a standard piece of equipment in many postharvest laboratories.

While the chroma meter is a standard measure, there are now an increasing number of apps that can also measure colour using the camera in a mobile phone or tablet. So long as lighting is consistent, these may be used to record colour values in a variety of scales including RGB (red – green – blue, as used on computer screens) and CMYK (cyan, magenta, yellow and black, as used in printing) as well as various other colour systems.

Software such as Adobe Photoshop can also be used to analyse colour in digital photographs. Again, if lighting is consistent, images, or parts of images can be easily analysed and reported as RGB, CMYK or even Lab. Photoshop has the advantage that it is possible to analyse the average colour of a whole vegetable—such as a whole cucumber or head of broccoli—rather than measuring a single point.

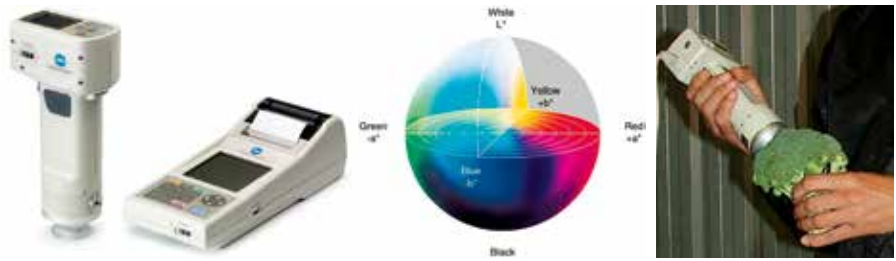


Figure 35 – The Minolta chroma meter (left) is used to objectively measure colour. This is often reported in the CIE Lab colour scale (centre) or as hue – which is an integration of 'a' and 'b' values. The device can be used in the field or laboratory (right).

Sugars

Sugars are generally considered more important in fruit than in vegetables. However, many vegetables do contain significant amounts of sugars and these contribute to their flavour.

The percentage of sugars in juice can be estimated using a refractometer (Figure 36). This measures the percentage of soluble solids, also known as °Brix. Soluble solids are closely related to sugar content in juicy products. However, it is not a reliable measure of sugar content for sweet corn, as the milky liquid in corn kernels contains many non-sugar compounds that are detected by the refractometer.

Figure 36 – A digital (left) and handheld (right) refractometer. These are used for measuring soluble solids, an indicator of sugar content.

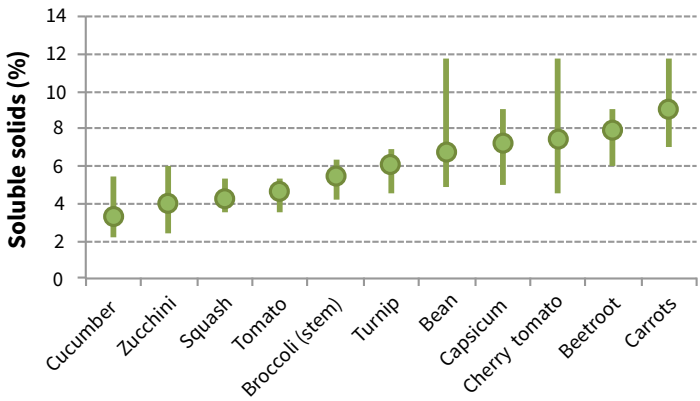


Figure 37 – Average % soluble solids content of different vegetables. Bars indicate maximum and minimum values. (Data compiled from numerous references).

Subjective measurements

Subjective measurements rely on judgements made by the assessor. They can include shape, colour, blemishes and general acceptability. Various devices can be used to increase the objectivity of such judgements. These include size guides for blemishes, visual grading scales and written descriptors.

Subjective quality assessments can include any attribute of the vegetable. Subjective assessments can include factors such as shape, colour, acceptability; even the presence of blemishes, disease or bruising is usually assessed subjectively, although some of these may include objective elements.

As subjective assessments rely on the judgement of the observer, there is clearly a wide scope for variability. Visual aids can be used to reduce variability and ensure assessments are consistent. Aids can include descriptive grading scales, colour chips, templates indicating size and pictures indicating what is acceptable and what is not.

For example, a specification may require a product to have spots or marks not exceeding a total of 2cm^2, or a discoloured area affecting 4cm^2. A guide such as shown below (Figure 38), printed on clear material, may be used to assess whether product will be acceptable. It may also be useful to have photographs of examples, or even a diagrammatic representation, to make it easy for packers to assess what is within or outside the specification.

For products that are variable in size, it may be more appropriate to specify defects in terms of the percentage surface area affected. For example, major defects may only cover 1% or 2% of the surface area, whereas a more minor issue such as ground spot may affect 20% of the surface. However, it can be very difficult for an observer to accurately estimate the percentage surface area affected by defects or discolouration, especially if it is a cumulative total of several defects.

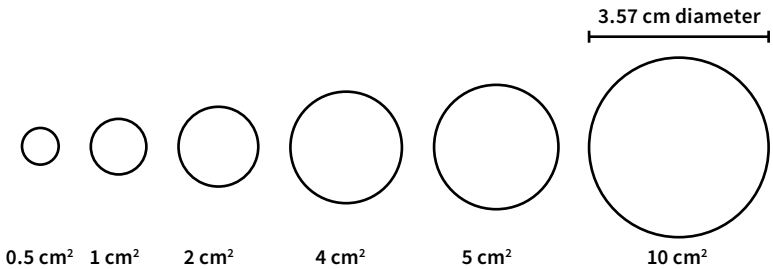


Figure 38 – Size guide for area of defects.

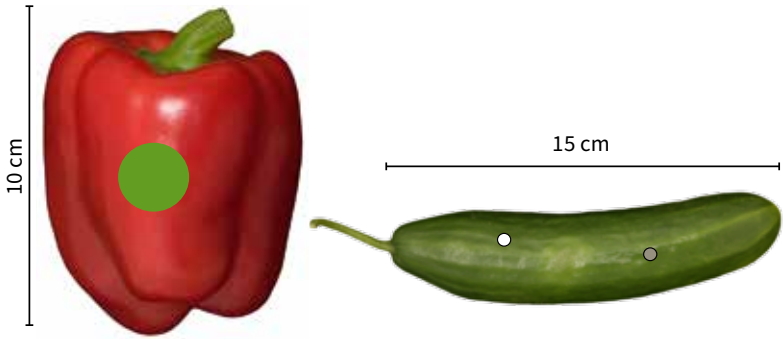


Figure 39 – Diagrammatic representation of 4cm² of green colour on a red capsicum, and blemishes totalling 0.5cm² on a greenhouse cucumber.

Diagrams, which show exactly what a certain percentage of the surface area of a vegetable looks like, based on calculated values, can improve consistency in how products are evaluated and avoid disputes between clients and suppliers.

This is particularly important as vegetables are mostly round, not flat, so surface area can be significantly larger than some may expect. This means an allowable defect of 2% surface area, or discolouration affecting 20% surface area, may actually be greater than some assessors imagine (Figure 40).

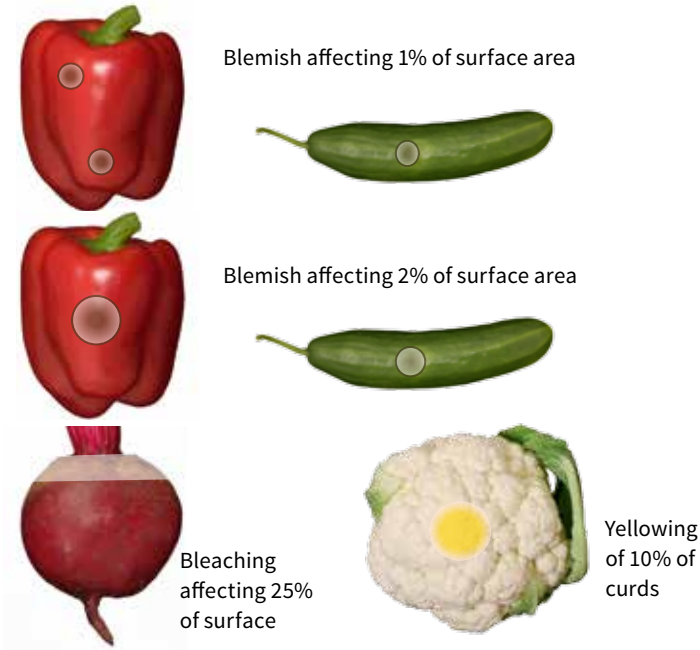


Figure 40 – Diagrammatic representation of various defect limits. Areas are calculated from the surface area of the product, with the spot shown, as the assessor would see it.

Wilting can be one of the most difficult things to assess with any degree of objectivity, yet many specifications require products to be 'without wilting or limpness'. Again, wilting may be better expressed using a diagram (Figure 41).

Photographic quality grading scales may also be used for overall appearance, acceptability, yellowing, or other defects. Grading scales that are developed and accepted by both client and supplier, particularly if combined with a 'product description language' describing each type of defect, have the potential to greatly improve communication within supply chains.

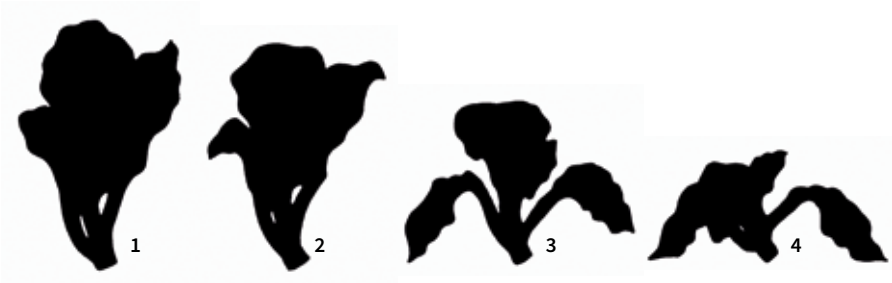


Figure 41 – Scale for assessing wilting of gai lan (Chinese broccoli).

8.3 Managing quality

Temperature monitoring

Monitoring temperature is one of the easiest ways to manage quality. Temperature loggers are increasingly cheap and easy to use and can provide valuable information about where quality loss may be occurring in supply chains.

The importance of good temperature control in minimising moisture loss, avoiding condensation, preventing disease development and extending saleable life has been discussed at length in other sections of this publication. Monitoring vegetable temperatures is therefore one of the easiest ways to assess where damage may be occurring and also prevent it from happening in the future.

Temperature measurements during shipping and transport used to involve large, unwieldy and relatively insensitive chart recorders that had to be retrieved and visually scanned for problems. Temperatures can now be recorded using tiny, inexpensive data recorders little bigger than a watch battery. They can record air temperatures (and humidity, if required) on the outside of a pallet, inside a carton, or inside the flesh of the product itself.

Data loggers are available that are GPS enabled, allowing the consignment to be tracked and monitored while it is en route. Some are designed to be single-use, avoiding the need for them to be returned for downloading; the finder simply plugs them into a computer or scans using a mobile phone, and the data can be automatically streamed back to source. Temperature monitoring systems are available that are entirely automated, avoiding any need for retrieval and downloading.

Measuring temperatures has therefore never been easier, and is likely to continue to get better as technology improves.

Temperature monitoring within supply chains can provide invaluable information about how products are being managed. If pallets are left on a dock in the sun, or inside a truck with the cooling system turned off, then this can account for significant loss of quality further along the supply chain. Conversely, if chilling sensitive products get too cold, this can also affect subsequent quality, even if the effects are not noticed straight away.

An example of temperature monitoring within a supply chain is shown in Figure 42. In this case, bitter melon from a farm in the Northern Territory was being shipped to Sydney Markets. Bitter melon is chilling sensitive, and not recommended for storage below 7°C. However, the consignment in truck 1 was stored at 3–4°C for several days. Despite this, the outcome may still be better than product in truck 2, where temperatures fluctuated significantly

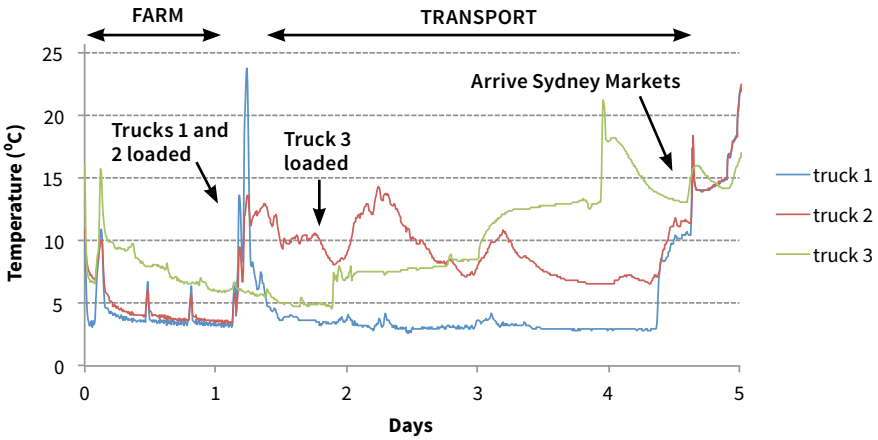


Figure 42 – Temperatures inside cartons of bitter melon (fu qua) during transport from the Northern Territory to Sydney Markets.

with daytime temperatures. This suggests the truck cooling system was not adequate to cope with the load, and significant condensation inside the boxes would have resulted. In the case of truck 3, the load appears to have changed trucks at least once en route, and possibly twice.

Temperature monitoring can also help identify where problems may be occurring still on farm, or during sale. In the example shown in Figure 43, product at the centre of a pallet failed to cool well after packing. Even after five days of cold storage a significant temperature difference remained between the inside and outside of the pallet. Although temperatures on the outside of the pallet warmed during loading onto the truck, the truck cooling system reduced temperature during transport. The truck cooling system was turned off several hours before delivery to the wholesaler. The product was then displayed on the floor of the wholesale market for two days. In between markets it was cooled to 5°C, but then immediately warmed again when returned to display. Such fluctuations are likely to increase disease development in packed product.

Identifying where breaks occur in the cool chain is the first step towards finding solutions.

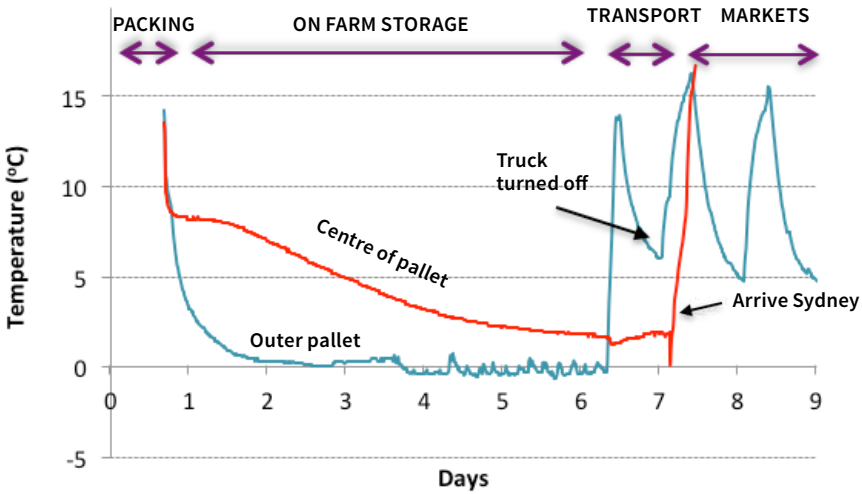


Figure 43 – Temperatures inside packed cartons on the inside or outside edge of a pallet initially stored on farm in Victoria, then transported to Sydney Markets. Stock was displayed for two days at wholesale before sale to a retail store.

Supply chain analysis

Analysing quality at different points in the supply chain can help identify where damage is occurring. Subjective assessments can be combined with data from impact recorders to identify and rectify critical areas.

Clearly not all quality issues relate to temperature. Preharvest practices can have a significant impact on postharvest quality, particularly in relation to harvest maturity. Damage can also be caused by harvest, packing or transport practices, use of inappropriate packing materials or mismanagement during storage.

If an issue is identified at wholesale or retail, a supply chain analysis can determine where damage is occurring. This usually involves sampling the product at each step of the chain to examine where damage is most likely. If, for example, rots were identified as a significant issue for pumpkin at retail sale, samples of pumpkins could be examined for signs of damage immediately after harvest, after transport to the packhouse, following packing into bins and after transport to wholesale market or retail distribution centre.

If it was identified that injuries were occurring at the packhouse, then the line could be examined in more detail to determine how this was occurring. One way to check for impacts is using an 'instrumented sphere'. This records impacts as it is processed down a packing line. Spheres are available in different sizes to simulate a range of products.

Another method is to use a 'shock logger'. These record impacts using built-in, three-dimensional accelerometers. As with temperature loggers, these are increasingly affordable and easy to use.

Combined with visual assessments, such devices can help identify where injury is occurring. Simple measures—such as adding extra foam padding on a packing line—can then be used to mitigate damage.

Figure 44 – An impact recorder on an apple packing line (left) and shock logger (right); devices that can be used to measure potential injury points during packing and transport.

9 Quarantine treatments

Market access can be an issue when exporting, moving produce interstate, or even moving between regions. Quarantine restrictions are in place to prevent pests carried in or on host vegetables moving into areas where they are not currently found. Access may depend on proving that the area or place of production is free of the pest species. Other methods include application of pre-harvest chemicals or postharvest treatments.

Products infested with significant numbers of pests—whether insect, fungus or nematode—are almost always unmarketable. Such product would never normally be packed for sale. Moreover, dead insects are nearly as unacceptable to a customer as live ones. In all probability, postharvest quarantine treatments rarely kill any pests. However, regulators often prefer them over in-field treatments or systems approaches because treatments can be proven experimentally to provide extremely high levels of quarantine security.

9.1 Quarantine pests and their hosts

Australia has many species of fruit fly. These create significant domestic and export market access issues for fruiting vegetables. Various leafy, root and tuber crops may also be restricted from certain markets due to the presence of insects, nematodes or diseases in their production region.

In Australia, fruit flies are responsible for more restrictions on produce movement than any other pest. These restrictions are a significant issue for many producers. While Queensland fruit fly (Qfly) is perhaps the most widely distributed, there are a number of different species that raise quarantine concerns. Species and distributions include:

- Mediterranean fruit fly (*Ceratitis capitata*) (Medfly) is only present in coastal areas of Western Australia.

Figure 45 – Qfly maggots in a chilli (left) and adult female Qfly laying eggs into a capsicum fruit.

- Queensland fruit fly (*Bactrocera tryoni*) (Qfly) is widespread along the east coast from Melbourne to Cairns. It is also increasingly endemic in inland, irrigated areas of NSW and Victoria. Major vegetable production areas in Bundaberg and Bowen are affected by this species.
- Cucumber fly (*Bactrocera cucumis*) is widespread along the east coast from Coffs Harbour to North Qld as well as parts of the Northern Territory.
- *Bactrocera neohumeralis* is closely related to Qfly and has a similar, although generally more northern, distribution.
- *Bactrocera jarvisi* is an increasingly significant pest. It is mainly found in northern Australia but potentially as far south as Sydney in coastal areas.

Fruit flies can infest any fruiting vegetable, although in some cases these products are not their preferred hosts. However, capsicum, chillies and tomatoes are highly attractive and susceptible to Qfly and Medfly. Cucurbits such as squash, zucchini and pumpkin are preferred hosts of cucumber fly, and can also be infested by other species.

Other pests of quarantine significance include:

- Various whitefly species including spiralling whitefly (*Aleurodicus dispersus*) and silverleaf whitefly (*Bemisia tabaci*).
- Melon thrips (*Thrips palmi*), which is found around Darwin, coastal north Queensland (Bowen to Cooktown) and north coastal NSW/ south Queensland (Lismore to Seventeen Seventy).
- Potato cyst nematode (PCN) in Victoria (*Globodera rostochiensis*).
- Currant lettuce aphid (*Nasonovia ribis-nigri*).
- Western flower thrips (*Frankliniella occidentalis*).
- Burrowing nematode (*Radopholus similis*).

9.2 Government regulations

Interstate movement of potentially pest-affected products are regulated under the Interstate Certification Assurance program. International access can be more difficult as protocols must be agreed on a government-to-government basis.

Within Australia

For some quarantine pests, potentially affected products can only come from areas that are certified as pest-free (eg through testing for PCN, a trapping and monitoring program for fruit flies) and/or with postharvest inspection to check that the products are free from infestation. For other products and markets, particularly for products susceptible to fruit flies, postharvest treatments may be required.

Mandated treatments for interstate access are defined by a series of Interstate Certification Assurance (ICA) documents. This system allows accredited businesses to perform their own treatments or inspections as set out in the regulations. For example 'ICA-04 – Fumigating with methyl bromide' sets out the principles of operation and design of fumigation chambers as well as dosages, time of exposure and treatment temperatures required. While ICAs are developed on a state basis, they are generally recognised throughout Australia.

International

International agreements relating to market access can take years to develop and yet change virtually overnight. Agreements are negotiated directly between the relevant government agencies using supporting documented evidence. This may include pest risk assessments, pest survey data, peer reviewed scientific papers, trial data and other materials that demonstrate freedom from, or control of, significant pests.

Each country has its own import requirements. These can be accessed on the MiCOR online database (**micor.agriculture.gov.au**). The minimum requirement for exporters is usually a phytosanitary certificate declaring that the consignment is free from pests, soil, weed seeds or other material.

Some products and markets may require additional declarations or endorsements. For example, brassica vegetables (broccoli, cauliflower) exported to Taiwan need to be inspected and found free of stem nematode, white-fringed beetle and Western flower thrips. The consignment also needs to be sealed to prevent later infestation by any of these pests. Chards (spinach, silverbeet) exported to Japan must be either inspected during production

and found free of burrowing nematode, or grown in areas free of this pest, as determined by soil sampling.

Vegetables usually cannot be exported if they could potentially be affected by a pest—such as Qfly or burrowing nematode—that is absent in the importing country and no treatment and/or inspection protocol has been agreed for that product. For example, Tasmania is the only part of Australia that can export capsicums and cucumbers to Japan, as it is the only state recognised as fruit fly-free. Although disinfestation protocols for capsicums and cucumbers do exist, suitable supporting data has not been presented to, and approved by, Japanese Government authorities. As no protocol is in place, importation to Japan is prohibited.

9.3 Probit mortality

Converting mortality data to 'probits' allows calculation of the dose required to kill a certain percentage (eg 50%) of the population. Postharvest quarantine treatments are often required to provide probit 9, equivalent to 99.9968% mortality. Given the low numbers of live pests likely to be present in any one consignment, this represents an extremely high level of quarantine security.

The standard often required of postharvest quarantine treatment is 'Probit 9'. Probit analysis was developed to linearise the sigmoid (S-shaped) dose response curve typical of insect mortality (Figure 46). This allows calculation of percentage mortality at different doses. For example, LD50 (the dose that kills 50% of the population) can be accurately calculated using this type of analysis.

Probits are also used to provide confidence in the result, as they are based on the

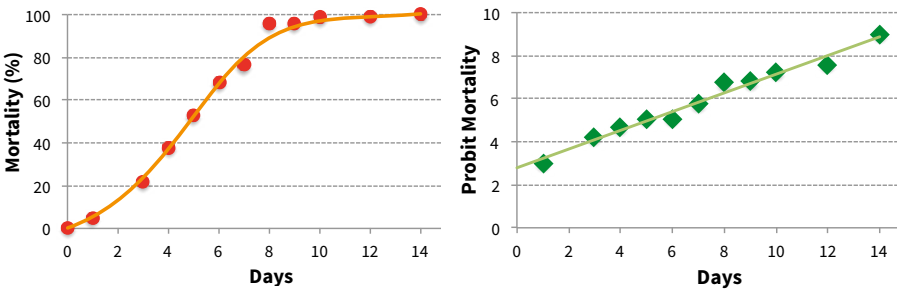


Figure 46 – Mortality of fruit fly exposed to a cold treatment, expressed as percentage mortality over time, and with the data converted to Probits.

number of insects killed. Killing a single insect provides only a very low level of confidence that the method will be effective, even if calculated mortality is 100%. Killing 1,000 insects provides considerably more confidence in the method, and killing 100,000 from a population of 100,000 provides a great deal of confidence.

Probit 9 mortality was first proposed as a measure of quarantine certainty by Baker (1939) in his paper 'The basis for treatment of products where fruit flies are involved as a condition of entry to the United States'. Probit 9 is equivalent to a mortality of 99.9968%. In effect, this represents three survivors from an initial population of 100,000 insects.

There are many reasons Probit 9 is not necessarily the best method of developing a quarantine treatment. Criticisms of Probit 9 include:

- It does not take into account the actual risk involved, that is, the probable infestation rate in the consignment
- It is an inappropriate use of the Probit analysis method
- It is an arbitrary standard not based on scientific method

Despite this, proof of either Probit 9 or Probit 8.7 mortality is still required by many importing countries. To standardise how this is achieved, the Japanese Ministry of Agriculture and Fisheries set out experimental procedures for demonstrating acceptable mortality. These measures have now been broadly adopted by many countries:

- A series of initial tests (minimum three full replications) are conducted to determine the most treatment-tolerant life stage of the target insect species (eg first, second or third instar larvae)
- These are followed by three large-scale trials under semi-commercial conditions (eg minimum loading rates in a cool room may be stipulated)
- Each large-scale trial should apply the proposed treatment to at least 10,000 larvae of the most tolerant treatment stage
- The treatment is regarded as successful if there are no survivors.

9.4 Quarantine treatments

Until recently (2012), postharvest treatments with the insecticides dimethoate and fenthion were used to provide quarantine security against fruit fly infestation. While preharvest application of these chemicals is still allowed for certain use patterns, they can no longer be applied postharvest to vegetables.

Currently accepted alternatives to chemical controls include cold storage, fumigation with methyl bromide and irradiation.

Cold storage

Cold storage is commonly used as a quarantine treatment for fruit crops against fruit flies. Temperatures under 3°C are required for 2 weeks or more. This limits use on chilling sensitive vegetables.

Cold storage is a commonly used method for ensuring that fruit do not contain live fruit fly larvae. Cold disinfestation is accepted by a number of Australia's trading partners (eg Japan, China, Taiwan, USA) for products such as citrus, stonefruit, grapes and kiwifruit. Cold disinfestation can be done in-transit, with data loggers used to provide proof of treatment.

Protocols may be on a sliding scale according to temperature. So, for example, Australian mandarins must be held at <1°C for 15 days, <2°C for 18 days or <3°C for 20 days in order to access Japan.

Such treatments are very conservative. Research on various fruit crops have all found ≥98% mortality after eight days at 3°C. A project on disinfestation of capsicums found that no fruit fly of any life stage survived when held at 3°C for 10 days. However, the shortest currently accepted protocol requires 14 days at <3°C.

There are currently no cold storage protocols for vegetables for a number of reasons:

- Most fruiting vegetables are considered chilling sensitive at the temperatures needed to kill fruit fly larvae (≤3°C).
- The relatively long storage times required to achieve Probit 9 mortality are difficult and expensive to implement within vegetable crop supply chains.
- Cold treatments are both crop and pest specific. Potential export markets are now raising concerns about fruit fly species other than Qfly and Medfly; trials may therefore need to prove effectiveness of a given time/temperature combination against additional species, such as *B. neohumeralis*, *B. jarvisii* and *B. cucumis*. This makes the development of disinfestation treatments expensive, logistically difficult and time consuming.

Heat treatments

Heat treatments are used as a quarantine treatment against fruit flies in chilling sensitive fruit crops. They are expensive, technically difficult and can damage the product.

Heat treatments are also primarily used to ensure products are free of live fruit fly larvae. They can be applied through water, air or vapour. Most require exposure times of 30 minutes to several hours at 40–50°C. Heat treatments have generally been focussed on chilling sensitive, high-value fruit crops such as mangoes, avocados and papaya. Treatments have also been developed for vegetable crops including zucchini, squash, and tomatoes. However, none have developed into commercial protocols. Difficulties with heat treatments include:

- They are expensive and technically difficult to apply.
- The time/temperature combinations necessary can damage the product.
- Like cold treatments, heat treatments are crop and pest specific, making it expensive to develop quarantine protocols. Also, at least one Australian fruit fly species may be highly resistant to heat treatment.

Atmosphere

High CO_2 and low O_2 can be combined with other quarantine measures to reduce treatment times. No quarantine treatments using this method are currently accepted.

Although reduced O_2 or increased CO_2 are not effective at killing insect pests when used alone, they can improve the efficacy of other measures. So, for example, high CO_2 combined with cold storage can reduce the time needed to achieve Probit 9 mortality by several days.

However, the gas concentrations needed are extreme; an atmosphere containing <13% O_2 or >7% CO_2 is deadly to humans, but insects can survive <0.5% O_2 and >50% CO_2. The best effects are gained using atmospheres containing >90% CO_2. Such atmospheres raise issues with worker health and safety as well as being expensive to measure and maintain. They can also damage the product.

In addition, regulators may be reluctant to accept treatments that rely on more than one measure, as they are relatively difficult to verify. There are currently no commercial protocols using modified atmospheres to kill pests.

Fumigation

There are a number of different fumigants, of which methyl bromide is still widely accepted. It is cheap to apply, fast and can be used as a generic treatment against a range of pests. Recapture technology can help mitigate environmental concerns.

Fumigation has a number of advantages in that it is relatively inexpensive, fast, leaves few residues and can be conducted on packed product so long as materials are vented. The fumigant methyl bromide (MB) remains the main generic quarantine treatment allowing international and interstate trade in fresh produce (Figure 47). So far, no other product has been found to be as effective as MB against fruit fly as well as other insect pests.

Although the Montreal Protocol banned most uses of MB due to its ozone-depleting properties (effective January 2005), quarantine treatments currently have a critical use exemption. Despite this, use is likely to become increasingly restricted; in 2010 the European Union banned quarantine use of MB on both local and imported products.

Figure 47 – Methyl bromide (MB) application under a tarpaulin system.

Figure 48 – Fumigation using a shipping container equipped with MB recapture equipment. This removes MB from the exhaust air after treatment.

The emissions of MB responsible for ozone depletion can be greatly reduced using recapture technology. After fumigation, the room or container air is pumped through activated carbon filters that absorb the MB (Figure 47). Once saturated, the carbon filter material can be deep buried, where the MB contained is naturally destroyed by soil bacteria. The carbon can, alternatively, be chemically treated to reduce it to non-toxic compounds or destroyed by pyrolysis.

The USA has set a target that all MB used for quarantine purposes should be recaptured by 2020. Similar targets exist in other countries, including New Zealand.

ICA-04 describes a methyl bromide fumigation protocol with sliding scale for dose and temperature. Products need to be warmed to at least 10°C (flesh temperature) before treatment, although at higher temperatures MB dosage can be reduced (Table 4). An approved fumigation chamber must be used with vegetables occupying 30–50% of the total chamber volume. Dosage is calculated on the total chamber volume (not the chamber volume less the volume of product) and treatment time is standardised at two hours.

Table 4 – Sliding scale for fumigation of vegetables with methyl bromide. Higher dosage rates are required at lower temperatures.

Methyl bromide ($g.m^{-3}$)	Flesh temperature (°C)
24	26 – 32
32	21 – 26
40	15 – 21
48	10 – 15

Phosphine is another common fumigant widely used against stored product pests (eg weevils in grain). It has the advantage that it can be applied at low temperatures. However, exposure times are much longer than those required for MB, being days rather than hours. Phosphine is also extremely toxic to humans and potentially explosive. A non-explosive formulation of phosphine with CO_2 (ECO_2FUME) has been shown to be effective against Qfly in citrus when applied for 48 hours.

Another alternative to MB is ethyl formate. This fumigant kills surface pests such as thrips and mealybugs yet is very safe for humans. Unfortunately, the high doses needed can damage vegetable skins, causing discolouration and pitting.

A similar problem exists with ethane dinitrile, a relatively new fumigant recently tested on vegetables. A dose of $30g.m^{-3}$ EDN for two hours at 15°C resulted in 100% mortality of fruit fly larvae in chillies, zucchini and capsicum. Unfortunately, doses of $5g.m^{-3}$ or more caused significant damage, including softening, pitting and rots, to all vegetables tested (tomatoes, capsicum, squash, cucumber and zucchini)[12].

Hydrogen cyanide (HCN) is sometimes used as a fumigant against surface pests such as mealybugs and aphids. It is used in some countries to treat bananas, pineapples and other tropical fruit. However, HCN is extremely toxic, being potentially deadly to humans through skin contact alone. It also causes skin damage to many fresh products.

12 Jessup AJ, Golding JG. 2012. 'Qfly proof of concept for ethane dinitrile (EDN) fumigation. Final Report HG10065'. Horticulture Australia Pty Ltd.

Irradiation

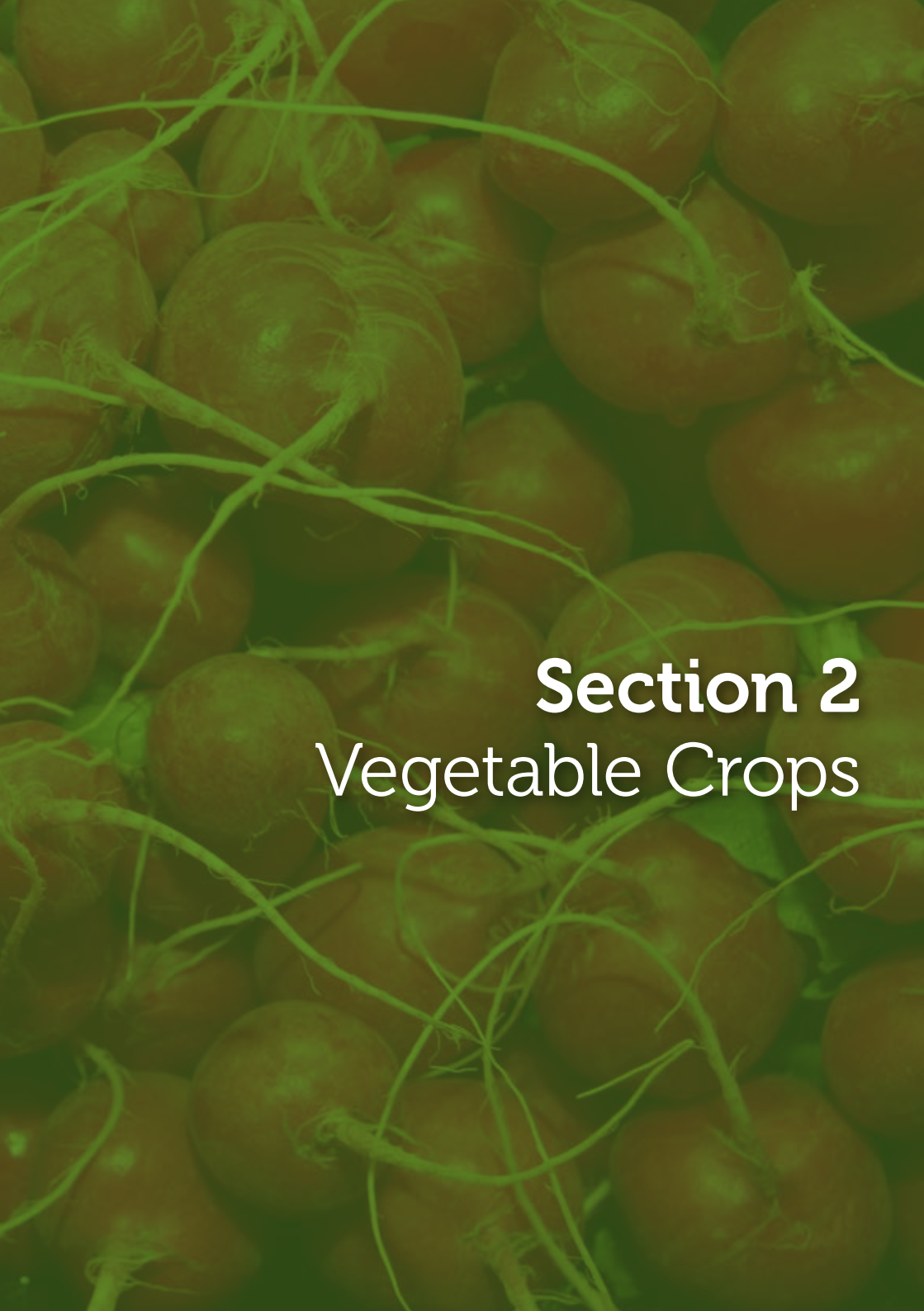
Irradiation is fast, accepted as a generic treatment for fruit fly and leaves no residue. However, there is currently only one commercial irradiation facility in Australia and customer acceptance is limited.

Irradiation involves exposing the product to ionising radiation. This is usually from a radioactive source (cobalt-60), but can also be produced electronically. Irradiation may not kill insects immediately, but stops them from continuing to develop and reproduce.

A dose of 150 Gy is accepted by some countries (including USA) as a generic treatment for fruit fly. This treatment has been approved by FSANZ for capsicums and tomatoes, based on studies showing nutritional qualities were unaffected.

Irradiation has significant advantages, particularly, the acceptance of a generic dose against insect pests. It leaves no residues, is fast, and can be applied to packed product. However, many export markets, including Japan, Taiwan and the European Union, do not permit irradiation. Where it is accepted (eg New Zealand) products must be labelled as such, which limits consumer acceptance.

Other barriers to use of irradiation include cost and logistical difficulties; the only Australian commercial irradiation facility is in Brisbane. The delay in insect mortality also creates issues, although a new ELISA test that can detect changes in irradiated insects may help overcome this barrier.



Section 2
Vegetable Crops

1 Asian Leafy Vegetables

Buk choy
Brassica rapa
subsp. *chinensis*

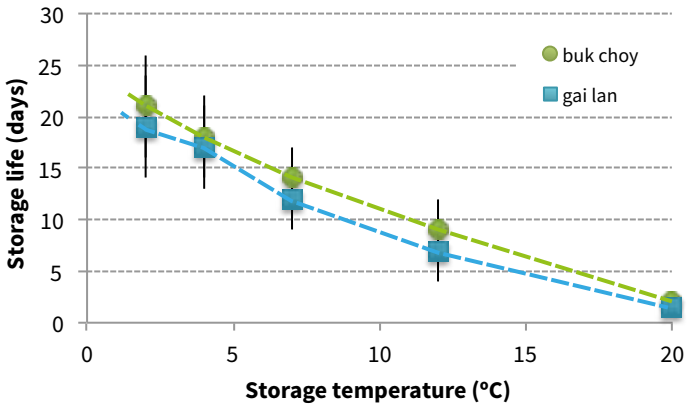
Pak choy
Brassica rapa
subsp. *chinensis*

Choy sum
Brassica rapa
subsp. *chinensis*

Gai lan
Brassica oleracea
var. *alboglabra*

Wombok
Brassica rapa
subsp. *pekinensis*

- Most leafy Asian vegetables are fast growing plants with little protection against water loss. They should ideally be harvested when weather is cool and plants are fully hydrated (eg early morning) to limit wilting.
- Asian leafy vegetables are increasingly grown hydroponically, sometimes under protective structures. Vegetables grown this way may have fewer leaf diseases but be more susceptible to wilting than field-grown plants.
- Rapid cooling to below 5°C after harvest is essential to retain quality. Hydro-vacuum cooling is the most efficient method. Hydrocooling or misted room cooling can also be suitable.
- Storage life is maximized at close to 0°C. However, Asian leafy vegetables are highly susceptible to freezing. At 2–4°C with >90% RH Asian leafy vegetables remain acceptable for up to 4 weeks without risking damage.
- Wombok is less susceptible to freezing than open leafy types, so can be stored at 0–2°C. Storage life may be 6 weeks to 3 months, depending on variety.
- Some wombok varieties appear to be slightly chilling-sensitive, developing brown stains along the mid-ribs and dead areas on leaves following extended storage (>4 weeks) at 0°C.
- Ethylene production is usually low, but sensitivity to ethylene is relatively high. Ethylene exposure increases yellowing and the onset of leaf diseases. Yellowing or diseased outer leaves greatly increase ethylene production.
- Elastic bands are used to secure bunches. However tight banding damages stems. Broken stems look unattractive and are susceptible to rots.



Storage life of buk choy and gai lan at different temperatures. Bars indicate the likely variability around each mean value.

- Leafy Asian vegetables contain >93% water. Most are highly susceptible to moisture loss so can benefit significantly from packaging materials and/or misting on retail display.
- Major diseases include bacterial soft rots, various leaf diseases and white blister.
- Important disorders include leaf yellowing, particularly of the older leaves, and pepper spot of wombok (gomasho).

Yellowing can be diffuse (left) or associated with leaf spots (centre). Gomasho is a disorder of wombok (right).

2 Baby spinach

Spinacia oleracea

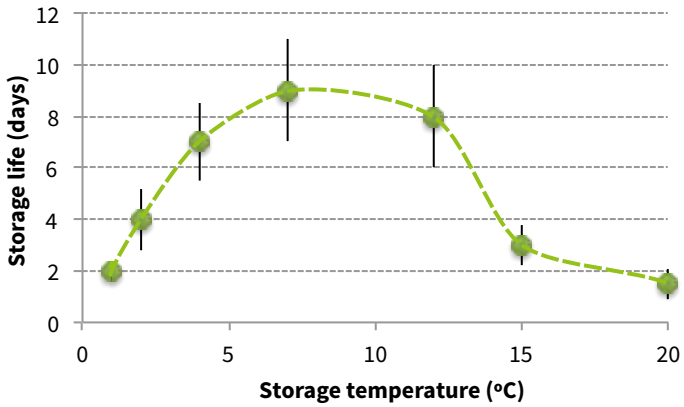
- Immature or 'baby-leaf' products such as baby spinach are extremely perishable, having high rates of respiration and little resistance to water loss.
- Good quality leaves should be young, tender and dark to bright green. Smaller, thicker leaves have a longer storage life than larger or thinner leaves.
- Harvesting should occur when the crop is cool and fully hydrated but dry. This is likely to be early morning during spring or summer but may be any time of day during winter.
- Spinach crops are usually mechanically harvested then processed through a series of washes and inspections. Minor leaf bruising during harvest and processing does not affect quality, with symptoms disappearing after 7 days at 5°C. However, more severe bruising has a major impact, increasing rots and reducing storage life.
- Cooling baby spinach as soon as possible after harvest will minimise rots and yellowing. Hydrocooling is fast and increases product weight, so is highly suitable. Hydro-vacuum cooling and forced air systems are also appropriate but can cause some tissue damage. Room cooling is comparatively slow but can be suitable if product is harvested while cool.
- Cooled product can be stored for at least 48 hours before processing without affecting quality of the finished product.
- Storage life is maximized at close to 0°C with >95%RH. However, good quality baby spinach can remain in excellent condition for three weeks or more at 2–4°C. This is sufficient for most marketing purposes and avoids the risk of freezing damage.
- Storage life varies significantly among cultivars and is generally longer for crops grown during winter than those produced under warmer conditions.
- The end of storage life is usually due to the onset of rots rather than leaf yellowing. Including an effective sanitiser in wash water is therefore essential.
- Baby spinach is highly susceptible to moisture loss so is always packed using plastic liners or bags. Excess water should be removed before packing.
- Baby spinach produces minimal ethylene but is very ethylene sensitive. Exposure accelerates leaf yellowing.
- Bacterial soft rots are the main postharvest disease affecting baby spinach.

3 Beans

Phaseolus vulgaris

- Beans are an immature seedpod. They are growing and developing rapidly at harvest so have a rapid respiration rate, little protection against moisture loss and few storage reserves.
- Beans should ideally be harvested when conditions are cool (overnight or early morning) and cooled as quickly as possible to 7–10°C using forced air or hydrocooling. At 7–10°C with >90% RH beans can stay fresh for 7 to 12 days. Temperatures over 12°C result in rapid deterioration.
- Beans are chilling sensitive, so should not be stored below 5°C for extended periods. Symptoms of chilling injury include brownish red russetting, pitting and water-soaked areas.
- Beans packed wet in lined cartons are likely to develop rots.
- If beans lose ≥5% moisture they will be soft and unmarketable. Packaging can protect beans from moisture loss, extending storage life.
- Important diseases include cottony leak, grey mould and Sclerotinia (white rot).

Russetting due to chilling damage

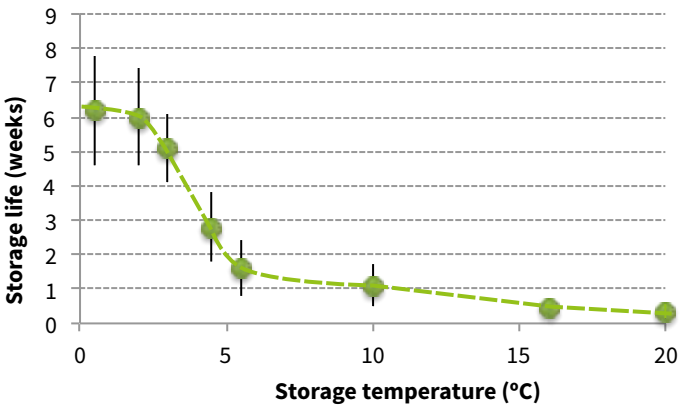


Storage life of beans at different temperatures. Bars indicate the likely variability around each mean value.

4 Broccoli

Brassica oleracea var. *italica*

- Broccoli is an immature flowering head. Broccoli florets are easily crushed and broken, so careful handling is essential to prevent damage.
- Harvest maturity is based on the head size desired by the target market. Overmature heads have loose, open florets and reduced shelf life.
- Broccoli should be cooled below 5°C as soon as possible, especially if it has been harvested under warm conditions.
- Hydro-vacuum cooling is a fast and energy-efficient method of cooling broccoli. Forced air cooling and hydrocooling can also be effective.
- Storage life is maximised at 0°C combined with high RH. Broccoli usually remains in excellent condition for at least 3 to 5 weeks at 0–3°C. Below 5°C ethylene sensitivity is reduced and storage life is usually ended by rots. Above 5°C storage life is limited by ethylene induced floret yellowing and general deterioration.



Broccoli storage life at different temperatures. Bars indicate the likely variability around each mean value

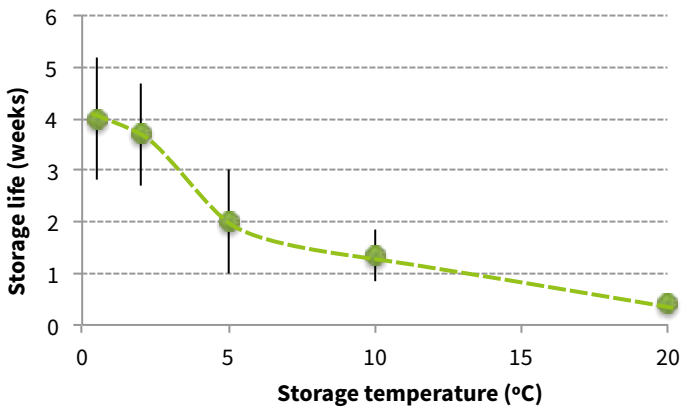
- Broccoli florets have a rapid respiration rate and both produce and respond strongly to ethylene. They yellow within 2–3 days at 20°C.
- Broccoli should not be stored wet. Moisture increases stem rots and splitting as well as disease in the florets and discolouration of the cut leaf bases.
- Cooled broccoli may be packed in lined cartons or top-iced in styrofoam cartons. Top icing keeps the product cool and hydrated during breaks in the cold chain and is expected by some customers. However, this practice has significant cost disadvantages, can increase rots and is environmentally unsound.
- There is an increasing move to field-packed broccoli. By reducing handling this can decrease costs and avoid damage to the heads. Packed broccoli can be cooled using hydro-vacuum or forced air systems.
- Broccoli responds well to modified atmospheres (MA) if stored for an extended period (>3 weeks). Atmospheres containing 7–10% CO_2 and 2–8% O_2 are usually recommended. Any off odours normally dissipate after a few hours in normal air.
- Broccoli can lose up to 6% weight and remain marketable.
- Bacterial rots in the florets and stem base are the main postharvest diseases affecting broccoli. Preharvest infection with white blister affects postharvest quality.

Bacterial rots can occur in florets (left) or stem base (centre). White blister infection results in deformed heads (right).

5 Brussels sprout

Brassica oleracea var. *gemnifera*

- Brussels sprouts are young leaf buds. Good quality sprouts are sweet and tender, bright green with a clean white cut at the base.
- Brussels sprouts should be cooled below 5°C as soon as possible, especially if harvested under warm conditions. Hydro-vacuum cooling, hydrocooling and forced air systems are all suitable.
- Storage life of Brussels sprouts is maximised at 0°C with >90%RH. Sprouts can remain in good condition for 3 to 5 weeks at 0–3°C. At 5°C and above storage life is ended by yellowing.
- Brussels sprouts are moderately sensitive to ethylene but produce very little themselves.
- Brussels sprouts are sometimes packed in top-iced styrofoam cartons. If the ice melts this can increase rots and discolouration. Freezing at contact points can cause dark, water-soaked spots.
- If sprouts lose more than 5% moisture they will be unmarketable.
- Major postharvest diseases affecting Brussels sprouts include bacterial soft rots and peppery leaf spot (*Pseudomonas syringae* pv. *maculicola*).

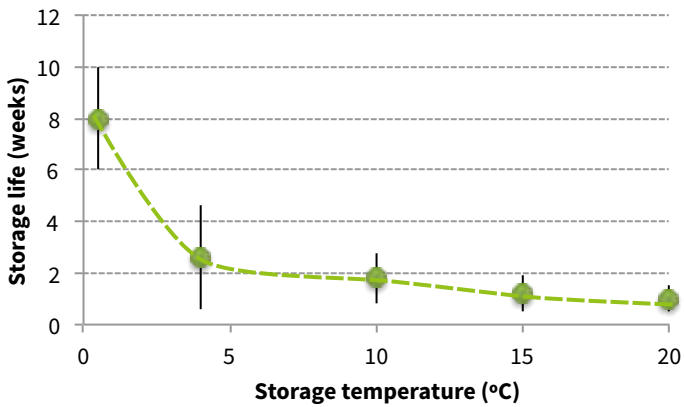


Storage life of Brussels sprouts at different temperatures. Bars indicate the likely variability around each mean value.

6 Cabbage

Brassica oleracea var. *capitata*

- Cabbages are harvested when the head is firm and heavy and of a size suitable to the market.
- Cabbage leaves often have a waxy bloom. Combined with the densely overlapping leaves, this protects them from moisture loss.
- The outer leaves of cabbages are usually trimmed before storage so that they do not interfere with air circulation, but continue to protect against physical damage and water loss.
- Cabbages can remain acceptable for up to 4 months if held close to 0°C with >95% RH, although this varies with cultivar. Storage life is 3 to 6 weeks at 2–4°C, which is usually enough for normal transport and retail.
- The dense structure of cabbages makes them relatively difficult to cool. Hydro-vacuum cooling is less efficient for cabbage than other leafy vegetables. Forced air cooling can be effective.
- Cabbages stored for extended periods lose their sweetness and may develop bitter flavours.
- Cabbages are sensitive to ethylene, which increases leaf yellowing.
- Diseases affecting cabbage include white mould (*Sclerotinia sclerotiorum*), black rot (*Xanthomonas campestris*) and bacterial soft rots.

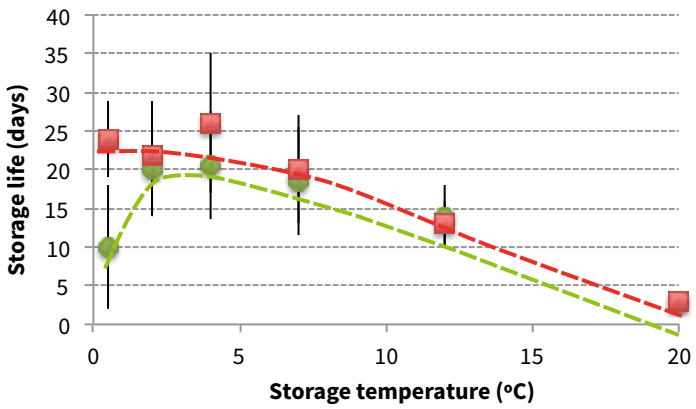


Effects of temperature on storage life of cabbage. Bars indicate the likely variability around each mean value. Data compiled from original research and published literature.

7 Capsicum

Capsicum annuum

- Capsicums (and chillies) are fruit. Market preferences are for capsicums that are either fully green or fully red (or yellow, orange, purple etc.) and while coloured fruit usually receive the highest price, delaying harvest can increase losses.
- Although capsicums cannot be artificially ripened after harvest, they will continue to develop colour during storage at 8–20°C.
- Capsicums should not be harvested while wet. Capsicums harvested in hot weather should be immediately placed in the shade to avoid dehydration and sunburn.
- The waxy skin of capsicums lacks either lenticels or stomata. This makes them relatively resistant to water loss. However, only 3% weight loss results in detectable softening.
- Field-grown fruit usually need to be washed. Capsicums should never be immersed in water, but cleaned with brushes and water jets. Chilled water should not be used. Sanitisers can help reduce microbial load and, therefore, storage rots.
- Glasshouse grown fruit do not normally need to be washed.



Storage life of red (■) and green (●) greenhouse grown capsicums at different temperatures. Bars indicate the likely variability around each mean value.

- Capsicums and chillies should ideally be cooled below 8°C within 24 hours of harvest. Forced air and well-circulated room cooling systems are suitable. Longer delays increase softening and development of rots, particularly in the stem and calyx.
- Capsicums are chilling sensitive. However, sensitivity depends on growing conditions, cultivar and harvest maturity. For example, red fruit are less chilling sensitive than green fruit.
- Storage life is maximised between 1–5°C. Storage is normally ended by rots, so is highly variable.
- Capsicums and chillies have low sensitivity to ethylene.
- A number of fungal species can cause internal rots due to infection during flowering. These are undetectable at harvest.
- Other important postharvest diseases are caused by Alternaria spp. Anthracnose (*Colletotrichum* spp.), grey mould (*Botrytis cinerea*) and bacterial soft rots.
- Insect feeding (eg thrips) during development can result in deformed, scarred or russetted fruit.
- Sunburn results in dry, bleached areas and/or dehydration and wrinkling.

Internal rots are undetectable at harvest (left). Other disorders include deformation due to insect feeding (centre) and sunburn damage (right).

8 Carrots

Daucus carota

- Carrots are storage roots. They evolved to enable the plant to re-shoot after death or removal of the foliage. Carrots therefore contain relatively large reserves of starch and sugars.
- Carrots are usually mechanically harvested, pre-washed to remove dirt, and then polished to remove the outer layer of skin. At least two washes are used. A sanitiser should be included in the final wash.
- Carrots lack a waxy skin and are very susceptible to moisture loss after harvest, particularly if they have been polished.
- Hydrocooling is a very suitable cooling method. Forced air systems can also be used in combination with high RH.
- Young carrots can remain in good condition for 4 to 6 weeks at close to 0°C. At 5°C storage life is reduced to 2 to 3 weeks. Large, older carrots have longer storage life and may last as long as 6 months.
- Potential storage life is greatly reduced if carrots are harvested with leaves attached (Dutch carrots).
- Polishing damages the outer cells in carrot skin, which become very susceptible to dehydration. These dry cells can form an unattractive, chalky 'bloom' on the carrot surface. Formation of lignin on damaged areas can increase this effect.

White bloom on the surface of an abraded carrot

- Carrots are highly sensitive to ethylene. Even low levels (eg 0.5ppm for two weeks) has been demonstrated to stimulate formation of isocoumarins - bitter compounds which greatly reduce acceptability

- Carrots should not be stored wet as this increases development of bacterial soft rots and fungal diseases such as black root rot (*Thielaviopsis basicola*), grey mould (*Botrytis cinerea*) and white mould (*Sclerotinia sclerotiorum*).
- The main disorders affecting carrots are cracking (due to uneven moisture during growth) and forked or poor shape.

Bacterial soft rots after washing (Photo: L DuToit WSU)

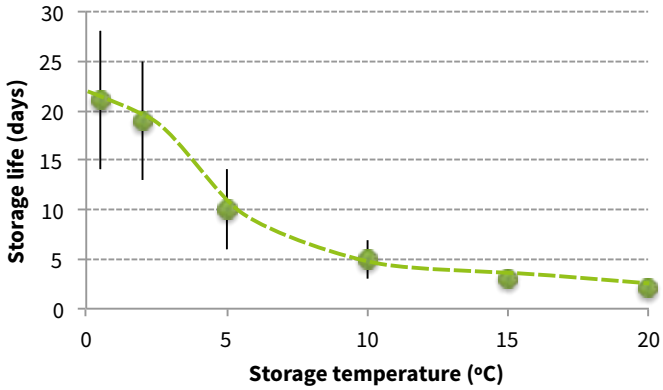
White mould (Photo: H Pung Peracto)

Black root rot (Photo: L DuToit WSU)

9 Cauliflower

Brassica oleracea var. *botrytis*

- A cauliflower is an unopened flower head composed of (deformed) buds. They are fragile and must be handled gently to avoid damage.
- Cauliflower heads should be firm and tight. The white curds are best quality if protected from sunburn, wind rub and other damage by the leaves. Overmature heads become loose and soft.
- Cauliflowers should be cooled below 5°C as soon as possible after harvest. Hydro-vacuum cooling and forced air systems are effective. Hydrocooling times must be long enough to cool to the core. Room cooling in bins is not recommended.
- Storage life is maximised at close to 0°C with >90% RH. Cauliflowers can last 3 to 4 weeks depending on the cultivar and growing environment. Moisture loss and discolouration end storage life within only a few days at >10°C.
- Black spotting—curd blackening—is an important disorder affecting cauliflower. While the causes are not well understood, cold temperatures reduce curd blackening. Packaging and low O_2 storage may also limit development.
- Cauliflowers should be dried thoroughly before packing to avoid increasing bacterial head rots and white mould (Sclerotinia spp.).
- Modified atmospheres containing <5% O_2 and <5% CO_2 can extend cauliflower storage life, but are not currently used commercially.
- Disorders include riciness, warm weather syndrome and curd discolouration.



Cauliflower storage life at different temperatures. Bars indicate the likely variability around each mean value.

10 Celery

Apium graveolens

- Celery is harvested once plants reach marketable size. If left in the field too long the internal tissues of the outer petioles start to become spongy and dry or 'pithy' .
- Preharvest stresses such as uneven watering, cold temperatures and flower induction can also cause pithiness.
- Celery is around 95% water. Rapid cooling after harvest is essential to keep it crisp. Hydro-vacuum cooling is the most efficient way to cool celery. Hydrocooling is also effective.
- Storage life can be 5 to 7 weeks at close to 0°C. However, celery is very susceptible to freezing. Storage at 2°C can provide a margin of safety without compromising quality. At 5°C storage life may be reduced by half.
- Celery consists of thick leaf stems (petioles) clasping a central heart. At temperatures >4°C the internal leaves can continue to grow, which reduces quality.
- Celery is increasingly trimmed into various sizes before packaging for retail sale. Trimming blades need to be kept as sharp as possible: blunt knives cause additional damage; resulting in a whitened, dry appearance on the cut surface.
- Point of sale packaging can help maintain celery quality during retail display.
- Celery can lose up to 8% water and remain acceptable.
- Major postharvest diseases affecting celery include bacterial soft rots, white mould (*Sclerotinia* spp.) and fungal leaf spots.
- Blackheart is a form of tipburn caused by calcium deficiency during growth. It can affect the inner, hearting leaves, which turn brown and eventually black.

Bacterial soft rots

Blackheart (Photo: ST Koike UCD Extension)

11 Cucumber

Cucumis sativus

Green field / slicer

Continental

Lebanese

- Cucumbers are fruit. They are harvested while still immature, before the seeds enlarge and harden. In some varieties, the flesh in the core develops a translucent appearance at harvest maturity.
- Some cucumber varieties (green field, crystal apple) have a relatively hard, waxy skin. Others (Continental, Lebanese) have a thin skin that is easily damaged. Gentle handling is essential to prevent cuts, scratches or bruises, as these are likely to develop into rots.
- Ideally, cucumbers should be harvested when conditions are mild and fruit are dry such as early morning. They should be cooled as soon as possible, using forced air systems or room cooling to limit moisture loss.
- Cucumbers should never be packed wet, as this will increase disease. Washing thin-skinned varieties is not recommended.
- Cucumbers are highly chilling sensitive. Susceptibility is strongly affected by variety and growing conditions. Chilling injury can be reduced if there is a delay between harvest and cold storage.
- Temperatures below 7–10°C reduce storage life due to chilling injury. At temperatures over 12°C cucumbers rapidly yellow and rot.

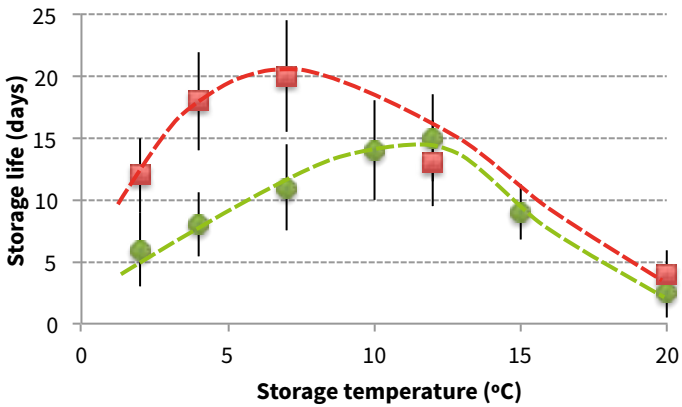
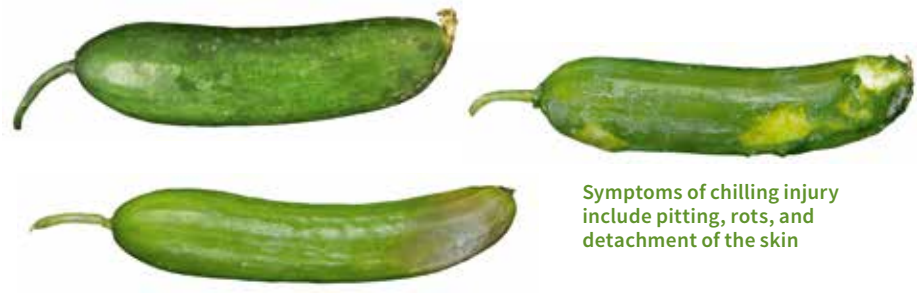


Figure 55 – Storage life of green field (■) and Lebanese (●) cucumbers at different temperatures. Bars indicate the likely variability around each mean value.

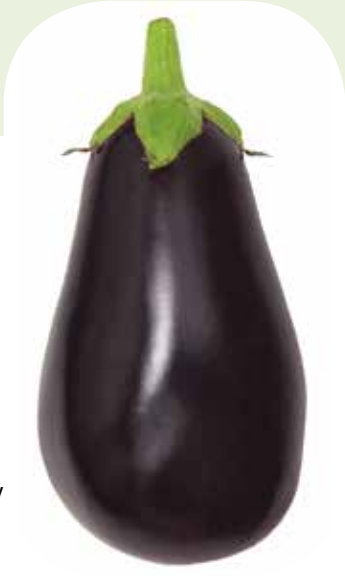
- Ethylene production of green cucumbers is generally low. However, cucumbers are very sensitive to ethylene, which increases yellowing and shortens storage life. Ethylene production increases greatly if cucumbers yellow or rot.
- Cucumbers contain >95% water. Weight loss of 3–5% results in noticeable softening and reduces marketability.
- The rate of moisture loss from thin-skinned Lebanese cucumbers is 3–4 times that of a green field cucumber at the same temperature and humidity.
- Packaging materials can reduce water loss and chilling sensitivity. Point of sale materials are particularly useful for extending shelf life of thin-skinned varieties.
- Continental cucumbers are usually sold shrink-wrapped. Shrink wrap reduces physical damage and water loss without the risk of condensation.
- Cucumbers can be affected by many postharvest fungal diseases, especially if damaged by chilling temperatures. *Alternaria* spp., *Rhizopus* spp., *Botrytis cinerea* and *Fusarium* spp. are common rots affecting cucumbers.
- Symptoms of chilling injury include increased water loss, sunken pits and lesions, detachment of the skin from the underlying flesh and rot development.



Symptoms of chilling injury include pitting, rots, and detachment of the skin

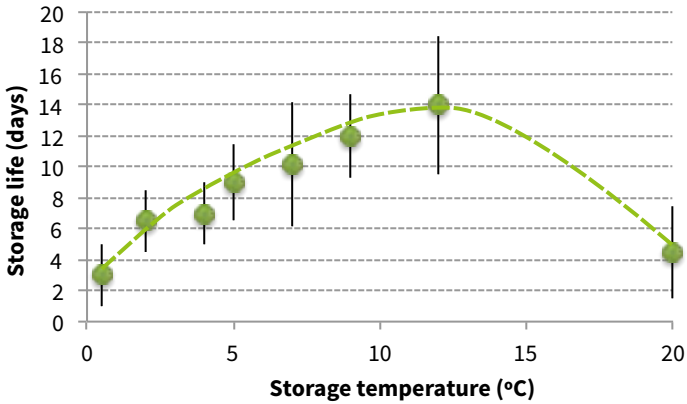
12 Eggplant

Solanum melongena



- Eggplants are an immature fruit. If left on the plant too long the seeds develop and darken and the flesh becomes spongy.
- Eggplant cultivars vary widely in colour, shape and size and can be grown in the field or in protected cropping systems. Variety and production method strongly affect storage characteristics.
- All eggplants have smooth, glossy skin with no stomata or lenticels. This makes them relatively resistant to water loss. Fruit must be handled carefully to avoid marking the skin.
- Eggplants should be forced air or room cooled below 20°C within 12 hours and below 12°C within 24 hours of harvest to maximise quality.
- Eggplants are chilling sensitive. Storage life is generally maximised at 8–12°C.
- Chilling sensitivity is reduced if cold temperatures occur during growth or there is a delay between harvest and low temperature storage.
- Chilling injury symptoms include surface pitting, brown 'scald' patches over the skin, bleaching of the calyx tissue, darkening of the flesh and seeds and increased decay.

Chilling injury causes pitting (left) as well as brown, scalded patches on the skin (right)



Eggplant storage life at different temperatures. Bars indicate the likely variability around each mean value. Data compiled from original research and published literature.

- More than 2% moisture loss results in significant softening of eggplant. However benefits of packaging are generally low.
- Diseases affecting eggplants include *Alternaria* spp., *Anthracnose* spp. and grey mould (*Botrytis cinerea*).

Eggplants are very susceptible to compression damage if packed too tightly

Severe sun damage on eggplant

13 Green onions

Bunching onion
(Spring onion, shallot)
Allium fistulosum

Spring onion
(Salad onion, globe)
Allium cepa

Leek
Allium ampeloprasum

- Green onions fall into three types:
  - Non-bulbing (*Allium fistulosum*), which do not develop a bulb when mature and have hollow leaves.
  - Bulbing (*Allium cepa*), but which are planted at a high density and harvested before the bulb fully forms. These also have hollow leaves.
  - Leeks (*Allium ampeloprasum*), which do not form a bulb when mature and have flat, strap-type leaves.
- Maturity of green onions is determined by market requirements for size and development.
  - Bunching onions should have a long white shank at the base and straight, erect leaves wrapping around the central core.
  - Spring onions should have a white, round to oval bulb at the base, clean neck and straight, erect leaves
- Leeks are harvested when they reach a minimum core diameter. The length of the white to pale green shank is an important quality attribute.
- Harvest should ideally be conducted when conditions are cool and plants are fully hydrated, such as early morning. As these are rapidly growing young plants, green onions should be washed and trimmed as soon as possible after harvest.

- Cooling within 3 hours of harvest is recommended. Hydrocooling, forced air and hydro-vacuum cooling are suitable cooling methods. Storage life is maximised at close to 0°C and >95% RH. Under these conditions bunching onions can remain in good condition for 3-4 weeks, while leeks can be stored for up to 3 months.
- The inner leaf whorls of green onions continue to elongate after harvest. This reduces firmness and quality. Bunching onions are also gravitropic, so the leaves will bend upwards if vegetables are stored flat for an extended period. Low storage temperatures slow, but do not prevent, these processes.
- Bunching onions lose moisture rapidly. Moisture loss results in leaf wilting and drying of the outer leaf sheath. Leeks are less susceptible to wilting and can lose 10–15% moisture while remaining marketable.
- Green onions are generally tolerant of condensation. Packaging materials can maintain quality as well as unitise bunches or multi-packs of trimmed product.
- Green onions are not very sensitive to ethylene.
- Few diseases or disorders affect green onions. The main risks are freezing injury and infection by bacterial soft rots such as *Erwinia* sp.

14 Lettuce – hearting

Latuca sativa

Iceberg Cos (Romaine)

- Harvest maturity is based on market requirements.
  - Iceberg lettuce is normally harvested once the heads are firm with internal leaves closely packed.
  - Cos lettuce is harvested once the heart has started to form. Cos lettuce may be harvested as 'baby' cos or left longer to mature.
  - Lettuces may be left longer in the field if intended for processing, however, the core length should not exceed 75mm.
- Lettuces are >94% water and susceptible to moisture loss. To maximise yield they should be harvested when conditions are cool and plants are fully hydrated.
- Diseased and soiled leaves should be trimmed in the field. If this is not possible, the outer leaves should be removed within one day of harvest. Delays in trimming reduce storage life, unless the degree of trimming is increased.
- Lettuces should be placed, not thrown, into bins to avoid crushing damage.
- Rapid postharvest cooling is essential. Hydro-vacuum cooling is fast and efficient, usually taking 20–40 minutes to thoroughly cool. Forced air systems can take 3–6 hours to reduce temperature to close to 0°C.
- Lettuces should not be harvested or packed wet as this increases development of bacterial rots and, possibly, pink rib.
- Storage life is maximised at close to 0°C with >95% RH. Under these conditions storage life is 2 to 4 weeks, depending on variety.
- As lettuce is highly susceptible to freezing, 1–2°C may provide sufficient storage life while reducing the risk of freezing damage.

- The overlapping leaves of head lettuces reduce the rate of water loss, particularly from internal leaves. However, only 3% weight loss results in wilting and lack of crispness.
- Cut surfaces, such as the stem base, discolour during storage due to oxidation of the contents of the damaged cells.
- Lettuces are very sensitive to ethylene. Concentrations >0.5ppm can cause russett spotting—the development of elongated, brownish pitted lesions, mainly on the mid-ribs.
- The disorder 'pink rib' is associated with overmature iceberg lettuce types. Symptoms increase at higher storage temperatures (>5°C).
- High CO_2 levels (>2%) during storage can cause 'brown stain'. This takes the form of large brownish patches, mainly on the mid-ribs.
- Common diseases of lettuce include grey mould (*Botrytis cinerea*), white mould (*Sclerotinia* spp.) and bacterial soft rots (*Erwinia* spp.)
- The disease varnish spot (*Pseudomonas cichorii*) affects only the inner leaves, so is not always apparent at harvest.

Russetting due to ethylene exposure

Pink rib

Varnish spot

15 Lettuce – loose leaf

Latuca sativa

- Hydroponic loose leaf lettuces may be harvested whole with roots intact or trimmed at the base. Field-grown lettuce intended for sale as whole products are trimmed at the base by hand.
- Mechanised systems are usually used to cut and collect lettuce leaves for salad/babyleaf products. In some circumstances lettuces may be cut more than once.
- Lettuces are >94% water and susceptible to moisture loss. To maximise yield they should be harvested when conditions are cool and plants are fully hydrated.
- Rapid postharvest cooling is essential. Cooling within 30 minutes of harvest significantly increases storage life compared to cooling after a 2-hour delay. Hydro-vacuum cooling is the fastest and most efficient cooling method, usually taking 20–30 minutes to thoroughly cool whole loose-leaf lettuce. Forced air systems can take 2–5 hours to reduce temperature to close to 0°C.
- Excess water should be removed from cut babyleaf lettuce leaves before packing to reduce disease.
- Storage life is maximised at close to 0°C with >95% RH. Under these conditions leaves may remain acceptable for up to 3 weeks.
- Lettuce is highly susceptible to freezing. Storage at 2 – 4°C may provide sufficient storage life while reducing the risk of damage.
- Cut surfaces discolour during storage due to oxidation of the contents of the damaged cells. Browning can be reduced by keeping cutting equipment sharp, treating cut surfaces with acidifiers and storing cut leaves in low oxygen atmospheres.
- Loose leaf lettuce types lose moisture and wilt easily; rates of water loss are three times those of iceberg lettuce.
- Packaging is effective at reducing wilting of loose leaf lettuce leaves or whole plants.

Bacterial soft rot. (Photo: S Grigg)

Anthracnose (Photo S Grigg)

- Lettuces are sensitive to ethylene. Symptoms include premature yellowing, increased disease and russet spotting of the mid-ribs.
- Common diseases of loose-leaf lettuce include grey mould (*Botrytis cinerea*), white mould (*Sclerotinia* spp.), bacterial leaf spots (*Pseudomonas* sp.) and bacterial soft rots (*Erwinia* spp.).

Bacterial leaf spot (Photo L Tesoreiro)

16 Parsnips

Pastinaca sativa

- Parsnips are storage roots. They evolved to enable the plant to re-shoot after death or removal of the foliage. Parsnips therefore contain relatively large reserves of starch and sugars.
- Parsnips are usually mechanically harvested once the diameter of the root reaches 30–60mm. Harvest must occur before plants bolt (flower). Overmature parsnips can develop woody centres with fibrous texture and poor flavour.
- The green leaves are trimmed off (5–15mm remaining) and any small feeder roots removed.
- At least two washes are used; a pre-wash to remove dirt followed by a final wash with sanitiser.
- Parsnips have a thin skin and are very susceptible to moisture loss after harvest. Weight loss of 6% makes parsnips limp and unmarketable.
- Hydrocooling is a very suitable cooling method. Forced air systems can also be used in combination with high RH.
- Good quality parsnips can be stored for 4–6 months at close to 0°C. At 5°C storage life is reduced to 3 to 4 weeks.
- Parsnip varieties which have thin skins or which are grown in coarse, sandy soils are more susceptible to browning during storage, which can limit storage life.
- Good quality parsnips have a sweet, nutty flavour. They can contain up to 10% sugars at harvest, mainly as sucrose. Cold storage for 2–3 weeks results in conversion of starch into sugar, increasing sweetness.
- Parsnips are highly sensitive to ethylene. Even low levels can stimulate formation of bitter compounds.
- The main diseases affecting parsnips are black canker (*Itersonilia perplexans*), grey mould (*Botrytis cinerea*) and bacterial soft rots (*Erwinia* spp.).
- The main disorders affecting parsnips are cracking (due to uneven moisture during growth) and forked or poor shape.

Black canker / Itersonilia canker of parsnips (Photo: L Tesoriero)

17 Pea (edible pod)

Pisum sativum var. *macrocarpon*

- Unlike garden peas, snow peas and sugar snap peas have soft, edible pods.
- Sugar snap peas are harvested when the seeds have begun to develop and the pods are plump, but before the pod becomes tough or stringy. Snow peas are harvested while the seeds are still very immature and pods are flat.
- As peas are an immature seed, they are respiring rapidly at harvest and lose moisture easily.
- Snow peas contain around 4% sugar, most of which is in the form of glucose. Sweetness is a key quality attribute. Rapid cooling is therefore essential to prevent pods losing sweetness as well as their bright green colour.
- Hand-harvesting reduces physical injury to the delicate pods. Damage becomes evident during storage as whitened areas on the skin.
- Harvesting must be conducted every few days to select appropriate sized pods. Mature pods are 60–120mm length (snowpeas) or 60–90mm length (sugar snaps).

Physical damage

- Forced air cooling is the most suitable cooling method, although hydrocooling and vacuum cooling may also be appropriate.
- Storage life is maximised at close to 0°C and >95% RH. Under these conditions snow peas and sugar snap peas remain acceptable for at least 3 weeks.
- Packaging can increase storage life of peas by reducing water loss. However, high humidity can increase growth of grey mould, particularly on the calyces and damaged areas.
- Modified atmospheres have been shown to significantly improve storage life of snow peas, so long as CO_2 does not exceed 5%. High concentrations of CO_2 result in off flavours.
- Peas produce very little ethylene and are fairly insensitive to ethylene, particularly if stored at low temperatures.

Grey mould

18 Pumpkin

Cucurbita maxima

Kent pumpkin

Butternut pumpkin

- Pumpkins should be harvested only when fully mature:
  - Butternut pumpkins are mature once the skin has lost any green tinge or striping and the flesh is dark yellow to orange.
  - The pale mottles on the skin of Kent pumpkins turn from greenish yellow to beige at maturity and the flesh loses any green tinge under the skin.
  - Queensland blue pumpkins develop a whitish, waxy skin at maturity and have even, orange-coloured flesh.
- Pumpkins cannot be further ripened after harvest. Undermature pumpkins are often tasteless, astringent and lack firm texture.
- Field packed pumpkins should be wiped and packed dry. Shed packed pumpkins should be washed and brushed dry before packing. It is essential to include an effective sanitiser during washing to minimise postharvest rots.
- Pumpkin skins are relatively soft at harvest but harden during storage. This 'curing' of the outer skin helps prevent later deterioration. It is not recommended to cool pumpkins until their skins have hardened.
- Careful handling and packing is important to avoid damaging fresh pumpkins. A common issue is 'headstock damage' caused by the cut stem of one pumpkin puncturing the skin of another.

- Pumpkins are best stored at ambient temperatures less than 25°C. Undamaged pumpkins can be stored in good condition for 2 to 3 months at 20°C with 70-80% RH. Longer storage times can result in flesh becoming dry and fibrous. High RH increases disease.
- Pumpkins may lose 2–4% of their initial weight while the skins are curing and hardening. After curing pumpkins lose little additional weight.
- Brown etch (*Fusarium solani*) and ground spots both cause superficial discolouration of pumpkin skin. Eating quality is usually unaffected.
- Postharvest diseases affecting pumpkin include fruit rots (*Rhizopus* spp., *Fusarium* spp.) and bacterial soft rots.
- Sunburn causes bleached areas that may be susceptible to disease.

Brown etch

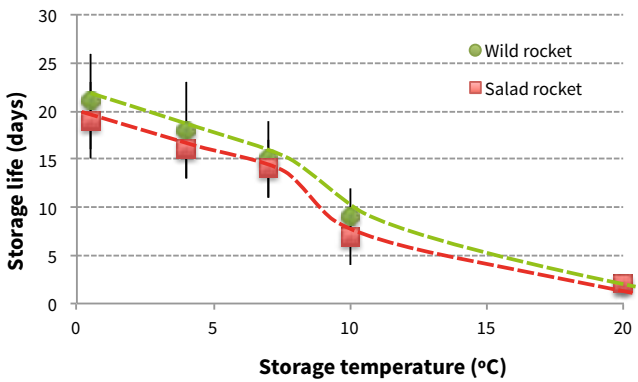
Soft rots caused by *Rhizopus stolonifer* (left) and *Fusarium* spp (right)

19 Rocket

Wild rocket
Diplotaxis tenuifolia

Salad rocket
Eruca sativa

- Although somewhat similar in appearance and flavour, wild rocket and salad rocket are unrelated species.
  - Wild rocket is a perennial plant while salad rocket is an annual.
  - Wild rocket does not grow as fast as salad rocket. However, wild rocket re-shoots after cutting, making it suitable for multiple harvests; salad rocket can yield a second, smaller harvest but then needs to be re-sown.
  - Both wild rocket and salad rocket can be mechanically harvested for use in bagged salads. Salad rocket is also sold as whole plant in bunches.



Storage life of wild rocket (Diplotaxis tenuifolia) and salad rocket (*Eruca sativa*) at different temperatures. Bars indicate the likely variability around each mean value.

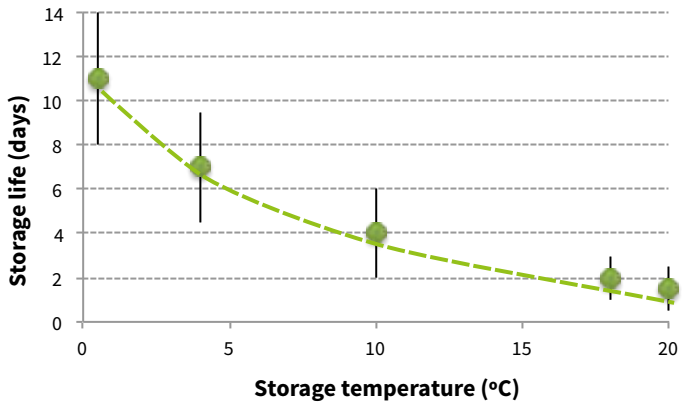
- Immature or ‘baby-leaf’ products such as wild and salad rocket are extremely perishable, having high rates of respiration and little resistance to water loss.
- Harvesting should occur when rocket is cool and fully hydrated but dry. This is likely to be early morning during spring or summer but may be any time of day during winter.
- Rocket is usually mechanically harvested then processed through a series of washes and inspections.
- Cooling rocket as soon as possible after harvest will minimise rots and yellowing.
- Storage life is maximized at close to 0°C with >95%RH. Wild rocket has a slightly shorter storage life than salad rocket. However, both remain acceptable for approximately 2 weeks at 4°C.
- Storage life does not vary greatly between cultivars and is unaffected by the level of N fertilisation before harvest (unlike some leafy crops).
- Storage life of wild rocket is greatest in summer, whereas salad rocket has maximum storage life when grown during winter.
- Rocket produces minimal ethylene but is very ethylene sensitive. Exposure accelerates leaf yellowing.
- Downy mildew (*Peronospora* sp.) is a pre-harvest disease of rocket, however symptoms can become more obvious following harvest and washing. Bacterial rots are a major cause of postharvest loss.

Downy mildew on stored rocket

20 Silverbeet

Beta vulgaris

- Silverbeet is usually harvested when the outer leaves are at least 30cm long. Leaves should be dark green and glossy with bright white (or coloured) mid-ribs.
- The whole plant is usually harvested by cutting at the base with a sharp knife. Alternatively, pulling off the outer leaves leaving the inner shoots intact allows multiple harvests from a crop.
- Leaves are made into bunches >35cm long and 8–10cm width where banded, usually weighing between 800–1,200g.
- Silverbeet contains 92% water and is very susceptible to moisture loss. Silverbeet should be harvested when plants are fully hydrated and cool, such as early morning. Freshly harvested bunches must be protected from wind and sun eg by placing damp hessian on bins.
- Bunches should be cooled as soon as possible after harvest. Hydro-vacuum cooling is highly suitable. Forced air-cooling is also suitable so long as humidity is kept high. Storage life is maximized at close to 0°C and >95%RH.



Silverbeet storage life at different temperatures. Bars indicate the likely variability around each mean value. Data compiled from original research and published literature.

- No washing is needed if silverbeet is picked clean. If washed, bunches can be left slightly wet at packing.
- Firm leaf stems reduce postharvest wilting. Side dressing with sulfate of potash during production has been reported to increase stem firmness and storage life.
- Silverbeet can lose 3–6% moisture before it becomes obviously wilted and unacceptable. Plastic sleeves reduce moisture loss and wilting during transport and retail.
- Ethylene production by silverbeet is very low, however sensitivity is high. Exposure results in leaf yellowing and rapid deterioration.
- Cercospora leaf spot (*Cercospora* spp.) and anthracnose (*Colletotrichum dematium*) are the major diseases affecting silverbeet. Boron deficiency can result in brown lesions on the mid-ribs.

Anthracnose (Photo: L Tesoriero)

Cercospora spot

21 Sweet corn

Zea mays

- Sweet corn kernels are developing seeds. They are high in starch and sugar, but have a high respiration rate. Cobs are harvested when the pollination silks have dried, husks are green and tight and cob diameter has maximized. Mature kernels are plump, releasing milky liquid when squeezed. Immature kernels contain clearer liquid.
- Moisture content of the kernels is generally 75–85% at harvest. Higher and lower moisture contents indicate cobs are immature or over-mature respectively. Over-mature kernels develop sunken ends called 'dimpling'.

Dimpling of kernels due to overmaturity at harvest (Photo: QDAF)

- Sweetness is a key quality factor. At harvest, sweet corn generally contains around 6–12% sugar, most of which is sucrose.
- Sugars in fruit are usually estimated using a refractometer to measure total soluble solids (TSS or °Brix) in the juice. This method is not suitable for sweet corn as the kernel 'milk' contains large amounts of non-sugar compounds.
- Sweet corn should ideally be harvested during cool conditions, such as night or early morning. However, it is often necessarily harvested during warm-hot conditions (>27°C). At these temperatures sugars decrease extremely quickly. Sugar is lost 4x faster at 10°C and 10x faster at 30°C than at 0°C.

- Cooling within 1 hour of harvest slows loss of sugars, retaining flavour during storage. Storage life is optimised at close to 0°C.
- Hydro-vacuum cooling and hydrocooling are both suitable for sweet corn. Hydro-vacuum cooling can reduce temperature from 30°C to 5°C within 20–40 minutes. Hydrocooling by drenching or immersion is slower, taking up to 1 hour to thoroughly cool sweet corn. Forced air-cooling can be used by smaller operations.
- Sweet corn is traditionally sold whole in the husk, simply trimmed of excess leaf. Husks protect the kernels but dehydrate the cobs during storage.
- Increasingly, corn is sold trimmed and partly de-husked in multi-packs. Combined with rapid cooling and good temperature control, this maximizes storage life.
- Sweet corn produces only trace ethylene and is relatively ethylene insensitive.
- Fusarium cob rot can be a postharvest issue with sweet corn.

Fusarium cob rot.

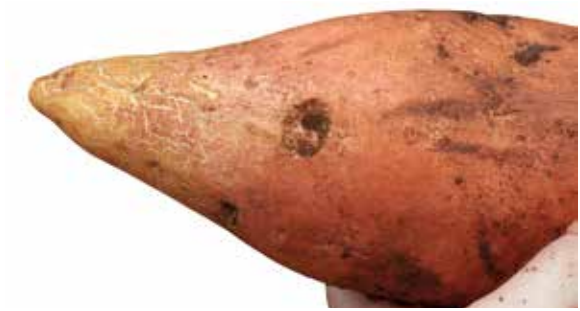
22 Sweetpotato (kumara)

Ipomea batatas

- A storage root, sweetpotato is high in starch and sugars. There are many varieties, with flesh colour ranging from purple to white and dark orange. These can be divided into sweet, dessert types and high starch, staple types.
- Sweetpotato does not have a defined maturity stage. The roots are harvested once many reach marketable size.
- The roots have a thin skin and are easily damaged, so must be harvested by hand.
- In Australia, sweetpotato is marketed as a fresh vegetable. The harvested roots are washed in a two stage (or more) process. The final wash should include a sanitiser.
- Sweetpotato should be cooled to 16-18°C after washing and packing. Forced air-cooling is energy efficient and ensures even cooling through the pallet.
- Fresh, washed sweetpotato can remain in good condition for approximately 1–2 months at 16–18°C and 80–90% RH. If sweetpotato is to be stored for a longer period then roots should be left dirty, as wet roots are more likely to rot.
- In the USA sweetpotato is left dirty and 'cured' at approximately 30°C with 90-95% RH for 4-6 days after harvest. This allows healing of harvest injuries and reduces chilling sensitivity. Cured sweetpotato can be stored at 13°C for up to 1 year.

Rhizopus rot

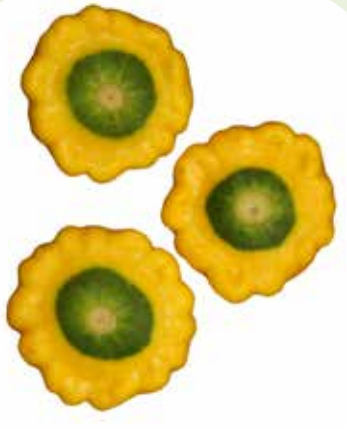
- Postharvest diseases affecting sweetpotato include bacterial soft rots, root rot (*Fusarium* spp.) and storage rot (*Rhizopus* spp.).
- Sunburn causes cracked, bleached areas on roots. Other disorders include alligator skin, corky root (swollen lenticels), 'veins' on roots, growth cracks and sprouting.



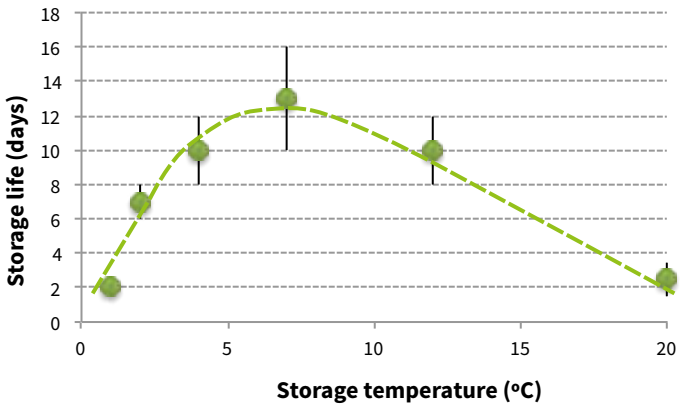
Clockwise from top: Sunburn, sprouting and corky root.

23 Zucchini and summer squash

Cucurbita pepo

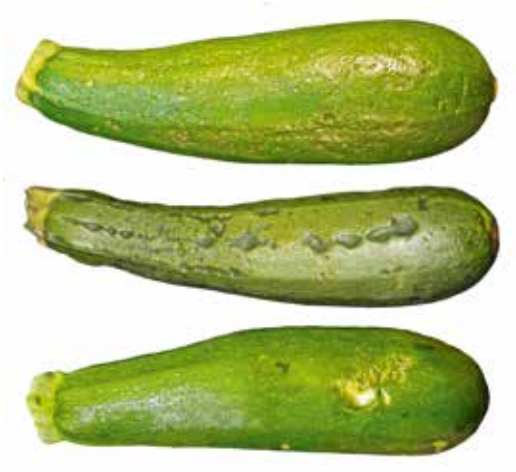


- Zucchini and other squash are immature fruit. They are growing and developing rapidly at harvest, so deteriorate rapidly if not managed well.
- Harvests must be conducted regularly (often every 2–3 days) to pick fruit while still young and tender. Zucchini >250mm long and squash >70mm diameter are considered overmature.
- Zucchini have a thin, glossy skin, so are easily damaged if not handled carefully. Harvesting while wet can reduce skin scuffing but may increase disease.
- The storage life of zucchini and other summer squash is maximised at 6–10°C. Optimum temperature depends on growing environment and variety.
- All summer squash are chilling sensitive, so cannot be stored below 5°C for more than a few days. Symptoms include shallow pitting, deeper connecting pitting, and detachment of the skin from the underlying flesh.



Storage life of zucchini at different temperatures. Bars indicate the likely variability around each mean value.

- Chilling sensitivity of zucchini can be reduced by keeping fruit at 12–20°C for at least a day after harvest. The temperature can then be reduced to 6–8°C for storage and transport.
- Zucchini and squash are susceptible to moisture loss. They can lose up to 7% weight and remain acceptable.
- Zucchini are moderately sensitive to ethylene, which causes premature yellowing.
- Postharvest diseases affecting zucchini and squash include grey mould (*Botrytis cinerea*), cottony leak (*Pythium* spp.) and storage rot (*Rhizopus* spp).
- Poor pollination and physical damage (wind rub) early in development result in misshapen fruit.



Symptoms of chiling injury include (from top) shallow pitting, deep pitting and detachment of the skin.

Grey mould

Section 3
Summary tables

1 Storage temperatures

	Best storage conditions			At 5°C
	Temperature (°C)	Relative humidity (%)	Storage-life*	Estimated storage life**
Asian leafy – buk choy	2	95–100	3 weeks	2–3 weeks
Asian leafy – choy sum	2	95–100	3 weeks	10–14 days
Asian leafy – gai lan	2	95–100	2 weeks	7–10 days
Asian leafy – pak choy	2	95–100	3 weeks	10–14 days
Asian leafy – wombok	0	95–100	3 months	3–6 weeks
Baby spinach	2	95–100	3 weeks	2–3 weeks
Beans	7–10	90–95	7–12 days	6–8 days
Broccoli	0	95–100	6 weeks	2-3 weeks
Brussels sprout	0	95–100	4 weeks	1-3 weeks
Cabbage	0	95–100	8 weeks	2–3 weeks
Capsicum – green	2–5	90–95	2–3 weeks	2–3 weeks
Capsicum – red	1–4	90–95	3–4 weeks	2–3 weeks
Carrot	0	95–100	6 weeks	2–3 weeks
Cauliflower	0	95–100	3 weeks	7–12 days
Celery	2	95–100	6 weeks	2–4 weeks
Cucumber – green field	6–9	90–95	2–4 weeks	2–3 weeks
Cucumber – Lebanese	10–12	90–95	10–16 days	5–10 days
Eggplant	10–14	90–95	10–16 days	6–12 days
Green onions	0	95-100	3 weeks	2–3 weeks
Kale	0	95-100	3 weeks	7–10 days
Leek	0	95–100	12 weeks	3–4 weeks
Lettuce – hearting	2	95–100	3 weeks	1–2 weeks
Lettuce – loose leaf	2	95–100	2 weeks	1–2 weeks
Parsnip	0	95–100	6 weeks	2–3 weeks
Pea, edible pod	0	90–95	3 weeks	2–3 weeks
Pumpkin	20	70-80	2–3 months	2–3 weeks
Rocket	2	95–100	3 weeks	2–3 weeks
Silverbeet	0	95-100	2 weeks	7–10 days
Squash (pattypan)	8–10	90–95	8–12 days	6–10 days
Sweet corn	0	95–100	2 weeks	3–5 days
Sweetpotato	16–18	80–90	2 months	7–10 days
Zucchini	6–10	90–95	10–16 days	8–12 days

* Storage life is likely to vary significantly according to cultivar, growing conditions, harvest and postharvest management. Values are guides only; representing the average time product is likely to remain commercially acceptable and saleable.

** Storage life at 5°C has been estimated as a range using available data.

2 Cooling methods

	Room cooling	Hydrocooling (immersion)	Forced air cooling	Hydro-vacuum cooling
Asian leafy – buk choy		✔	✔	✔✔
Asian leafy – choy sum		✔	✔	✔✔
Asian leafy – gai lan		✔	✔	✔✔
Asian leafy – pak choy		✔	✔	✔✔
Asian leafy – wombok		✔	✔	✔✔
Baby spinach		✔✔	✔	✔
Beans	✔	✔✔	✔✔	✔
Broccoli		✔	✔	✔✔
Brussels sprout		✔	✔	✔✔
Cabbage	✔	✗	✔	
Capsicum – green	✔	✗	✔✔	✗
Capsicum – red	✔	✗	✔✔	✗
Carrot		✔✔	✔	
Cauliflower		✔	✔	✔
Celery		✔	✔	✔✔
Cucumber – green field	✔		✔	
Cucumber – Lebanese	✔		✔	
Eggplant	✔		✔	
Green onions		✔	✔	✔
Kale			✔	✔✔
Leek	✔		✔	
Lettuce – hearting		✗	✔	✔✔
Lettuce – loose leaf		✗	✔	✔✔
Parsnip		✔✔	✔	
Pea, edible pod	✔	✔	✔✔	✔
Pumpkin	✔	✗		✗
Rocket		✔	✔	✔✔
Silverbeet		✔	✔	✔✔
Squash (pattypan)	✔		✔✔	
Sweet corn		✔	✔	✔✔
Sweetpotato	✔✔			✗
Zucchini	✔		✔✔	

KEY; ✔ = Suitable, ✔✔ = Very suitable, ✗ = Unsuitable

3 Nutritional composition

	Content in 100g fresh vegetable					
	Moisture content (%)	Energy (kJ)	Protein (g)	Carbohydrates (total, g)	Sugars (g)	Dietary fibre (g)
Asian leafy – buk choy	96	81	2.6	0.6	0.6	2.4
Asian leafy – choy sum	94	71	1.3	0.9	0.8	2.8
Asian leafy – gai lan	94	92	1.1	3.8	0.8	2.5
Asian leafy – pak choy	95	54	1.5	2.2	1.2	1.0
Asian leafy – wombok	95	44	1.1	0.9	0.9	1.1
Baby spinach	92	101	2.6	0.7	0.7	4.1
Beans	90	122	2.4	2.7	1.3	3.1
Broccoli	91	124	4.4	0.4	0.4	3.6
Brussels sprout	86	150	3.8	2.1	2.1	4.5
Cabbage	92	109	1.6	3.4	3.4	2.7
Capsicum	92	106	1.5	3.5	3.5	1.8
Carrot	88	132	0.8	5	5	3.9
Cauliflower	92	99	2.1	1.9	1.9	2.7
Celery	95	64	0.6	2.3	1.2	1.5
Cucumber – green field	96	50	0.8	1.2	1.2	1.4
Eggplant	92	89	1	2.4	2.4	2.5
Green onions	90	104	1.6	3.2	3.2	1.9
Kale	85	205	4.3	8.8	2.3	3.6
Lettuce – hearting	95	64	1.3	1.1	1.1	1.4
Lettuce – loose leaf	95	40	1	0.4	0.4	1.5
Parsnip	80	241	1.8	10.2	4.9	3.6
Pea, edible pod	79	151	2.9	4.5	2.8	2.6
Pumpkin	92	186	1.4	8.1	6.1	2.6
Rocket	92	105	2.6	3.7	2.0	1.6
Silverbeet	92	70	1.6	1.1	1.1	1.9
Sweet corn	76	297	1.9	14.1	6.5	3
Sweetpotato	73	395	3.9	12.5	3.7	5.6
Zucchini	94	61	0.8	1.6	1.6	1.2

4 Physiology

	Respiration rate*	Ethylene production**	Ethylene sensitivity***
Asian leafy – buk choy	Moderate	Moderate	Moderate
Asian leafy – choy sum	Moderate	Moderate	Moderate
Asian leafy – gai lan	Moderate	Moderate	Moderate
Asian leafy – pak choy	Moderate	Moderate	Moderate
Asian leafy – wombok	Moderate	Moderate	High
Baby spinach	High	Low	High
Beans	High	Low	Moderate
Broccoli	High	Low	High
Brussels sprout	High	Moderate	High
Cabbage	Low	Low	High
Capsicum – green	Low	Low	Low
Capsicum – red	Low	Low	Low
Carrot	Moderate	Low	High
Cauliflower	Moderate	Low	High
Celery	Low	Low	Low
Cucumber – green field	Low	Moderate	High
Cucumber – Lebanese	Moderate	Moderate	High
Eggplant	Moderate	Moderate	Moderate
Green onions	Moderate	Low	Low
Kale	High	Low	High
Leek	Moderate	Low	Low
Lettuce – hearting	Moderate	Low	High
Lettuce – loose leaf	Moderate	Low	Moderate
Parsnip	Moderate	Low	Moderate
Pea, edible pod	Very high	Low	Moderate
Pumpkin	Low	Moderate	Moderate
Rocket	Very high	Low	High
Silverbeet	Moderate	Low	High
Squash (pattypan)	Moderate	Moderate	Low
Sweet corn	Very high	Low	Low
Sweetpotato	Low	Low	Low
Zucchini	Moderate	Moderate	Moderate

* Respiration rate at 5°C. Low = <5ml.kg^{-1}.h^{-1}; Moderate = 5–15ml.kg^{-1}.h^{-1}; High = 15–30ml.kg^{-1}.h^{-1}; Very high = >30ml.kg^{-1}.h^{-1}

** Ethylene production at 20°C. Low = <0.1µl.kg^{-1}.h^{-1}; Moderate = 0.1^{-1}.0µl.kg^{-1}.h^{-1}; High = >1.0µl.kg^{-1}.h^{-1}

*** Ethylene sensitivity. Low = not considered ethylene sensitive. Moderate = some damage may occur with prolonged exposure. High = damaged significantly by short exposure / low levels of ethylene.

Note that respiration rate is highly variable and is strongly affected by variety and growing conditions.

Data sourced from the UC Davis postharvest technology database, USDA ARS Handbook 66, and the scientific literature.

5 Cold sensitivity

	Freezing point (°C)	Susceptibility to freezing	Chilling sensitivity	Display on ice?
Asian leafy – buk choy	-0.2	High	–	✔
Asian leafy – choy sum	-0.2	High	–	✔
Asian leafy – gai lan	-0.2	High	–	✔
Asian leafy – pak choy	-0.2	High	–	✔
Asian leafy – wombok	-0.9	Moderate	Low	✔
Baby spinach	-0.3	High	–	✖
Beans	-0.5	High	High	✖
Broccoli	-0.6	Moderate	–	✔
Brussels sprout	-0.8	Low	–	✔
Cabbage	-0.9	Low	–	✔
Capsicum – green	-0.7	Moderate	Moderate	✖
Capsicum – red	-0.7	Moderate	Low	✖
Carrot	-1.4	Low	–	✔
Cauliflower	-0.8	Moderate	–	✔
Celery	-0.5	High	–	✔
Cucumber – green field	-0.5	Moderate	High	✖
Cucumber – Lebanese	-0.5	Moderate	High	✖
Eggplant	-0.8	Moderate	High	✖
Green onions	-0.7	Moderate	–	✔
Kale	-0.5	High	–	✔
Leek	-0.9	Low	–	✔
Lettuce – hearting	-0.2	High	–	✔
Lettuce – loose leaf	-0.2	High	–	✖
Parsnip	-0.9	Low	–	✔
Pea, edible pod	-0.6	Moderate	–	✔
Pumpkin	-0.8	Low	Moderate	✖
Rocket	-0.2	High	–	✖
Silverbeet	-0.8	Moderate	–	✔
Squash (pattypan)	-0.5	Moderate	High	✖
Sweet corn	-0.6	Moderate	–	✔
Sweetpotato	-1.3	Low	High	✖
Zucchini	-0.5	Moderate	High	✖

6 Display considerations

	Rate of water loss*	Benefit of point of sale packaging **
Asian leafy – buk choy	Very high	High
Asian leafy – choy sum	Very high	High
Asian leafy – gai lan	Very high	High
Asian leafy – pak choy	Very high	High
Asian leafy – wombok	High	Moderate
Baby spinach	Very high	Very high
Beans	High	High
Broccoli	Very high	Moderate
Brussels sprout	High	Moderate
Cabbage	Low	Low
Capsicum – green	Low	Low
Capsicum – red	Low	Low
Carrot	Very high	High
Cauliflower	Moderate	Moderate
Celery	Moderate	High
Cucumber – green field	Low	Low
Cucumber – Lebanese	Moderate	High
Eggplant	Low	Low
Green onions	High	Moderate
Kale	Very high	High
Leek	Moderate	Low
Lettuce – hearting	Moderate	Moderate
Lettuce – loose leaf	Very high	High
Parsnip	Very high	High
Pea, edible pod	High	Moderate
Pumpkin	Low	Low
Rocket	Very high	Very high
Silverbeet	Very high	High
Squash (pattypan)	Moderate	Moderate
Sweet corn (de-husked)	High	Very high
Sweetpotato	Low	Low
Zucchini	Moderate	Moderate

* Rate of water loss indicates the approximate rate of moisture loss (% initial weight per day) for unprotected product at 5°C + 80% RH, based on storage trial data.

Low = <0.7% /day; Moderate = 0.7 to 1.2%. /day; High = 1.2 to 1.6%. /day; Very high = >1.6%. /day.

** Benefit of POS packaging is defined as the potential extension of the time product can be displayed at ambient temperatures without major quality loss (shelf life).

- Low = little or no benefit;
- Moderate = shelf life slightly increased to doubled;
- High = shelf life approximately tripled;
- Very high = shelf life more than tripled.