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Maintaining the post-harvest quality of fruits and vegetables

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7.1 Introduction

To achieve a high quality processed product, it is important that the raw materials used in the product are also of high quality. This chapter focuses on maintaining fresh produce quality prior to its processing. It assumes that the produce has been selected on the grounds of suitability for end-use and presents an overview of how the harvest quality may be maintained up to the point of processing or consumption.

In section 7.2 the author identifies appearance, texture and flavour as the qualities which are most likely to be key to acceptability of produce whether consumed fresh or processed. The factors that influence quality deterioration in fresh produce are then explored in sections 7.3–7.6. The tissues of fruits and vegetables remain alive after harvest. They eventually die through natural senescence, rotting or when they are consumed, cooked or similarly processed. All living tissues respire and the consequences of this are quite profound for the maintenance of quality and maximisation of shelf-life of these products. Factors that slow respiration can slow senescence and maintain quality; however, some respiration must continue or the products will rapidly senesce and die. Cooling the produce can slow many undesirable changes in fruits and vegetables but many fresh commodities are intolerant of low temperatures. Thus understanding the physiology of fresh produce is fundamental to understanding their stability and likely shelf-life.

It would be a great advantage to managing fresh produce quality if the shelf-life of a product could be accurately predicted. In practice the variability inherent in fresh fruits and vegetables makes this very difficult. In section 7.7 the commercial application of shelf-life testing for fruits and vegetables and its rationale is discussed. The methods in common use for measuring fresh produce quality are reviewed.

The demand for all-year-round supplies at ever-higher quality standards by both the processing industry and retail sector is driving the development of new technical and managerial strategies. Although refrigeration throughout the cool-chain is likely to remain the most important technology for maintaining product quality, a broader range of approaches are increasingly in use, such as modified atmospheres during transport, storage and in individual produce packages. In sections 7.8–7.12 the broad range of post-harvest technologies used to maintain quality and extend shelf-life of fresh fruits and vegetables are briefly reviewed. Finally in section 7.13 some technologies that are likely to become available or of increasing importance to the fresh produce industry in the near future are suggested. One clear trend is that more fresh produce will be consumed in a minimally processed form, that is partially or fully prepared for consumption. The shelf-life of these products is often much reduced compared to that of the intact product. Non-destructive, on-line quality testing, the expansion of non-chemical control of fresh produce diseases and disorders and the availability of genetically modified crops are predicted by the author to have the most influence in quality management in the coming years.

7.2 Quality criteria for fresh produce: appearance, texture, flavour and aroma

7.2.1 Introduction

The specific qualities required in fruits and vegetables will depend on their end-use and the selection of appropriate cultivars for particular products is of paramount importance. The quality of an individual product is also affected by its specific preharvest 'experience'. So, for example, the position of a fruit on the tree will determine its nutrient and water status and its exposure to environmental factors such as sunlight or pests and diseases. All these factors may ultimately influence post-harvest shelf-life (Hofman and Smith, 1994; Sharples, 1984). Experience may enable those who regularly handle certain produce types to predict variations in shelf-life of produce from different sources, for example, based on soil type or weather factors before and during harvest.

Fresh fruits and vegetables are not considered to be high-risk products with respect to food safety as they normally become completely undesirable for consumption long before any hazardous microorganisms or toxins might develop. There is, however, evidence that sealing fresh vegetables in modified atmosphere packaging may extend shelf-life, while still allowing the growth of pathogenic bacteria, in particular *Listeria* spp and *Escherichia coli* O157 (Phillips, 1996). For most fresh produce, shelf-life is best defined as the period within which the product retains acceptable quality for sale to the processor or consumer. It is necessary, therefore, to identify what 'acceptable quality' means before it can be decided at what point the product no longer satisfies those expectations.

For the fresh produce market, specific minimum quality standards exist in many countries; however, owing to the international nature of the fresh produce

market, there is a trend towards international standardisation of quality grades. The European Commission was one of the first organisations to develop international standards for fresh fruits and vegetables (MAFF, 1996a–c). Many of these standards have been adopted by the Organisation for Economic Cooperation and Development (OECD). Usually, standards required for multiple retail outlets are considerably more stringent than these minimum standards and will be defined for the supplier by the retailer. Providing the quality standards have been met, the factors which limit storage and shelf-life fall into the following categories: appearance, texture and flavour/aroma. With respect to the processing industry, each company will have its own carefully defined quality criteria based on the nature of the processing undertaken. These criteria will be agreed in advance with the supplier.

7.2.2 Appearance

Appearance is the key factor for consumers in making purchases of fresh produce. As the multiple retail sector has come to dominate food retailing in many countries, consumers have come to expect fresh produce to have near perfect visual appearance. Displays of fruits and vegetables are characterised by uniformity of size, shape and colour. Vital components of visual quality include colour and colour uniformity, glossiness, and absence of defects in shape or skin finish and freedom from disease.

The importance of appearance in the processing industry will depend on which part of the produce is used in the product and whether the appearance can readily be enhanced during processing, for example by the use of natural colouring additives. In most products, the peel will be removed from the produce, so purely surface blemishes will be of little consequence. Internal flesh colour is usually more important than peel colour. Size and shape may be highly important where processing is automated rather than manual; however, for some products these attributes are less important, for example for juice extraction.

Many fruits and vegetables undergo colour changes as part of the ripening process. Unripe fruit is usually green (the so-called ‘ground colour’) and in many types of fruit, the green colour becomes lighter during ripening and maturation owing to breakdown of chlorophyll, for example in apples, grapes, papaya. This may reveal underlying yellow or red pigments (Tucker, 1993). Peel and pulp often undergo different colour changes, as in apples and bananas. In some cases, fruit colour is a strong indicator of eating quality and shelf-life, for example, tomatoes and bananas, whereas in others it is not. Many pre-harvest factors can affect fruit colour independently of other ripeness characteristics. So, for example, the peel of oranges grown in tropical regions may remain green despite having attained acceptable eating quality. Yellowing of green vegetables such as broccoli and spinach will reduce their quality as may browning of cut tissues, for example butt-ends of Brussels sprouts. Other aspects of appearance which reduce quality include the loss of freshness, like the wilting of leafy crops, loss of surface gloss or skin wrinkling and the development of external and internal defects

caused either by natural senescence, physiological disorders or the growth of disease organisms.

7.2.3 Texture

Eating quality includes a complex of textural properties which are not readily defined or measured. Crisp firm tissues are generally desired in vegetable crops; however, the development of tough fibres during storage in stem crops such as asparagus is not at all acceptable. Some aspects of texture can be judged visually as described above, for example, where produce has begun to wilt or shrivel. Although some degree of softening is required for optimal quality in fruit, over-softening is undesirable and is a sign of senescence or internal decay. The maintenance of textural quality is often critical in certain types of processing, for example in canning and freezing.

7.2.4 Flavour and aroma

Flavour is a complex of taste and aromatic components. Total flavour can rarely be assessed by the consumer prior to purchase but it is critical in the repeat purchase of a particular product or product cultivar. Key taste components in fresh produce are sweetness, acidity, astringency and bitterness. Sweetness of some fruits may increase dramatically during ripening owing to starch to sugar conversions, for example in apples, bananas, mangoes and pears. At the same time, astringent factors (tannins) will disappear (Tucker, 1993). Sugar levels of fruits are often measured to determine whether produce has reached the required ripeness for marketing. Sugar levels do not usually fall significantly during storage; however, maintaining the sugar to acid balance can be important to the fruit flavour balance, for example, in citrus species and grapes. Acid levels generally decrease during storage. If the acid/sugar ratio falls too low, the product can become bland and lose acceptable eating quality. This will also be of importance in processed products in which extra sugars or acids are not added. Bitter components can develop in various fruits and vegetables under certain storage conditions (see physiological disorders in section 7.6.1) or when infected with certain pathogens.

Aroma can be determined to some extent before purchase by the consumer but it tends to be important as a positive factor only in highly aromatic products such as certain cultivars of melons or mangoes. With the emphasis on visual quality which has dominated retailing, it has been claimed that flavour and aroma have been lost from many fresh products as breeding has concentrated on cultivars which will survive the rigours of post-harvest handling without loss of visual and textural quality. Refrigeration also tends to limit the development of aroma volatiles in ripening fruits. The aroma profile can change dramatically during the post-harvest life of fresh produce, particularly in climacteric fruits in which the dominant volatile may be quite different in the unripe fruit, the ripe fruit and the over-ripe or senescing fruit (Morton and Macleod, 1990). Unpleasant aromas

may develop from a number of causes described in later sections (7.3.2 and 7.5). An unexpected or unpleasant aroma may make a product unmarketable even if all other quality factors are quite acceptable. Therefore aroma can be an important factor in the storage and shelf-life of fresh produce.

7.3 Quality deterioration of fresh produce: respiration, ethylene, senescence and breaking of dormancy

7.3.1 Introduction

Many factors can lead to loss of quality in fresh produce, hence the common description of these products as 'perishable'. Some of these factors are part of the life cycle of living produce, that is, over-ripening of fruits or sprouting in root and bulb crops. Others are a consequence of the act of harvesting. Once severed from the mother plant, the plant organ is deprived of its source of water, nutrients and antisenescent hormones. As a consequence normal factors such as transpiration and respiration lead ultimately to water loss and senescence of the product. The growth of pathogens or physical damage will cause direct loss of product quality through their visual impact but both also stimulate senescence. Furthermore, the storage environment will play a highly significant role in determining the speed of all quality changes.

7.3.2 Respiration

Fruits and vegetables are living commodities and their rate of respiration is of key importance to maintenance of quality. It has been commonly observed that the greater the respiration rate of a product, the shorter the shelf-life. Immature products such as peas and beans tend to have much higher respiration rates and short shelf-lives caused by natural senescence whereas the opposite is true for mature storage organs such as potatoes and onions.

Respiration is the metabolic process by which cells convert energy from one type of chemical structure into another form more useful to the cell for driving metabolic reactions. Under normal circumstances, fresh produce undergoes aerobic respiration, during which oxygen and glucose is consumed while carbon dioxide, water and heat are produced (Kays, 1991). In non-storage tissues, for example in leafy crops such as lettuce or spinach or immature flower crops such as broccoli, there is little by way of energy reserves and hence excessive respiration will eventually lead to metabolic collapse. Cell membranes will break down and allow the contents to leak out. Saprophytic bacteria may grow in these tissues and give rise to off-odours. Visible symptoms of tissue collapse and yellowing caused by senescence breakdown of chlorophyll in the chloroplasts may appear. Without adequate cooling, respiratory heat will further stimulate respiration leading to even more rapid deterioration.

Certain types of fruits (known as climacteric) can be harvested unripe and ripened artificially at a later stage (e.g. avocados, bananas, mangoes, tomatoes).

During ripening, the respiration of these fruits increases dramatically over a short period of time (Biale, 1960). Without careful temperature control, the fruit will rapidly over-ripen and senesce leading to internal tissue breakdown and the production of volatiles characteristic of the over-ripe fruit. Failure to control respiratory heat also can increase water loss from the produce. Furthermore, the increased warmth and moisture levels, which can develop in storage, are highly conducive for the development of bacterial and fungal infections.

7.3.3 Ethylene

Ethylene is a plant hormone that plays a key role in the ripening and senescence of fruits and vegetables (Reid, 1992). All plant cells produce low levels of ethylene; however, anything that causes stress to the plant tissues will stimulate ethylene synthesis. Stressors may include excessive water loss, physical damage or pathogenic attack. Climacteric fruits produce high levels of ethylene during initiation of ripening and the hormone is believed to stimulate and coordinate the physiological and biochemical changes which occur during ripening. Exposure to exogenous ethylene can lead to an acceleration of maturation and senescence, for example, green vegetables lose their chlorophyll more rapidly, thickened fibres can develop in asparagus, premature ripening can occur in unripe fruits and cabbages and cauliflowers can lose their leaves through accelerated leaf abscission.

7.3.4 Senescence

Senescence is the natural ageing of the plant tissues and is stimulated by the presence of ethylene and anything else that speeds up respiration rates as described above. Senescence ultimately affects all aspects of quality, ending in the death of the product. Some senescence changes can specifically affect certain types of fresh produce processing, for example, changes to the chemical and physical structure of the cell wall (Jimenez *et al*., 1997). Although in fresh produce, texture is highly dependent on cell turgor (see section 7.4 below), the integrity of the cell wall is important to the texture of some processed products (Femenia *et al*., 1998). In some fruits and vegetables (e.g. apples and tomatoes), the breakdown of intercellular adhesion between cells leads to a condition known as mealiness which is generally perceived as a loss in textural quality (Van der Valk and Donkers, 1994). In potatoes, so-called senescence sweetening is where, over time, storage starch is gradually converted to sugars. Concentrations of reducing sugars of greater than 0.1% in potato tissues being processed into chips and crisps can lead to browning or blackening of the product during the cooking process (Van der Plas, 1987).

7.3.5 Breaking of dormancy

Root, tuber and bulb crops have a natural dormancy period that can be considerably extended under suitable storage conditions. Storage and shelf-life is often

limited by the breaking of dormancy. Most commonly this is seen as the growth of sprouts, for example, in onions or potatoes. Under high moisture conditions, the development of roots may also occur. Neither sprouts nor roots are acceptable in marketed produce (Schouten, 1987). Although roots and shoots can be trimmed off during processing, the internal quality of the produce generally deteriorates during the breaking of dormancy owing, for example, to the conversion of stored starch into sugars that are transported to the growing points.

7.4 Quality deterioration of fresh produce: water loss

Plant tissues are covered with protective tissues, which serve to protect the plant from insect and pathogen attack, physical injury and excessive water loss. The primary protective layer is the epidermis but if the plant organ undergoes secondary growth, a multilayered periderm may develop, for example, on apples or potatoes. The epidermis is covered with a waxy cuticle of cutin while the cell walls of periderm tissues generally become impregnated with suberin. Both cutin and suberin can reduce water losses from plant surfaces; however some water loss is inevitable. Water vapour can permeate the cuticle and is also lost through lenticels, which are gaps in the periderm which form to enable gas exchange for respiration. If the epidermis or periderm is damaged, water loss can be massively exacerbated.

Mature plant organs such as stems, roots and some fruits develop strengthening tissues such as collenchyma or lignified schlerenchyma to maintain their structure. The presence of tough fibrous components is not, however, desirable in fresh produce, so many vegetable crops are harvested immature. Structure and thus textural properties of fresh produce are almost entirely dependent on the maintenance of adequate cell turgor pressure, that is, the force generated when the solute filled vacuole presses against the relatively inelastic cell wall. If too much water is lost from the tissues, turgor pressure will fall, leading to wilting or shrivelling of the product.

The speed of post-harvest water loss is dependent primarily on the external vapour pressure deficit; however, other factors will influence the situation. Products with a large surface to volume ratio such as leaf crops will lose a greater percentage of their water far quicker than large spherical fruits. The specific structure of the cuticle and the extent of suberisation in the periderm appear to be more important than thickness in improving resistance to the movement of water vapour. Produce varies in the percentage of water which can be lost before quality is markedly reduced. Fruits with thick peels can lose a considerable amount of moisture from the skin without compromising edible quality, for example citrus species, bananas. The appearance of the fruit will, however, deteriorate steadily with increasing water loss. Other thin-skinned fruits are more susceptible to water loss, for example, table grapes (Ben Yehoshua, 1987). Furthermore, dehydration of all products can stimulate the production of ethylene (as described above).

7.5 Quality deterioration of fresh produce: fungal and bacterial pathogens

The most important microorganisms causing post-harvest wastage of fresh produce are fungi. This is particularly true for fruits, where the relatively acid conditions tend to suppress bacterial growth. Vegetables with a higher pH can, however, suffer high losses from bacterial infections. The most important pathogens of fruits and vegetables are described by a number of authors (Beattie *et al*., 1989; Coates *et al*., 1995; Dennis, 1983; Snowdon, 1990; 1991). The majority of pathogens rely on damaged tissues to obtain entry into fresh produce (wounds or sites of physiological injury). For example, the *Penicillium* species which cause blue and green mould infections of citrus and other fruit crops are classic wound pathogens, incapable of invading an undamaged fruit. An intact, fresh commodity is resistant to the majority of potential pathogens. The physical barrier of the skin and the presence of antimicrobial compounds in the skin and flesh are sufficient protection.

Some pathogens can gain entry through natural openings such as stomata and lenticels. Bacteria may use this penetration route. The most common group of bacteria causing significant reductions in shelf-life is the soft rotting species of the genus *Erwinia.* Under suitable conditions of warmth and the presence of free water, the bacteria can readily colonise produce such as potatoes through the lenticels. They produce large quantities of extracellular enzymes which rapidly macerate the tissues. Sometimes, soft rots are accompanied by the growth of saprophytic bacteria which give rise to highly unpleasant off-odours (Lund, 1983).

Only a small number of fungal pathogens are capable of direct penetration of the undamaged skin of the produce. On the whole, these latter pathogens are particularly problematic owing to the fact that they may infect produce before harvest but remain quiescent in the tissues until conditions become favourable for growth. This phenomenon is largely seen in fruits, where initial pathogen development and subsequent quiescence occurs in the unripe fruit. As the fruit ripens, quiescence is broken and the pathogen colonises the fruit tissues (Swinburne, 1983). *Colletotrichum gloeosporioides* is a common pathogen showing this behaviour on a number of tropical fruits such as mango and papaya. Typical symptoms on ripe fruits are sunken, lens-shaped lesions, which may develop salmon-coloured sporing structures. *Colletotrichum musae* causes similar symptoms on bananas. *Botrytis cinerea* may also show quiescent behaviour on certain fruits, for example, in strawberries, fungal spores contaminate the flowers, germinate and the hyphae grow into the developing fruit where they remain symptomless until the fruit is fully ripe. The subsequent disease development can be extremely rapid and the whole fruit is completely colonised and covered with a grey, sporulating mycelium within a few days at 20°C.

Skin diseases may remain superficial but cause large market losses owing to the blemished appearance of the produce. The potato industry has a major problem with a number of skin diseases, such as black scurf (*Rhizoctonia solani*),

black dot (*Colletotrichum coccodes*), silver scurf (*Helminthosporium solani*) and common scab (*Streptomyces scabies*) which can spread rapidly on the tubers after the temperature rises in retail outlets (Snowdon, 1991).

On the whole, fungal and bacterial infections are stimulated under high humidity conditions and in particular in the presence of free water. Pathogens of fruits and vegetables are variable with respect to their ability to grow and reproduce at different temperatures; however, most will grow between 6 and 35°C. Some will survive and even grow slowly at temperatures as low as 1°C, for example, *B. cinerea*. The incidence of particular pathogen species is thus affected by both pre-harvest and post-harvest conditions. So, for example, *B. cinerea* is particularly important on produce grown in cool temperate climates, whereas infections caused by *Botryodiplodia theobromae* or *Aspergillus niger* tend to cause serious losses in warm regions.

Certain pathogens can impact heavily on the fresh produce processing industry: for example, the presence of just a few citrus fruits infected with *Alternaria* rot in a consignment can result in off-flavoured juice (Patrick and Hill, 1959). The presence of certain cell wall degrading enzymes from infecting pathogens, for example *Rhizopus* spp., can cause continuing softening of canned products even after the fungus has been killed during the sterilisation process (Harper *et al*., 1972).

7.6 Quality deterioration of fresh produce: physiological disorders and physical injury

7.6.1 Physiological disorders

Physiological disorders are adverse quality changes that occur in fresh produce because of metabolic disturbances. These disturbances can be caused by internal factors such as mineral imbalances or may be due to non-optimal environmental factors such as inappropriate storage temperatures or atmosphere composition. The symptoms may be unique to a particular condition on a specific produce type; however, in many cases the symptoms are similar in a range of conditions with differing underlying causes. Mild symptoms are often confined to superficial tissues which may not be too significant if the produce is to be processed, but can strongly decrease marketability of the fresh product owing to visual disfigurement. Furthermore, physiological disorders can increase the susceptibility of the commodity to invasion by pathogens. The onset of disorders may be determined by pre-harvest conditions, the cultivar, maturity or stage of ripeness.

Poor nutrition will generally give rise to poor field growth and field symptoms. There are, however, a number of nutritional imbalances, which have no obvious pre-harvest significance but which give rise to symptoms during post-harvest storage. One of the most important nutrients in this respect is calcium which plays an important role in maintaining cell wall stability. A classic example is 'bitter pit' in apples in which hard, sunken brown pits develop both on the skin and internally. Affected tissues have a slightly bitter taste.

There is a wide range of disorders related to exposure of produce to temperatures which are too high or too low. High temperatures caused, for example, by excessive exposure to the sun or inappropriate post-harvest heat treatments, may cause skin damage and uneven fruit ripening. Only a few commodities destined for fresh consumption can survive mild freezing, for example parsnip and onions, however, the majority of fruits and vegetables destined for fresh consumption cannot tolerate any freezing at all. Ice crystals form inside the cells leading to membrane rupture, and the tissue collapses upon defrosting leading to unacceptable textural changes. These changes are less obvious to the consumer in produce with a relatively low water content and/or which will be cooked before consumption, for example, peas, sweet corn, parsnips, potatoes, carrots, broccoli and spinach.

Chilling injury is quite distinct from freezing injury and may occur at temperatures well above freezing point (Saltveit and Morris, 1990). Tropical and subtropical commodities are particularly susceptible although there may be considerable differences in chilling sensitivity between cultivars and between immature and mature or unripe and ripe produce. Symptoms include water soaking, surface pitting, internal discoloration, failure to ripen, accelerated senescence and increased susceptibility to decay. Symptoms may not become obvious until the produce temperature has been raised to non-chilling levels. At temperatures below 8–10°C and maximal at about 2°C, Irish potatoes are susceptible to reversible low temperature sweetening (Burton, 1989). The reducing sugars produced cause problems to the processing sector (see section 7.3.4 above).

If produce is stored in an atmosphere with insufficient oxygen or excessive carbon dioxide, for example in poorly ventilated stores, respiratory disorders can develop. At higher temperatures, the produce respires more quickly so that an unsuitable atmosphere can develop more rapidly. Symptoms depend on the product in question, so for example, potatoes may develop a black centre whereas lettuces may have pale midribs. Some apple cultivars suffer external injury and others develop internal browning owing to excessive carbon dioxide in the tissues. Very low oxygen levels can lead to alcoholic fermentation with accompanying off-odours. Tolerance levels are variable, for example, some apple cultivars tolerate levels less than 1% O_2, whereas sweet potatoes are highly sensitive and fermentation may set in if O_2 levels fall below 8%. Anaerobic conditions will also encourage the growth of soft-rotting bacteria in potatoes.

A range of specific symptoms in stored fruits and vegetables have been attributed to exposure to ethylene (Kader, 1985). Some examples include russet spotting of lettuce (at concentrations >0.1 ppm) which is associated with increased activity of phenylalanine ammonium lyase (PAL) and phenolic content, formation of the toxin pisatin in peas, and production of phenolics in sweet potatoes and in carrots. In carrots, the phenolic isocoumarin gives a bitter flavour and bitter flavours have also been noted in beetroot.

There are also a number of well-defined miscellaneous disorders of certain fresh produce which are beyond the scope of this book. Further information can be found in books by Snowdon (Snowdon, 1990; 1991).

7.6.2 Physical injury

Physical injury is possibly the most important cause of loss in fresh produce. This is not due to the direct losses, although these can be significant in some crops but rather to the indirect effect of creating a wound in the surface of the produce. This wound is an ideal entry point for many post-harvest pathogens as described above. Injury also allows water loss which compromises the quality of the produce. Furthermore, physical injury stimulates ethylene production in plant tissues, which can lead to premature yellowing or ripening of commodities.

Physical injury can arise at any stage of the life of the crop, from insect injuries in the field to poor post-harvest handling. Many fungi invade through the stem end where the produce was severed from the mother plant. Poor packaging can create problems from cuts caused by sharp edges or hard parts of adjacent produce, for example pineapple crowns, to grazes caused by lack of padding or underfilling of cartons allowing movement of produce within the pack during transport and handling. Bruising can occur from dropping or compression bruising can occur if produce is stacked too high or packs are overfilled. Significant levels of wastage occur in the potato industry owing to internal bruising of potato tubers during storage and handling (Balls *et al*., 1982). The shelf-life of many fresh products is considerably reduced by physical damage caused by rough handling at the retail level, particularly where the produce is loose and can be 'picked over' by the potential customer.

7.7 How quality of fruits and vegetables is measured: appearance, texture and flavour

7.7.1 Introduction

To ensure optimal quality of the produce sold for fresh consumption or for processing, it is essential to be able to monitor quality changes during storage. Ideally those who manage the fresh produce chain would also like to be able to predict the likely shelf-life of the produce. Some types of produce may need rapid transport, for example, out of season, highly perishable produce may need to be air freighted rather than carried by ship from overseas. Other products with a longer shelf-life can be stored and released as the market requires.

The commercial measurement of shelf-life of fresh produce is usually carried out by the quality control staff of retail supply companies (importers and distribution centres). It is considered to be part of the due diligence procedure expected by the customer. Samples of product are removed from the packing line and placed in shelf-life rooms at a temperature that roughly reflects the likely retail conditions. The produce will be assessed for quality changes over a period of time which covers the shelf-life period expected by the retailer for a particular product plus a couple of extra days. Commodity specific evaluation sheets will be filled in and archived. Shelf-life tests are used to forewarn of potential quality problems and will enable action to be taken promptly to identify and limit the problem. They provide some comeback to retailers if there is a problem which may have occurred since the

produce left the supplier. For larger organisations who provide particular products all year round, shelf-life testing may reveal temporal patterns in quality, which can be used in decisions such as when to change the supply source.

At the time of writing, accurate prediction of shelf-life is not really feasible for fresh produce. Efforts to try to develop predictive models for produce shelf-life based on both internal quality factors and environmental factors experienced by the produce have been described in the scientific literature (Polderdijk *et al.*, 1993); however, success in this area remains elusive. The difficulty is primarily due to the inherent variability in all the quality factors of fruits and vegetables that might be used to determine shelf-life. Even if the measurement of certain qualities were able to predict shelf-life accurately, individual differences in produce means that, ideally, each individual item would need to be assessed and tests would need to be extremely rapid. At the time of writing, many of the tests in use cause damage to the produce and therefore can only be used on a small sample of the produce.

In many processed products, for example juices, purees and chopped canned or frozen produce, the impact of raw product variability problems can be reduced when the produce is mixed or blended together. However, it is worth emphasising again that top quality products can only be made from top quality raw ingredients, so the ability to measure raw product quality is no less important in the processing industry than the fresh produce sector.

7.7.2 Appearance

Colour

Measurement of colour in horticultural crops is reviewed by Francis (1980). The fresh produce industry uses produce-specific colour matching charts to assist in the grading and shelf-life assessment of many fruits. These charts are cheap and easy to use for training personnel. In larger pack houses, photoelectric techniques may be installed to sort strongly coloured products into at least three grades. For research purposes, colour is generally measured using a surface colour-difference meter (e.g. those manufactured by Minolta or Hunter). This type of instrument measures the characteristics of light reflected from the product surface. The output is processed to give a standard data based on a tristimulus system, for example, numbers for hue, chroma and lightness, which together accurately describe the colour of the object (Minolta Co. Ltd., 1994). The main limitation of this kind of spot colour measurement is the lack of uniformity in the produce itself, for example an apple or mango may be a completely different colour on one side compared to the other.

External and internal defects

The assessment of visual defects such as skin blemishes or greening in root crops is largely carried out by manual operators. Produce may be removed if it has greater than a certain percentage of its surface covered with the blemish in accordance with set quality standards. Some commercial applications of video imaging

techniques (machine vision) exist, for example, some factories use machine vision-based sorting to pick out green, black or unpeeled tubers from potatoes that are due for processing (Clarke, 1996). At the time of writing, the only method in use commercially for determining the presence of internal defects is to cut open samples of produce from each consignment of produce or removed at regular intervals from the pack line, and score the incidence of any discoloration, cavitation or other defects.

7.7.3 Texture

Firmness

The firmness of produce is, in many instances, a fairly good indicator of textural properties and is relatively easy to measure mechanically. Firmness can be assessed visually to some degree, for example whether a product appears shrivelled or flaccid. Resistance to light manual pressure is still a common means of evaluating firmness, although clearly this is highly subjective, with considerable experience required for accurate assessment. The most common method of assessing firmness is with a penetrometer such as the Magness-Taylor firmness tester or the Effegi penetrometer. These measure the total force required to puncture through a given portion of the fruit or vegetable to a standard depth using a standard diameter probe. The test may be carried out through the peel or a portion of the peel may be removed and the flesh firmness only determined. Non-destructive compression testers are also available on the market and can be created simply from penetrometer devices (Macnish *et al*., 1997). Shear instruments are used to measure the tenderness of peas and broadbeans destined for processing, for example, the 'Tenderometer', which uses two sets of hinged grids which simulate the action of chewing jaws (Salunkhe *et al*., 1991).

Firmness can also be assessed using vibration tests. If produce is tapped sharply, sound waves are propagated through its tissues and can be picked up with a microphone or piezoelectric sensor. The characteristics of these sound waves vary depending on the stiffness of the tissues (amongst other factors) and have shown good correlations with fruit firmness. Although the underlying physical principles of these tests have long been understood, it is only relatively recently that the tests are being applied commercially. An Israeli company (Eshet Eilon) is producing a non-destructive bench top firmness tester 'Firmalon' based on acoustic resonance for use with various fruits like apples and pears. (The 'Peleg Firmness Tester' is also available from Technion in Israel.) An on-line acoustic resonance firmness tester 'AvoScan' has been developed by a UK-based machinery company (Sinclair International, Norwich) based on research by Peleg *et al*. (1990). This is being used commercially to categorise fruits such as avocados into separate retail categories (for example 'ready to eat' with an expected short shelf-life).

Other textural factors

In the laboratory, universal testing machines (e.g. those made by Instron) are in common use for evaluating various components of the strength of plant tissues,

which change with storage. For example, mealiness is a textural defect common in some apple and potato varieties as they age. The development of artificial jaws attached to force gauges can simulate bite action and better evaluate textural qualities such as mealiness which limit shelf-life with respect to eating quality. These kinds of measurements are only used for research as suitable commercial applications have not yet been developed.

7.7.4 Flavour

Taste components

Sweetness is an important component of fresh fruit quality and will give a good indication of the state of fruit ripeness and hence potential shelf-life. In the fresh produce sector, sweetness is normally measured in terms of total soluble solids (TSS) content in °Brix. In most fruits and vegetables, sugar makes up the main component of TSS which is thus a reasonable indicator of percentage sugar levels. TSS is measured using a refractometer or a hydrometer. The former instrument operates on the basis of the refraction of light by juice samples and the latter on the basis of the density of the juice. Light reflectance in the near infrared has been correlated successfully with TSS in a number of commodities. This property is being developed as a non-destructive method of measuring sugar levels in crops such as melons.

Acidity is generally measured by titration with a suitable alkaline solution such as sodium hydroxide. Maturity standards for citrus species are based on Brix-to-acid ratios and both TSS and acidity are important measures of table grape quality. There is no rapid objective method for measuring bitterness or other undesirable flavours in fruits and vegetables. Sensory evaluation is the only commercial test used in the fresh produce sector. In the laboratory, bitter or astringent components (generally caused by phenolic compounds) can be extracted and measured by various analytical procedures, for example, high performance liquid chromatography.

Aroma components

The measurement of aroma is currently assessed by the industry on an informal basis, relying on off-odours in shelf-life samples being noted by produce quality managers. Laboratory measurements have traditionally been conducted by head-space analysis using gas chromatography (Wehner and Kohler, 1992). Separated components can be identified objectively (chemically) by various means or subjectively using 'odourmeters'.

Sensory evaluation

There are relatively few instrumental tests which give results which correlate well with consumer assessment of quality in fresh produce. Colour measurement is one of the few exceptions. The most comprehensive way of assessing overall quality is to use panels to conduct sensory evaluation of the products. People on

the panel may be trained to assess certain quality components in a statistically quantitative fashion (Lawless and Heymann, 1998). Alternatively a consumer panel may be used. In this case the assessment is hedonic, that is, made in terms of personal preferences. In the fresh produce sector, the use of sensory tests may simply involve the quality controller acting as a single 'expert' taster. Alternatively, informal taste panels may be run, say, once a month, using up to 15 members of staff, who may or may not be regular members of the panel. Recent initiatives by retailers, particularly in the UK, are encouraging the industry to standardise the use of trained sensory panels for the measurement of quality attributes.

7.8 Maintaining the quality of fresh produce: precooling

7.8.1 Introduction

Table 7.1 provides some examples of the variation in commercial storage conditions and expected shelf-life of some representative fruits and vegetables. The prevalence of physical damage or the presence of pathogens can, however, confound shelf-life predictions. The main factors causing deterioration in fresh produce were described in sections 7.3–7.6. Maintaining quality thus requires action to be taken to limit these factors. In some cases these are preventative measures, for example, providing suitable packaging to prevent physical injury. However, a wide range of proactive technologies must be applied to maximise the shelf-life of perishable commodities. Of primary importance are methods to reduce produce respiration, water loss and the growth of pathogens. Of these, refrigeration dominates as the most fundamental of all post-harvest technologies.

7.8.2 Precooling

Precooling to remove field heat as quickly as possible after harvest is essential for slowing down the rate of deterioration of highly perishable products. The method chosen is largely determined by the type of product in question and the cost to benefit ratio (Kasmire and Thompson, 1992; Mitchell, 1992).

Room and forced air cooling

In room precooling, harvested produce is placed in a refrigerated area. Typically refrigerated air is blown horizontally just below the ceiling, sweeping over and down through the containers of produce below. Upon reaching the floor, it moves horizontally to the return vent to be recycled. More rapid cooling is effected with forced air or pressure precooling. In this case, refrigerated air is forced along a pressure gradient through each package. This is achieved by lining up stacks of containers (pallet loads or individual cartons) on either side of an exhaust fan to give an air plenum chamber. Air is prevented from moving down between pallet

Table 7.1 Range of storage periods for selected fruits and vegetables under typical storage conditions of temperature and relative humidity

Commodity	Temperature (°C)	Humidity (%)	Storage period
Apples	–1–4	90–95	1–8 months
Aubergines (eggplants)	8–12	90–95	1–2 weeks
Avocadoes (unripe)	4.5–13	85–90	2–5 weeks
(ripe)	2–5	85–90	1–2 weeks
Bananas (green)	13–15	85–90	10–30 days
(ripe)	13–16	85–90	5–10 days
Beans (French)	7–8	95–100	1–2 weeks
Broccoli	0–1	95–100	1–2 weeks
Cabbage (green)	0–1	95–100	3 months
(white)	0–1	95–100	6–7 months
Carrots (immature)	0–1	95–100	4–6 weeks
(mature)	0–1	95–100	4–8 months
Cauliflower	0–1	95–100	2–4 weeks
Celery	0–1	95–100	1–3 months
Citrus (easy peel)	4–8	90	3–8 weeks
Courgettes (zucchini)	8–10	90–95	1–2 weeks
Cucumbers	8–11	90–95	1–2 weeks
Garlic	0	70	6–8 months
Grapefruits	10–15	90	4–16 weeks
Grapes	–1–0	90–95	1–6 months
Kiwifruits	–0.5–0	90–95	2–3 months
Leeks	0–1	95–100	1–3 months
Lemons	10–14	90	2–6 months
Lettuce	0–1	95–100	1–4 weeks
Mangoes	5.5–14	90	2–7 weeks
Melons	4–15	85–90	1–3 weeks
Mushrooms	0	90–95	5–7 days
Onions	–1–0	70–80	6–8 months
Oranges	2–7	90	1–4 months
Pears	–1–0	90–95	1–6 months
Peas	0–1	95–100	1–3 weeks
Potatoes (immature)	4–5	90–95	3–8 weeks
(mature)	4–5	90–95	4–9 months
Soft fruits	–1–0	90–95	2 days–3 weeks
Spinach	0–1	95–100	1–2 weeks
Stone fruits	–1–1	90–95	1–7 weeks
Sweet peppers (capsicum)	7–10	90–95	1–3 weeks
Tomatoes (green)	12–15	90	1–2 weeks
(ripe)	8–10	90	1 week

Note: storage conditions and storage life may differ from cultivar to cultivar. The data were adapted from the more comprehensive tables provided by Snowdon and Ahmed (1981).

loads or the sides of cartons by sealing these gaps with flexible baffles. The cold air from the room thus has to pass through the holes in the packaging and around the produce inside. This greatly speeds up the cooling time from one-quarter to one-tenth of that of conventional room cooling.

Hydrocooling
Water is better than air at transmitting heat. Many produce types can be cooled by bringing them into contact with flowing cold water (hydrocooling). Packaging restricts water movement and greatly reduces cooling efficiency. Produce is therefore usually hydrocooled in bulk bins and is rarely used after packaging. This method is commonly used for stem vegetables, many leafy vegetables and some fruits like tomatoes and melons. Some crops cannot be cooled in this way, for example strawberry, because free water on the surface greatly increases the risk of disease. Proper sanitation (usually by chlorination) of the water is required to prevent the build up of bacteria in the water and subsequent contamination of the produce.

Icing
Application of crushed ice may be appropriate for a few crops. This is generally used for temporary cooling during transport from the field, for example leafy greens, for package icing during shipment to retail outlets and in displays of produce at the retail level, for example root and stem vegetables, Brussels sprouts and some flower-type vegetables like broccoli. The primary disadvantage is the additional weight for transport.

Vacuum cooling
One of the most rapid and uniform methods of cooling is vacuum cooling. It involves decreasing the pressure around the produce to a point at which the boiling point of water is reduced. The consequent evaporation of the water absorbs heat. This is most efficient with produce that has a large surface area to volume like leafy crops such as lettuce, spinach and cabbage. Adequate cooling can normally be achieved with no more than about 3% water loss but this can be reduced by spraying the produce surface with water prior to cooling.

7.9 Maintaining the quality of fresh produce: prestorage treatments

7.9.1 Surface coatings and wraps

Many fruits and vegetables benefit from a surface coating which can slow down the loss of water (Kester and Fennema, 1986). This is particularly true for crops which are washed, because hot water or the inclusion of detergents can remove natural waxes from the fruit surface. Coatings can also reduce the movement of O_2 and CO_2 in and out of the fruit, respectively. This internal atmosphere modification can slow down respiration; however, the layer must not be too thick or O_2 levels may fall too low and lead to fermentation problems. Many of the coatings applied are derived from plant extracts, for example carnuba or sugar cane waxes or polymers of sugar esters; however, petroleum-based products such as paraffin wax may be added to improve water loss control. An alternative approach to controlling water loss in fresh produce is to shrink wrap the product individ-

ually in plastic films. High density polyethylene (HDPE) is highly suitable for this as it can be applied in a very thin layer, which is a good water vapour barrier but does not affect the movement of respiratory gases and the danger of off-flavours developing (Ben Yehoshua, 1987).

7.9.2 Curing of roots and tubers

Some root and tuber crops, for example sweet potato and Irish potato, retain an ability to heal minor wounds after harvest provided conditions are correct (Burton *et al*., 1992; Morris and Mann, 1955). This involves the development of a new periderm layer at the wound site. As these crops are highly susceptible to physical injury during harvesting and handling, it is generally beneficial to encourage wound healing before storage. This process is known as curing and requires the produce to be held at elevated temperatures and high relative humidity (RH) for a period of time. The actual conditions used depend on the likelihood of disease development. At higher temperatures, curing will be faster but bacterial infection becomes more likely. Irish potato tubers are typically cured at 15–25°C, RH 85–98% for 7–15 days. There is evidence, however, that curing at lower humidities may reduce the incidence of superficial infections (Hide and Caley, 1987). Sweet potato roots are typically cured at 29–32°C, RH 85–98% for 4–8 days.

7.9.3 Dehydration ('curing') of bulb crops

Bulb crops, that is onions and garlic, are unusual among fruits and vegetables in that some water loss is highly desirable in preparation for storage. This dehydration process is known as curing but is a quite different process from curing of roots and tubers. For bulb crops, the aim of curing is to lose water from the outer scales and stalk remnant. In temperate climates, artificial curing is often carried out (although field curing may still be carried out in some countries). Onions are topped and placed in store. Hot air is blasted over them. Temperatures are initially 30°C until the outer scales are dried. The temperature is then dropped to 27°C for about 4 weeks before storing the bulbs at low temperatures (O'Connor, 1979).

7.9.4 Chemical control of fungal and bacterial pathogens

In many instances, the fresh produce is washed prior to grading, processing and packing. The quality of the water is extremely important, particularly if it is recycled. Bacteria and fungal spores can build up in the water and become an excellent source of inoculum unless they are controlled. The most common control method is the addition of chlorine at an active level of between 50–200 ppm. Ozone is also being used in some parts of the industry (Beuchat, 1992).

As described in section 7.5, a number of pathogens that cause significant post-harvest losses in fresh produce are pre-harvest in origin. There are many ways of limiting the extent of pre-harvest infection that are beyond the scope of this book.

The use, however, of resistant cultivars, good crop sanitation, and measures which maintain crop vigour and hence their natural resistance to infection and the application of fungicides will all go a long way to minimising post-harvest disease problems. The use of antibiotics for bacterial control in crops is not accepted in many countries, owing to fears concerning the possibility that any antibiotic resistance arising from field applications might be transferred to human pathogens (Lund, 1983).

After harvest many crops which are to be stored are treated with one or more fungicide. There are about 20 types of fungicide with approval for use on fresh produce (Eckert and Ogawa, 1990), although approval varies from country to country. Fungal resistance to the benzimidazole-based fungicides, such as benomyl, thiabendozole and thiophthanate methyl, is extremely widespread and has led to an increasing use of the ergesterol biosynthesis inhibitors (EBIs) such as imazalil, etaconizole, bitertanol etc. Application methods are highly dependent on the fungicide type and the crop type. Fruits such as apples, pears, mangoes, citrus and various root crops are often either sprayed or dipped in fungicide baths. Some fungicides may be incorporated into waxes for surface application on, for example, citrus. Where it is undesirable for the product to be wetted, fumigants may be used, for example, potatoes may be fumigated with 2-aminobutane to control gangrene and skin spot and sulphur dioxide is applied to control grey mould on table grapes (Eckert and Ogawa, 1988). Many crops such as strawberries are not treated with any post-harvest chemical despite their high perishability which is caused by pathogens.

7.9.5 Sprouting suppressants for root, tuber and bulb crops

Control of sprouting in root and bulb crops can be carried out by pre-harvest applications of maleic hydrazide. The compound must be applied to the foliage three to six weeks before harvest. Root crops can also be treated post-harvest with various sprout suppressants (Burton *et al*., 1992), for example, propham/chlorpropham (IPC/CIPC) which is normally applied as a mixture at about 10 g/t. These compounds must be applied after curing as they suppress wound healing. Tecnazene (TCNB) is a commonly used alternative, which has some advantages over IPC/CIPC in that it has little effect on wound healing and also has some fungicidal properties. Application rate is about 135 mg active ingredient per kg. There are a wide range of alternative chemicals which have sprout-suppressant properties but they all have limitations compared to the conventional compounds described above (Prange *et al*., 1997).

7.9.6 Post-harvest chemical treatments to reduce disorders

Superficial scald is a skin disorder of certain apple cultivars which develops during storage and is due to the oxidation of a natural compound in the skin called α-farnesene. Commercially, the antioxidant compounds diphenylamine and ethoxyquin can be applied as a post-harvest dip to control this disorder (at

0.1–0.25% and 0.2–0.5%, respectively). Diphenylamine may also be applied in wax formulations or in impregnated wraps (Snowdon, 1991).

Another important post-harvest treatment of apples is the use of calcium, either as a pre-harvest spray or as a post-harvest dip, to control the storage disorder, bitter pit (Anon, 1984). Although calcium treatment can improve storage quality of many other fruits, it has not been developed owing to problems in getting sufficient calcium into the tissue by infiltration without causing fruit damage.

7.9.7 Irradiation

Many benefits of applying ionising radiation (X-rays, γ-rays or high energy electrons) to fresh produce have been shown, including sprout inhibition in root, tuber and bulb crops, control of some fungal diseases and increased storage potential through delays to the ripening processes of fruits (Dennison and Ahmed, 1975). A range of treatments have been approved in many countries, including the UK; however, consumers have shown considerable reluctance to accept irradiated food (Foster, 1991). In practice, very little fresh produce is actually irradiated owing to both these consumer concerns and legislative restrictions.

7.10 Maintaining the quality of fresh produce: refrigerated storage

7.10.1 Introduction

As discussed in section 7.8.2, the storage/shelf-life of fresh produce is considerably extended if respiration can be slowed down using refrigeration. Lists of recommended storage conditions for a wide range of fruits and vegetables are given in a number of publications (Kader, 1992; Snowdon and Ahmed, 1981; Thompson, 1996). Following precooling, it is important that the cold chain is maintained throughout the life of the product. This means that refrigeration should take place throughout transportation (Eksteen, 1998) and storage and preferably be maintained during retailing and in the home of the consumer. Typically, road and sea containers are refrigerated, as are the storage units at exporters, importers and retail distribution centres. Air freight is rarely cooled and relies on adequate precooling, good pack insulation and the speed of transport to maintain adequate quality (Frith, 1991). The cool chain tends to be broken in the retail store where fruits and vegetables are rarely displayed in chilled cabinets.

7.10.2 Control of humidity

Most cool stores or refrigerated containers are refrigerated by a direct expansion system (Thompson, 1992). Fans are usually necessary to circulate the storage air over the evaporator coils and then through the produce in the cooling space. Heat is removed from the cooling space, when the refrigerant gas is allowed to expand in the evaporator coils. The temperature gradient between the coil and the produce

is accompanied by a vapour pressure deficit, which increases water loss from the produce. To reduce water losses during longer term storage it is important to have as small a difference between coil temperature and produce storage temperature as possible. For produce particularly susceptible to water loss, for example leafy vegetables, an indirect cooling system may be used. Storage air is cooled to about 1–2°C and humidified to a RH of over 98% by passing it through a shower of cold water that has been cooled by mechanical refrigeration.

7.10.3 Control of ethylene

The presence of ethylene can stimulate senescence and give rise to a number of disorders as described in section 7.6.1. Good store management is needed to ensure that ripening fruit is not stored together with unripe fruit or other produce which is sensitive to ethylene (Dover, 1989). Exhaust gases from vehicles contain ethylene and must be kept well apart from produce stores. For fruits and vegetables which only produce low levels of ethylene, adequate ventilation from a clean air source is usually sufficient to keep ethylene at safe levels. Where ventilation is not sufficient to manage ethylene levels, ethylene can be destroyed by oxidation. Store air can be passed over the oxidising compound, potassium permanganate held on an inert substrate. Alternatively, ultraviolet (UV) light is in use commercially to destroy ethylene. The UV generates ozone production. It is believed that the ethylene is destroyed by active intermediates produced during the formation of the ozone (Reid, 1992). Ethylene can also be destroyed using catalytic converters by heating the air to over 200°C in the presence of a suitable catalyst such as platinum (Knee *et al*., 1985).

7.10.4 Control of chilling injury and low temperature sweetening

Chilling injury in tropical and sub-tropical crops may limit the use of refrigeration to temperatures well above freezing. Chilling injury is dependent not only on the temperature but the length of exposure at that temperature. The early stages of chilling injury are believed to be reversible and some produce can tolerate chilling temperatures for short periods of time without development of symptoms. A range of methods is available to limit chilling injury (Wang, 1991). These include stepwise reduction in storage temperature, or intermittent warming during storage (e.g. nectarines and peaches). Some fruits may become less susceptible to chilling when held under appropriate modified atmospheres, for example mango, avocado.

7.11 Maintaining the quality of fresh produce: controlled atmosphere (CA) storage

Respiration can also be controlled in many crops by reducing the levels of oxygen in store and/or by raising levels of carbon dioxide. This is known as controlled

atmosphere (CA) storage and its use with fruits and vegetables is reviewed by Thompson (1998). Lists of recommended CA conditions for a wide range of crops are provided in a number of other publications (Kader, 1997; Meheriuk, 1990). CA has long been in use as a means of extending the storage life of apples well beyond that achieved just by refrigeration, up to 10 months for some cultivars such as Granny Smith (Meheriuk, 1990). CA can also be useful for chilling sensitive crops, where refrigeration alone may not give adequate storage life. Transport of bananas is increasingly being carried out under CA (typically O_2 3% and CO_2 5%) giving reduced levels of premature ripening and controlling crown rot disease. CA storage of onions can give substantial extension of storage owing to its inhibitory effect on sprouting. The technology is, however, quite expensive to install and needs well trained technical staff to be operated effectively.

High levels of CO_2 can also have a direct inhibitory effect on certain pathogens. The upper limit for CO_2 levels depends on the sensitivity of the crop. Many berry crops have a high tolerance for CO_2, for example, blackcurrants destined for processing into juice are often held under 40% CO_2. Levels above 15% will significantly reduce incidence of grey mould on strawberries, raspberries, cherries and grapes (Kader, 1997) and small scale CA storage structures are in increasing use with these crops.

7.12 Maintaining the quality of fresh produce: packaging

7.12.1 Conventional packs

It is essential to minimise physical damage to fresh produce if it is to have optimal shelf-life. The use of suitable packaging is vital in this respect (Thompson, 1996). The most common form of packaging in this sector is the use of the fibreboard carton; however, for most produce, additional internal packaging, for example tissue paper wraps, trays, cups or pads, is required to reduce damage from abrasion. For very delicate fruits, smaller packs with relatively few layers of fruits are used to reduce compression damage. Moulded trays may be used which physically separate the individual piece of produce. Individual fruits may also be wrapped separately in tissue or waxed paper. This improves the physical protection and also reduces the spread of disease organisms within a pack. Detailed box designs are described in ITC (1988).

7.12.2 Modified atmosphere packaging (MAP)

Polymeric films have been used to package fresh produce for over 35 years, with a number of benefits, including control of water loss, protection from skin abrasion and reduced contamination of the produce during handling. They also provide a barrier to the spread of decay from one unit to another (Kader *et al.*, 1989). These films will also affect the movement of respiratory gases depending on the relative permeability of the film. This can lead to the development of lowered O_2 and raised CO_2 levels within the package and, as with CA storage,

this can reduce the respiration of the produce and potentially extend shelf-life. Bananas are commonly transported in sealed polyethylene bags. It has been shown that if a stable gas content of 2% O_2 and 5% CO_2 can be achieved, the shelf-life of bananas can be extended five-fold (Shorter *et al*., 1987).

A modified atmosphere can be created within the pack in two ways. Active modification involves the pulling of a slight vacuum within the pack and then replacing the atmosphere with the desired gas mixture. Absorbers of CO_2, O_2 or ethylene may be included within the pack to control the concentration of these gases. In passive modification systems, the atmosphere is attained through the respiration of the commodity within the pack. The final equilibrium atmosphere will depend on the characteristics of the commodity and the packaging film (Kader *et al*., 1989). Temperature control is extremely important with MAP, as this will influence the gas permeability properties of the film as well as the respiration rate of the product. One of the main drawbacks to MAP is the potential for O_2 levels to fall too low and cause the production of undesirable off-odours caused by fermentation of the tissues.

7.13 Future trends

7.13.1 Minimally processed products and MAP

One of the fastest growing trends in food retailing is that in ready prepared foods. In the fresh produce sector, this is observed in growing sales of so-called fresh cut or minimally processed salads. New developments are having to be made in MAP to prevent the rapid deterioration which occurs once fresh produce has been cut open (Day, 1996; Day and Gorris, 1993). Up to now, the development of new MAP solutions has remained something of an art, with selection based on trial and error. Attempts to put MAP design onto a more theoretical basis have led to a number of models being developed. However, the general applicability of these models has been limited by the complexity of the systems involved (Kader *et al*., 1989). With the continued expansion in computing power available, eventually models which can be used successfully to predict suitable MAP solutions will be developed.

These developments in MAP will be accelerated by the commercial availability of films for so-called 'active packaging', for example, polymer films which become more permeable to respiratory gases at higher temperatures (Day and Gorris, 1993). Packaging may include components which remove aroma or off-flavours, scavenge O_2, ethylene or water vapour or emit CO_2 or other preservative vapours (Robertson, 1991; Wills *et al*., 1998). Novel gas combinations such high O_2, argon or neon may have useful applications in this field (Day, 1996).

7.13.2 On-line technologies for non-destructive grading and shelf-life evaluation

Another market of growing importance is the 'ready-to-eat' market where the consumer is led by the product label to expect a fully ripe fruit for immediate

consumption. To guarantee good eating quality while minimising post-harvest losses, the development of robust non-destructive quality testing equipment for use on packing lines is required. This type of equipment will also be used for the detection of external and internal defects, thus reducing labour costs in the packhouse.

The physical science behind many non-destructive techniques for evaluating internal quality of fresh produce such as the use of near infrared, X-ray scattering, acoustic resonance, etc. is well understood (Chen and Sun, 1991). The goal of turning the science into technologies which can be applied commercially within the fresh produce sector has proved somewhat elusive. Flavour factors such as sugar content may eventually be routinely measured using near infrared (Peiris *et al*., 1999). Aroma profiles of fruits may be assessed using electronic nose technology based on polymer arrays which are sensitive to volatile compounds (Russell, 1995). At the time of writing, the response time of this equipment is too slow to be of practical use, that is, it is in the order of minutes rather than seconds. Some of this additional information could be incorporated on to labels applied on-line, perhaps indicating the expected shelf-life and percentage sugar content of each individual product.

Machine vision applications for the detection of external blemishes are rapidly making progress towards commercialisation (Tillett, 1991; Yang, 1992). Among the novel techniques being developed for the non-destructive detection of internal defects are computer-aided X-ray tomography and nuclear magnetic resonance (NMR) imaging. These are based on the measurement of differences in tissue density or proton mobility respectively and can be used, for example, to detect cavities or tissues disruption caused by insects, disease development or developmental disorders (Wills *et al*., 1998).

7.13.3 Replacements for post-harvest chemicals

In many countries there is a strong trend towards reducing the use of chemicals in horticulture, including post-harvest fungicides, sprout suppressants and antioxidants for scald control. Increasingly, consumers are prepared to pay for organic products and the retail sector is encouraging the trend (Geier, 1999). Another and perhaps more significant factor in the trend to reduce usage of post-harvest chemicals is the escalating costs to the agrochemicals industry of the registration of new pesticides or reregistration of currently used pesticides (Crossley and Mascall, 1997). Post-harvest use of pesticides on fruits and vegetables is an extremely small market compared with pre-harvest applications on major world crops such as cereals and oilseed crops. Many chemicals are now being voluntarily deregistered by their producers for post-harvest use. Others have been deregistered by regulatory bodies on the basis of new health and safety data. In 1994 the EU began the process of harmonising maximum residue levels (MRLs) for each crop/pesticide active ingredient combination in use across EU countries. Where the chemicals have been found to be out of patent and where no chemical company is willing to pay the cost of the new data requirements, the active ingredient is being or has been

banned. The implications of this pesticide 'harmony' in Europe are potentially serious for the European horticulture industry as well as international growers exporting to Europe (Aked and Henderson, 1999).

It is clear that the fresh produce sector urgently needs alternatives to post-harvest chemicals and developments of these technologies will grow in the future. Among the technologies already in use or in development are controlled and modified atmosphere storage, for example, to manage scald in apples (Dover, 1997) and physical treatments such as heat (Barkai-Golan and Phillips, 1991), the use of biocontrol agents (Koomen, 1997), 'natural' chemicals such as plant extracts and methods to stimulate natural disease resistance in crops such as UV applications (Joyce and Johnson, 1999).

One new chemical which may gain future approval for use on fresh produce is the gaseous inhibitor of ethylene action, 1-methylcyclopropene (1-MCP). 1-MCP inhibits ripening in climacteric fruit and ethylene-stimulated senescence and is active at very low (ppb) concentrations (Serek *et al*., 1995).

7.13.4 Increased emphasis on the health aspects of fresh produce consumption

Consumers have long been encouraged by government health advisors to increase their consumption of fresh produce on the basis that these food products are vital dietary sources of certain minerals and vitamins. However, it is now widely believed that high levels of fresh produce consumption may ward off many fatal diseases such as cancer and heart disease (Joshipura *et al*., 2001; Wallstrom *et al*., 2000). As further advances are made in understanding the links between diet and disease, it is likely that the nutritional value of fruits and vegetables will become an important quality factor. Thus the maintenance throughout storage of key chemical components that are found to have specific health benefits will pose additional challenges to the post-harvest technologist.

7.13.5 Genetically modified (GM) fruits and vegetables

Despite consumer concerns about the desirability of genetically engineered crops, it is likely that new GM products (for example, with altered colour, flavour or nutritional properties) will become available on the market in the future. Novel properties in a product may change its responses to storage and require new approaches to maintaining product quality. Genetic alterations have already been directed to reducing unwanted quality changes. The first GM fresh product to be marketed was the FlavrSavr tomato which was engineered using antisense RNA technology to have reduced levels of polygalacturonase (Fuchs and Perlak, 1992). This increased the shelf-life of the tomato by preventing the excessive softening which accompanies over-ripening. Other fruits such as tomatoes and melons have been manipulated to reduce ethylene synthesis. Such fruits can have extremely extended shelf-lives. Susceptibility to post-harvest damage and disorders has been manipulated in a number of crops, for example, polyphenol oxidase activity has been reduced in potatoes (Bachem *et al*., 1994) removing sensitivity to bruising. Other

research around the world seeks to do the same thing in a diverse range of crops, including pineapples, apples, lettuces and grapes to prevent a range of browning reactions which accompany physical and physiological injury (Thwaites, 1995). There are other ways in which the shelf-life of fresh produce could be extended genetically, for example, by enhancing the synthesis of antimicrobial compounds.

7.14 Conclusions

The fresh produce sector is a growth market driven by improvements in quality, variety and all year round availability. The industry has to satisfy ever higher quality requirements combined with high labour costs, an emphasis on reductions in chemical inputs, both pre- and post-harvest, and market demand for ready prepared products. For growth to continue, the industry has to be prepared to adopt a wide range of technologies to enable extended shelf-life while maintaining product quality. Continued research and development is therefore needed worldwide to find improved ways of increasing the stability and shelf-life of fruits and vegetables. Providing consumer confidence can be gained, genetic engineering may hold the key to dramatic changes in the management of fresh produce shelf-life in the future.

It can be concluded that those who wish to improve the control of fresh produce quality need a broad knowledge base, including aspects of horticulture, physiology, biochemistry, plant pathology and molecular biology. They also need to be familiar with a wide range of technologies and management strategies, ranging from packaging options to cool chain management. Maintaining quality of fresh produce for both the fresh produce markets and processing industries promises to remain a challenging but fascinating activity.

7.15 Sources of further information and advice

7.15.1 Research organisations

Owing to the huge number of organisations that carry out research into fresh produce quality worldwide, the author has limited references to UK establishments only. The following organisations engage in research relevant to the storage and shelf-life of fresh produce. Those who are still funded to some degree by the public sector may provide some advice and information free of charge. Organisations funded to a large extent by industry usually charge for information and may only provide scientific data to paying members.

Campden and Chorleywood Food Research Association, Chipping Campden, Gloucestershire GL55 6LD, UK: this government and industry sponsored research organisation has research and training programmes in aspects of MAP and HACCP for fresh produce.

Institute of Food Research, Norwich Research Park, Colney, Norwich NR4 7UA, UK: this is a research organisation supported by grants from the Biotech-

nology and Biological Sciences Research Council. It carries out basic and strategic research on food safety, quality, nutrition and chemistry.

Horticulture Research International (Headquarters), Wellesbourne: this is a multisite government research organisation with a number of groups carrying out research to extend the storage potential of UK grown fruits and vegetables.

Leatherhead Food Research Association (Fruit and Vegetable Panel), Randalls Road, Leatherhead, Surrey KT22 7RY, UK: this is an industry sponsored research organisation with a product panel on fruits and vegetables and some training programmes relating to fresh produce processing.

Shipowners Refrigerated Cargo Research Association, 140, Newmarket Road, Cambridge CB5 8HE, UK: this industry sponsored organisation carries out research on shipping of cargo, including fresh produce.

Silsoe Research Institute, Wrest Park, Silsoe, Bedford MK45 4HS, UK: the Institute is government funded with relevant research being conducted on physical properties of fresh produce, non-destructive testing techniques and machine vision technology for harvesting and grading horticultural products.

The following university sector organisations are known by the author to conduct research and/or provide training on aspects of shelf-life extension of fresh produce:

Cranfield University at Silsoe (Postharvest Technology Laboratory), Silsoe, Bedford MK45 4DT; *Natural Resources Institute* (Postharvest Horticulture Group), University of Greenwich, Chatham, Kent ME4 4TB; *Nottingham University* (Plant Sciences Division), Sutton Bonnington Campus, Loughborough LE12 5RD; *Reading University* (Department of Agricultural Botany), Reading, Berkshire RG6 6AS; *Scottish Agricultural College* (Food Systems Division), Craibstone Estate, Buckburn, Aberdeen AB21 9YA; *Writtle College*, University of Essex, Chelmsford, Essex CM1 3RR; *Wye College*, University of London (Department of Agriculture and Horticulture), Ashford, Kent TN25 5AH.

7.15.2 Written and electronic sources

The following books should be referred to for an overview of fresh produce biology and relevant post-harvest technologies for fruits and vegetables (Kader, 1992; Kays, 1991; Thompson, 1996; Weichmann, 1987; Wills *et al.*, 1998). The journals *Postharvest Biology and Technology* and *Scientia Horticulturae* (Elsevier) and *Postharvest News and Information* (CABI Publishing) publish scientific papers relating to horticultural produce. Review articles and abstracts of relevant papers can be found in the CAB International publication, *Postharvest News and Information*. The following website is produced by the Postharvest Technology Research and Information Centre, Department of Pomology, University of California, Davis, CA, USA. It provides produce fact sheet, properties and recommended conditions for storage of fresh fruits and vegetables and fact sheets on physiological disorders of fruits and vegetables. http://postharvest.ucdavis.edu/

Extensive postharvest information has been collated at the FAO website. http://www.fao.org/inpho/. Subscribers to the Postharvest Mailing List can exchange information with other users. Contact: posth@hra.marc.cri.nz

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