2

Assessment of crop maturity

The principles that underlie at which stage of maturity a fruit or vegetable should be harvested are crucial to its quality as well as its subsequent storage and marketable life. Maturity may be defined in terms of either their physiological maturity or their horticultural maturity and are based on the measurement of various qualitative and quantitative factors. There are certain guiding principles to be followed when selecting fruit or vegetables to be harvested. Harvest maturity should be at maturity that:

- allows them to be at its peak condition when they reach the consumer
- allows them to develop an acceptable flavour or appearance
- allows them to have an adequate shelf-life
- gives a size acceptable to the market
- is not toxic.

The methods used to assess the maturity of produce may be based on the subjective estimate of people carrying out the operation. To achieve this, sight, touch, smell, morphological changes and resonance may be used. These methods may be made more objective and perhaps more consistent by the use of aids such as colour charts (Figure 3). Chemical and physical analyses are also used. These depend on sampling procedures and can therefore be used only on crops where a small representative sample can be taken. Computation is also used by calculating such factors as time after flowering as a guide to when to harvest fruit. Many of the methods, which use a qualitative attribute of the crop, may also be used to determine its postharvest quality. Almost all the measurements described here can also have that function.

Field methods

Skin colour

Skin colour is used for fruit where changes occur as the fruit ripens or matures, but in some fruits there are no perceptible colour changes during maturation. Colour changes may occur on particular cultivars but not on others. Also with some tree fruit colour of skin may be partly dependent on the position of fruit on the tree or the weather conditions during production, which may confound its use as a maturity measurement. There are many examples of the commercial use of skin colour as the determinate of harvest maturity. For apricots Fan *et al.* (2000) defined maturity stage 1 as light green, partially turning to a straw colour and maturity stage 2 as straw colour on most of the fruit surface. In South Africa the Deciduous Fruit Board produced a colour chart for apricots. For loquat Hamauzu *et al.* (1997) described eight stages of harvest maturity from stage 1 (green, small) through to stage 7 (yellowish orange) and stage 8 (slightly over ripe) and indicated that stage 7 is the optimum harvest maturity. In mangosteen harvest maturity is

Fruit and Vegetables: Harvesting, Handling and Storage, Volume 1, Third Edition. A. K. Thompson.

in Florida takes 60 – 70 days to reach harvest maturity. Fruits harvested too early tend to brown severely during storage (Campbell 1989). The time after flowering can also be used to determine harvest maturity in mango. In India Alphonso exhibited a sigmoid pattern of growth and took 16 weeks from fruit set to attain harvest maturity (Rao *et al.* 1995). Rajput *et al.* (1999) showed that the fruit growth of the cultivars Langra, Sunderja, Mallika and Amrapali also followed a sigmoid pattern, and in general it was rapid between 30 and 90 days after fruit set. Kienzle *et al.* (2012) evaluated harvesting mangoes 83 – 107 days after full bloom for the cultivar Chok Anan. They found that fruit that were harvested 89 days after full bloom and stored at 14 °C and 50 – 60% r.h. with ethylene absorption took 18 ± 1 days to reach eating ripeness.

Mangoes of the cultivars Karuthacolomban, Velleicolomban and Willard, grown in Sri Lanka, were harvested at 10, 11, 12 and 13 weeks after flowering. Peel colour development could be used to determine harvest maturity in Willard. Changes of dark green to light green with maturity could not be considered a reliable index for the other two cultivars. Rising of shoulders with maturity was a better indicator of maturity than peel colour development, and it could be used as a reliable index to harvest all three cultivars. Though mature fruits of Willard and Velleicolomban passed the float test, Karuthacolomban did not respond consistently. The mean value of total soluble solids recorded from Karuthacolomban and Velleicolomban harvested 13 weeks after flowering was 18 °Brix, while titratable acidity was 0.3%. Total soluble solids and titratable acidity of Willard were similar to these values in the 12th week after flowering. The fruits harvested before the optimum stage of maturity contained significantly lower total soluble solids, higher titratable acidity and poorer sensory properties than mature fruits (Amarakoon *et al.* 1999).

Leaf changes

This is a characteristic that is used in both fruit and vegetables to determine when they should be harvested. In many root crops the condition of the leaves can indicate the condition of the crop below ground. If potatoes are to be stored then the optimum harvest time is after the leaves and stems have died down. If they are harvested earlier the skins are less resistant to harvesting and handling damage and are more prone to storage diseases. Bulb onions that are to be stored should be allowed to mature fully before harvest, which is judged to when the leaves bend just above the top of the bulb and fall over. When the leaf dies in whose axis a fruit is borne in melons then that fruit is judged to be ready for harvesting. In some cucurbits when the leaf, in whose axis the fruit has been produced, dies this may be an indication that the fruit is sufficiently mature for harvesting.

Abscission

As part of the natural development of fruit an abscission layer is formed in the pedicel. This can be judged by gently pulling the fruit. However, fruit harvested at this maturity will be well advanced and have only a short marketable life.

Firmness

Fruit may change in texture during maturation and especially during ripening where they may rapidly become softer. Excessive loss of moisture may also affect the texture of crops. These textural changes may be detected by touch, and the harvester may simply be able to gently squeeze the fruit and judge whether to harvest it. A non-destructive firmness test was investigated at Cranfield University, which simulated the practice of customers who may test a fruit's ripeness by feeling it. A narrow metal cylindrical probe was pressed onto the skin of the fruit (approximately 1 N was sufficient), and the amount of the depression of the skin was very accurately measured on an Instron Universal Tester (Curd 1988, Allsop 1991). This was found to correlate well with maturation and ripening of the fruit and also caused no detectable damage. Similar studies had previously been carried out by Mehlschau *et al.* (1981) who used steel balls, one each on opposite sides of the fruit, to apply a fixed force. They then measured the deformation that was caused to the surface of the fruit. Perry (1977) described a device, which applied low pressure air to opposite sides of fruit and then measured the surface deformation. Corrêa *et al.* (2004) reported a modified version of a pressure tester with a double plate that allowed flesh firmness to be measured in Hass avocados and cherimoya. They also reported that a puncture test, used to measure skin resistance, can also be considered an indicator of maturity degree in Hass avocados.

Firmness, or what is usually called solidity, can be used for assessing harvest maturity in many leafy vegetables. The harvester who slightly presses vegetables such as cabbages and hearting lettuce with his or her thumb and fingers can do this by hand. Harvest maturity is assessed on the basis of how much the vegetable yields to this pressure. Normally the back of the hand is used for testing the firmness of lettuce in order to avoid damage (John Love, personal communication).

Postharvest methods

Sugars

In climacteric fruit carbohydrates are accumulated during maturation in the form of starch. As the fruit ripens starch is broken down into sugars. In non-climacteric fruits it is sugars not starch that are accumulated during maturation. In both cases it follows that measurement of sugars in the fruit can provide an indication of the stage of ripeness or maturity of that fruit. In practice the soluble solids (TSS), also called °Brix, is measured in the juice of samples of fruit because it is much easier to measure. Usually sugars are the soluble solids that are in the largest quantity in fruit. So measuring the TSS in samples of the juice can give a reliable measure of its sugar content. This is done either with a suitable Brix hydrometer or in a refractometer (Figure 5). This factor is used in certain parts of the world to specify maturity of, for example, kiwifruit, honeydew melons, peaches and longan. In kiwifruit OECD (1992) stipulated that the minimum TSS content should be 6.2% based on the average of 10 sample fruit. Crisosto *et al.* (2012) reported that the minimum harvest maturity standards for the cultivar Hayward were 5.5 to 6.5% TSS, which assures adequate storage potential to avoid flesh breakdown and that they would ripen to a good flavour. Tongdee (1997) indicated that soluble solids could be used to determine harvest maturity of litchi using 15.5–16 °Brix. For grapes the optimum TSS at harvest varies between cultivars for example Pantastico (1975) reported that it should be 18–20% for Thompson Seedless and 12–14% for Bangalore Blue. In Lithuania Kviklienė *et al.* (2011) calculated harvest maturity as: firmness divided by TSS and for the cultivar Lodel the optimum was 0.20–0.13.

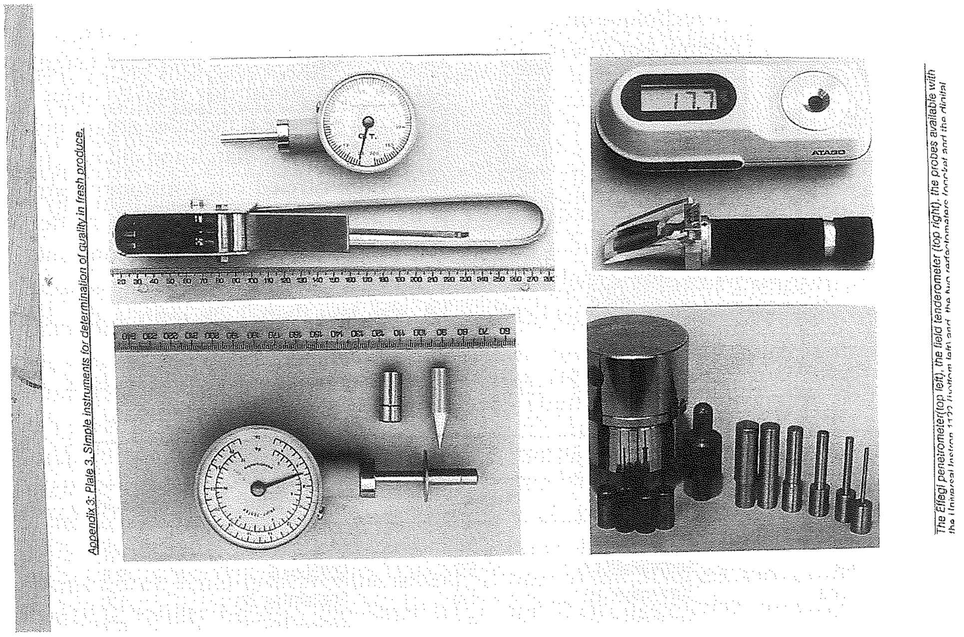

Figure 5 Texture measuring equipment, also with refractometers at the top right. (Source: Ssemwanga 1990. Reproduced with permission of Cranfield University.)

Starch

In apple and pears carbohydrates are accumulated during maturation in the form of starch. Starch is converted into sugar as harvest time is approached. The measurement of starch content in the developing fruit can provide a reliable method for assessing its harvest maturity, but it does not work for all cultivars. In Poland it was described for pears, but there was considerable variation between cultivars and it also varied over the two seasons when it was evaluated (Table 5). Measurement of starch involves taking a representative sample of fruit from the orchard as the harvest time approaches. These fruit are cut into two and the cut surface dipped in a solution containing 4% potassium iodide and 1% iodine. The cut surface will be stained a blue-black colour in the places where starch is present. It is possible, often with the use of Perspex templates marked with concentric rings, to determine the percentage starch (Figure 6). In Turkey prepared charts have been developed for several popular cultivars (Figure 7). In practice, in England, samples would be taken from pears from mid-August, when the whole fruit surface should contain starch and harvesting should be carried out when samples show about 65 to 70% of the cut surface which has turned blue-black (Cockburn and Sharples 1979). Studies using this technique on apples gave inconsistent results in England, but it was very effective on several cultivars in Turkey. Wawrzyńczak *et al.* (2006) reported that there was a slight statistically non-significant increase in TSS of pears during CA storage in both 2003/2004 and 2004/2005. This increase may have been due to starch degradation, especially in Delbuena, which had a starch index of 1 at harvest time. The only cultivar to show a slight, but statistically non-significant decrease in TSS content was Nojabrska, which had a starch index of 10 at harvest time.

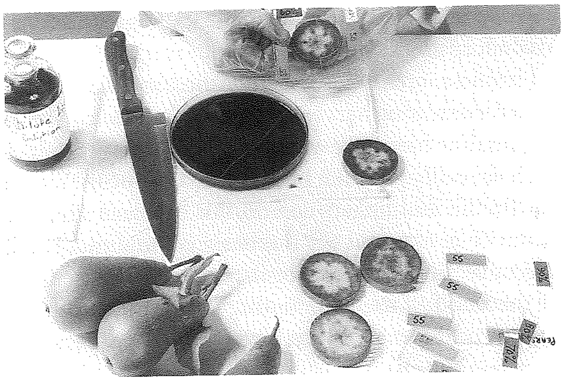

Figure 6 The starch iodine test used to determine the harvest maturity of pears and apples. (Source: Dr R.O. Sharples.)

Dry matter

Dry matter has been used to relate harvest maturity with quality. Saranwong *et al.* (n.d.) reported that dry matter and starch could be used as harvesting indices for hard green mangoes as they had a strong relationship with the level of TSS of ripe eating quality, while individual sugars and fruit density did not. Crisosto *et al.* (2012) reported that researchers from various countries have proposed using dry matter at harvest as a worldwide quality index for Hayward kiwifruit, because it includes sugars, acids, structural carbohydrates and starch and did not change postharvest. They carried out consumer tests over several years which indicated that dry matter and acidity of ripe fruit were related to consumer acceptance of kiwifruit. In most California seasons, when ripe TA was less than 1.2%, only a dry matter greater

Table 5 Starch index for six Polish pear cultivars at harvest during two seasons, where 1 = black (maximum starch) and 10 = white (no starch) (source: adapted from Wawrzyńczak *et al.* 2006)

	Season 2003/2004		Season 2004/2005	
Cultivar	Harvest date	Starch index	Harvest date	Starch index
Alexander Lukas	September 17	5.9	September 20	7.5
Amfora	September 17	5.2	October 6	9.4
Delbuena	September 10	1.0	September 20	1.0
Delmoip	September 10	6.4	September 27	6.7
Erica	September 17	6.7	October 6	10.0
Nojabrska	September 22	9.8	October 4	10.0

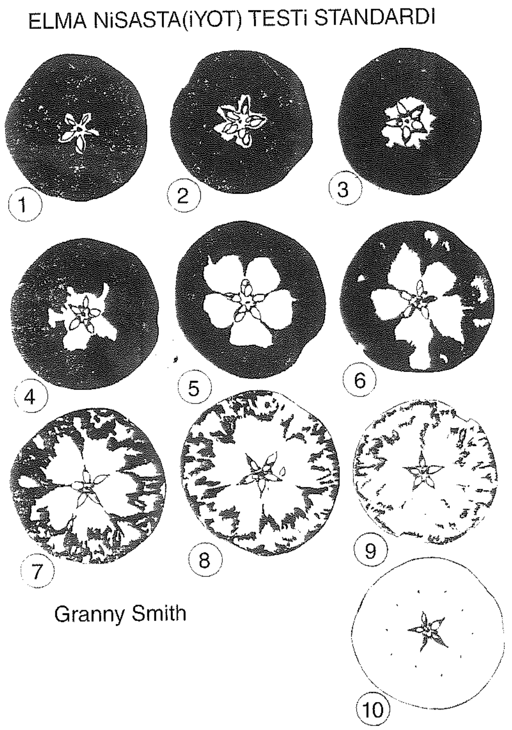

Figure 7 Starch iodine test template used for apples in Turkey where 1 is cut surface completely turned blue/black and 10 with none of the cut surface turned blue/black.

than or equal to 15.1% was required for consumer acceptability. They found that their results provided strong evidence that dry matter would be a reliable quality index candidate for California kiwifruit, especially if TA of ripe fruit was factored in.

Firmness

In some cases a representative sample of fruit may be taken from the orchard and tested in a device which will give a numerical value of texture; when that value reaches a predetermined critical level then the fruit in that orchard are all harvested. These pressure testers were first developed for apples (Magness and Taylor 1925) and are currently available in various forms (Figure 5). Firmness is commonly expressed as kgf (kilograms force). Hand-held pressure testers could give variable results because the basis on which they are used to measure the firmness of the crop is affected by the angle at which the force is applied. An experienced operator may be able to achieve consistent and reliable results, but greater reproducibility can be achieved if the gauge for measuring firmness is held in a stand so that the angle of force applied to the crop is always constant. The speed with which the probe presses against the fruit can also affect the measurement of firmness, so instruments have been developed which can control it. The performance of a firmness penetrometer developed by DeLong *et al.* (2000) was evaluated over two growing seasons with post-storage apples against the Effegi, Magness–Taylor and electronic pressure tester. Highly significant instrument by operator interactions indicated that the influence of operators on instrument performance was not consistent but overall the newly developed penetrometer performed as well or better than the other instruments tested. In a comparison between a penetrometer (puncture) test and a flat plate compression test Sirisomboon *et al.* (2000) found that the penetrometer was superior for analysing the texture of Japanese pears. A computer-assisted impact-testing device with a 49.29 g stem and a 0.04 m height was used to test the firmness of Hass avocados. Impacts proved to be non-destructive under these conditions and therefore they could be used to determine their ripening stage (Corrêa *et al.* 2004). Pressure tests can be used for plums but Hulme (1971) commented that it is usually easier to test texture by feel. Perry (1977) described a device that applied low-pressure air to opposite sides of plums to measure the surface deformation for assessing fruit firmness. Another non-destructive technique for assessing the harvest maturity uses a ballistic collision technique (Harvey *et al.* 1995). In crops such as peas a shear cell is used to measure texture and is called a tenderometer (Knight 1991). Pressure testers used for fruits and tenderometers are destructive tests which assume that the sample taken is representative of the crop. Shmulevich *et al.* (2003) described a low-mass impact firmness tester produced by the USA Sinclair International Company for measuring firmness of avocados. Valero *et al.* (2007) also used the Sinclair iQ^{TM} firmness tester for a non-destructive test and a modification of the Magness and Taylor type penetrometer for their destructive measurements. They tested the relationship between these two methods and characterized them in terms of segregating peaches, nectarines and plums according to their stages of ripening by discriminant analysis. Discriminant analysis consistently segregated non-destructive firmness measured fruit into different classes. They concluded that both destructive and non-destructive firmness measurements can be directly used to identify the stage of ripeness and potential susceptibility to bruising during postharvest changes.

Juice

The juice content of many fruits increases as they mature on the tree. By taking representative samples of the fruit, extracting the juice in a standard and specified way and then relating the juice volume to the original mass of the fruit it is possible to specify its maturity. In some countries legislation exists which specifies the minimum juice content before fruit can be harvested (Table 6).

Oil

This is probably only applicable to avocados where the oil level increases as the fruit matures on the tree. Also it is only applicable to those grown in the subtropics. This is because it is based on a sampling technique where it is assumed that the sample of fruit on which the oil analysis has been taken is representative of the whole field. In the subtropics there are distinct seasons, and flowering of avocados occurs after a cold season and the trees tend to flower and thus set fruit over a short period of time. Trees of the same variety in one orchard will have fruit that therefore mature at about the same time and so a representative sample can be taken. In the tropics the flowering period, even on the same tree, is over a much more protracted period and so there is a wide range of fruit maturities. It is rarely possible, therefore, to obtain a representative sample. In California Kader and Arpaia (2006) reported that the correlation between dry weight ratio and oil content was used as a maturity index, and minimum dry weight ratio should range between 19 and 25%. They also reported that at harvest the minimum of 8% oil content was specified as standard, and there was a correlation between dry weight and oil content.

Table 6 The minimum juice content levels for citrus fruits harvested in the United States

Type of citrus fruit	Minimum juice content (%)
Navel oranges	30
Other oranges	35
Grapefruit	35
Lemons	25
Mandarins	33
Clementines	40

Acidity

The acidity of many types of fruit changes during maturation and ripening. In many fruit acidity progressively reduces as the fruit matures on the tree. Taking samples of these fruit, extracting the juice and titrating it against a standard alkaline solution give a measure that can be related to optimum time of harvest. It is important to measure acidity by titration and not by measuring the pH of the fruit because of the considerable buffering capacity in fruit juices. Normally acidity is not taken as a measurement of fruit maturity by itself. It is usually related to soluble solids giving, what is termed, the °*Brix : acid ratio*. For example Lill *et al.* (1989) showed that TA in peaches and nectarines varied with cultivar and season, and the ratio of TSS : TA was found to be more closely related to quality than TA or TSS alone but it still varied between years.

Specific gravity

Specific gravity of solids or liquids is the relative gravity or weight compared to pure distilled water at 16.7 °C, which is reckoned to be unity. By comparing the weights of equal bulks of other bodies with the weight of water their specific gravity is obtained. In practice the fruit or vegetable is weighed in air and then in pure water, and its weight in air is divided by the loss in weight in water thus giving its specific gravity. As fruit mature their specific gravity increases. This parameter is rarely used in practice to determine when to harvest a crop but it could be where it is possible to develop a suitable sampling technique. It is used, however, to grade crops into different maturities postharvest. To do this the fruit or vegetable is placed in a tank of water and if they float they will be less mature than those which sink. To give greater flexibility to the test and make it more precise, a salt or sugar solution can be used in place of water in the tank. This changes the density of the liquid resulting in fruits or vegetables that would have sunk in water, floating in the salt or sugar solution. Lizada (1993) showed that a 1% sodium chloride solution was suitable for grading Carabao mangoes in the Philippines. Also in Thailand it was found that an increase in fruit density or specific gravity was well correlated with eating quality in mangoes (Kudachikar *et al.* 2001).

Diffuse light transmission

A strong light can be shone on a fruit, some of which may actually diffuse through it and can be collected and measured on the other side of the fruit. These light transmission properties of fruit can be used to measure their ripeness. The wavelength of peak transmittance of light through fruits was shown to have good correlation with their maturity (Birth and Norris 1958). This was tested on tomatoes, and a portable easy-to-use instrument was developed which was non-destructive and could be used on several types of fruit that reduces during maturation. In apricots the correlation coefficients were in the range of 0.84–0.93. The transmission of near-infrared light has been used as a non-destructive method for measuring the soluble solids content of cantaloupe melons (Dull *et al.* 1989). Czabaffy (1984, 1985) measured diffuse light transmission in the range of 380–730 nm through cherries and found that it was shown to be affected by the level of chlorophyll in the fruit. Chlorophyll decreases during maturation so this could be used as a maturity measurement.

Delayed light emission

Colour sorting equipment is commercially available for use in packhouses. Delayed light emission (DLE) is detectable for times ranging from milliseconds to many minutes and is induced by back reactions of the photosynthetic pathway and therefore requires functional chloroplasts. It is detectable only in the dark following light excitation. It yields very low energy and decays very rapidly (Abbott *et al.* 1994). Essentially DLE is used to measure chlorophyll content of fruit, which not only varies with maturity of the fruit but can also vary with cultivar. DLE measurements require selection of duration and intensity of illumination, dark period and temperature for each cultivar tested. DLE has been used on fruits such as Satsuma oranges (Chuma *et al.* 1977), bananas (Chuma *et al.* 1980a, 1980b), tomatoes (Forbus *et al.* 1985) and papaya (Forbus *et al.* 1987) to grade fruit objectively into different maturity groups postharvest. The fruit is exposed a bright light inside a dark enclosed compartment and then the light is switched off so the fruit is in the dark. A sensor measures the amount of light emitted from the fruit, which is proportional to its chlorophyll content and thus to its maturity.

Twist tester

Studman and Yuwana (1992) described a twist tester developed at Massey University in New Zealand. It consisted of a blade fixed at 90° to a horizontal spindle. The fruit was pushed onto the spindle and rotated around the spindle until the blade crushes the flesh and the fruit turns freely. The angle that the fruit rotated before tissue failure was measured using a potentiometer and this angle then was converted into a crushing strength using formulas. Essentially the twist tester measures firmness as crush strength by radial movement of a small calibrated blade at any point. In non-peeled nectarine fruit Griessel (1995) showed the differences in rate of softening between the inner and outer mesocarps and was used in the determination and prediction of harvest maturity for the cultivar May Glo. It has also been successfully used on kiwifruit.

Body transmittance spectroscopy

Body transmittance spectroscopy was used for optical grading of papaya fruits into ripe and not ripe groups (Birth *et al.* 1984). With this method it was possible to grade fruits that were indistinguishable by visual examination.

Photoelectric

A photoelectric machine was used for colour sorting citrus fruit (Jahn and Gaffney 1972). They used ESM model G and were able to separate oranges and limes into different classes on the basis of their chlorophyll levels. Watada (1989) has expressed transmittance data on scattering samples:

$$\text{optical density} + \log_{10}(E_o/E)$$

where

E_o = the incident energy
E = the transmission energy.

Diffuse reflectance

Diffuse reflectance measures the reflected light just below the surface of the crop. It was shown to be effective with persimmon with a diffuse reflectance of 680 nm suitable for automatic grading lines (Chuma *et al.* 1980a). In lettuce there was a shift in diffuse reflectance from 640–660 to 700–750 nm during maturation (Brach *et al.* 1982).

Colour difference meters

Colour difference meters can be used to measure the chlorophyll content of fruits and vegetables (Medlicott *et al.* 1992, Meir *et al.* 1992). Chlorophyll content can vary during maturation and senescence of crops and therefore it might be possible to adapt this method in objectively measuring crop maturity. A colour difference meter (Minolta Chroma CR-200) was successfully used to measure the surface colour of peaches and relate this to fruit pigments, soluble solids content and firmness (Kim *et al.* 1993). The range of dominant wavelengths varied between peach cultivars but they were all within the range of 565–780 nm (Kim *et al.* 1993). A colour difference meter, Minolta Chroma CR-200 (Figure 8), was successfully used to measure the surface colour of peaches and relate this to fruit pigments, soluble solids content and firmness (Kim *et al.* 1993). Colour difference meters measure various properties of colour expressed as L*, a* and b*.

Heat units

Day degrees or heat units are used to compute harvest dates for vining peas and predict maturity dates for cauliflower and broccoli (John Love, personal communication).

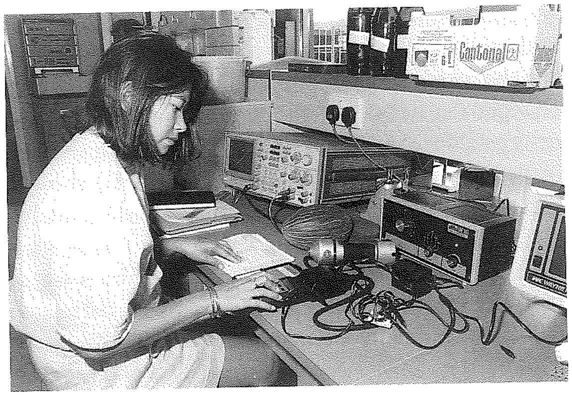

Figure 8 A colour difference meter being used to measure the colour of melons at Cranfield University in the United Kingdom. (Source: A.J. Hilton. Reproduced with permission of Cranfield University.)

Acoustic and vibration tests

The sound of a fruit as it is tapped sharply with the knuckle of the finger can change during maturation and ripening. Consumers sometimes use this method of testing when purchasing fruit. Fruits such as melons may be tapped in the field to judge whether they are ready to be harvested. This method may also be used postharvest to determine their maturity, for example in pineapples. The principle of the method has been applied in equipment that puts vibration energy into a fruit and measures the response of the fruit to this input (Figure 9). Although much of this work is in the experimental stage, good correlations

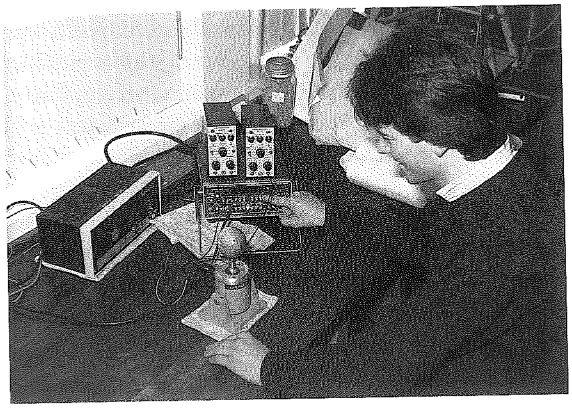

Figure 9 Equipment which puts vibrational energy into fruit and measures its response being tested on apples at Cranfield University. (Source: A.J. Hilton. Reproduced with permission of Cranfield University.)

have been found using the second resonant frequency to determine the maturity of apple, tomato, mango and avocado (Darko 1984, Punchoo 1988). The following formula was used based on the work of Cooke (1970):

$$f_2^{2} \cdot m^{2/3}$$

where:

f_2 = the second resonant frequency
m = the mass of the fruit.

Commercial audio speakers have been used as vibration exciters with the response of the fruit (Mutsu apples and Nijitsu-seiki pears) measured on a computer-controlled strain gauge. During storage for 20 days it was found that the resonance frequency shifted from 110 to 80 Hz suggesting that the method was measuring some quality change (Ikeda 1986). Velocity of propagation of mechanical pulses through whole apple fruits can be used to provide a non-destructive method of monitoring changes in the elastic properties of the tissue (Garrett and Furry 1974). These elastic properties may be related to the degree of fruit maturity and other characteristics such as fruit firmness and toughness (Garrett and Furry 1974). Self *et al.* (1993) have shown that there is a relationship between ultrasonic velocity and the maturity and ripeness of bananas, the ripeness of avocados and perhaps the internal browning in pineapples. Mechanical resonance techniques have been applied to apples and tomatoes (de Baerdemaeker 1989). The second resonant frequency in apples was shown to reduce with ripeness, with 600–750 Hz for non-attractive unripe fruits to 200–500 Hz for not attractive, over ripe fruit. Attractive, ripe fruit were in the frequency range of 400–600 Hz. Similar results were shown for the stiffness factor. The stiffness factor in tomatoes was also shown to decrease during storage. Equipment developed by de Baerdemaeker at the Katholieke Universiteit in Leuven in Belgium uses a small microphone mounted in a piece of plastic pipe containing shaped polystyrene on which the fruit is placed about a centimetre from the microphone. The fruit is tapped lightly with a small object (a pencil will do) on the side of the fruit opposite to the microphone, and the first resonant frequency, picked up by the microphone, is measured. The measurement was found to change with the changes in fruit ripeness.

Measurements of acoustic responses of apples were tested against human auditory sensing and found to correlate well in the first and second resonant frequencies (Chen *et al.* 1992). In Japan this technique, based on acoustic impulse responses, has been developed and installed in commercial packing facilities (Kouno *et al.* 1993c). It is being used for watermelons to detect both the ripeness and any hollowness in the fruit. Nine machines have been installed and they are as accurate in grading melons as skilled inspectors using 'the traditional slapping method'. Kouno *et al.* (1993b) described their ripeness and hollowness detector that was called MWA-9002.

A sensor system for automatic non-destructive sorting of firm (tree-ripe) avocado fruits used vibrational excitement of one side of the fruit, while measuring the transmitted vibration energy on the other. Special signal processing hardware and software were developed for computing several alternative firmness indexes, which were highly correlated with value obtained by the standard destructive piercing force test method. Optimal classification algorithms were developed whereby fruit could be classified into two or three firmness grades (Peleg *et al.* 1990).

While success has been shown with these methods, it is not always clear exactly what characteristic or group of characteristics of the fruit is being measured. Good correlation was shown between weight loss of fruit and changes in resonant frequency in apples (Ghafir and Thompson 1994a, 1994b). Terwongworkule (1995) showed that stiffness coefficient was related to weight loss in stored apples in that where the fruit were stored at high humidity the stiffness coefficient remained constant and when they were stored at low humidity it reduced in proportion to weight loss. It appears therefore that stiffness coefficient in apples is related to their moisture content or some related factor and would not be of use in measuring its maturity or ripeness.

Acoustic response measurements gave a reliable indication of the change in mechanical properties of fruit including fruit maturity and ripeness as well as water status, which was not detectable by conventional firmness measurements. Duprat *et al.* (1997) compared penetrometer measurements of firmness of Golden Delicious apples with an acoustic impulse method during 8 months of storage at 1 °C and 96% r.h. They found that the penetrometer measurements provided better discrimination between immature fruit, while the acoustic impulse response measurements were superior for ripe fruit. Tu *et al.* (2000) also used acoustic non-destructive measurements for changes in firmness of apples. Yurtlu (2012) compared a lateral impact test, low mass impact methods and acoustic impulse response and with a Magness and Taylor penetrometer on peaches. The best correlation of the data was found between modulus of elasticity and the non-destructive lateral impact parameter. The highest correlation in all parameters was found between low mass impact methods. Shmulevich *et al.* (2003) demonstrated the advantage of measuring avocado fruit by a low-mass impact technique compared to the acoustic technique.

Electrical properties

Studies have been carried out passing electrical currents through fruit. Some correlations have been shown between different characteristics of the fruit, some of which are related to fruit ripening, and the way the current passes through the fruit (Nelson 1983, Kagy 1989). Koto (1987) found a difference in electrical properties between fresh fruit and those that were spoiled or physically damaged. He showed that capacitance of deteriorated cells increased while resistance would decrease, and therefore these measurements could be used to determine the freshness or age of the fruit. McLendon and Brown (1971) also found that the dielectric properties (resistivity and conductivity) of peaches changed with fruit ripeness. At 500 Hz the dielectric constant of green peaches was 550 while for ripe peaches it was 150. At 5000 Hz the figures were 300 and 100, respectively. These figures appear to be high because the dielectric constant of water under these conditions is 80 and grain 4 (B.C. Stenning, personal communication). In watermelons specific electrical resistance appeared to decrease with increasing sugar content (Nagai 1975). In work on honeydew melons Kagy (1989) found no significant relationship between capacitance, loss tangent and resistance and weight loss firmness and sugar content. The measurement of electrical impedance of Granny Smith apples after impact tests showed good correlation with bruise levels, with no significant changes in the impedance properties of the fruit after the initial damage had occurred (Cox *et al.* 1993). These electrical properties are exploited widely in the measurement of moisture content of low moisture products (Dull 1986), but there are no publications to indicate that the method has been sufficiently developed for use in determining maturity of fruits and vegetables.

Electromagnetic

Nuclear magnetic resonance (NMR) spectroscopy has been developed in human pathology to provide real time images of the inside of the body. It can be used for detecting protons and the variation and binding state on water and oil. Such equipment can be used to provide similar micro-images of the internal structures of fruits (Williams *et al.* 1992). NMR has also been shown to correlate well with sugar content of bananas and apples (Cho and Krutz 1989) and oil content in avocados (McCarthy *et al.* 1989). The technique of using a surface coil NMR probe to obtain the oil/water resonance peak ratio of the signal from a region of an intact avocado fruit produced the best result and has desirable features for high-speed sorting (Chen *et al.* 1993). NMR was also shown to be effective in detecting the physiological disorder, water core, in apples (Wang *et al.* 1988). Magnetic resonance imaging has been used to obtain images of bruises on apples, peaches, pears and onions, pits in olives and prunes and insect damage in pears (Chen *et al.* 1989). Shewfelt and Prussia (1993) pointed out that its cost and speed of operation limit the great potential of magnetic resonance imaging. Williamson (1993) acquired three-dimensional data sets from using NMR microscopy with a high field spectrometer (7.2 T; 300 MHz), and with surface rendering techniques was able to display the spatial arrangement of seeds and vascular tissue of soft fruit.

Near-infrared reflectance

Near-infrared reflectance (NIR) can be used for measuring moisture content using light-emitting diodes. These operate at water-absorbing wavelengths, which may find application in rapid on-line determination of soil moisture, milk and feed composition (Cox 1988). An NIR spectrum analyser has also successfully been used to test the taste of rice and results correlated well ($r = 0.926$) with results from a taste panel (Hosaka 1987). NIR has been studied in relation to measuring the internal qualities of fruit. Correlations between sugar content of apples, peaches, pineapples and mangoes and NIR measurement have been shown (Kouno *et al.* 1993a). NIR measurement was achieved, using a Nireco model 6500 near-infrared spectrophotometer, by placing the fruit so that the light beam on the surface was at right angles to the fruit surface and covered with a black cloth to avoid the influence of external light. Four places around the equator of the fruit were selected and the NIR beam was irradiated at 2 nm intervals from 400 to 2500 nm onto the fruit and the average absorbance was measured (Kouno *et al.* 1993b). Fruit firmness, acidity and soluble solids content were measured directly afterwards on the same fruit, and adequate correlations were shown between the NIR measurement and soluble solids content for both mangoes (multiple regression coefficient of 0.954) and pineapples (multiple regression coefficient of 0.825). Results for acidity and firmness were also encouraging for mangoes that had a multiple regression coefficient of 0.856 for acidity, 0.949 for the firmness of the unpeeled fruit and 0.920 for the peeled fruit. For pineapples the multiple regression coefficients were 0.686 for acidity, 0.460 for firmness of unpeeled fruit and 0.568 for peeled fruit (Kouno *et al.* 1993b). Near-infrared techniques have been used in the measurement of moisture content in crops (Williams and Norris 1987) and have been shown to be able to measure sugar content of fruit non-destructively (Chen and Sun 1991). NIR spectral data gave good correlations with nitrogen and calcium concentrations of pear fruit peel. It may therefore be possible to obtain information on the actual percentage of fruits with undesirable mineral concentrations, and non-destructively segregate desirable and undesirable fruits before they are placed into store (Righetti and Curtis 1989). Peirs *et al.* (2000) showed for Jonagold, Golden Delicious, Elstar, Cox's Orange Pippin and Boskoop apples that it is possible to use NIR spectroscopy as a non-destructive technique for measuring internal apple quality. Saranwong *et al.* (n.d.) used dry matter as harvesting indices for hard green mangoes and developed NIR calibration equations that were sufficiently precise for determining dry matter and starch of hard green mangoes. Ripe mangoes would have excellent eating quality and high TSS if the fruit contained sufficient amounts of dry matter and starch at harvest date. They found that the TSS of ripe mangoes could be precisely predicted from the dry matter and starch measured non-destructively with NIR at harvest. NIR was also shown to have the capability of measuring TSS and DM in the ripe mango cultivar Caraboa (Saranwong *et al.* 2003). Lu *et al.* (2000a, 2000b) evaluated the potential of NIR diffuse reflectance between 800 and 1700 nm for determining the firmness (compared to a Magness and Taylor firmness test) and sugar content of Empire, Golden Delicious and Red Delicious apples. From the data they developed statistical models using principal component analysis/regression. Improved predictions were obtained when NIR reflectance was correlated with the slope of the Magness and Taylor force-deformation curves. NIR reflectance also showed good correlation TSS content in peeled apples. This was confirmed by Park *et al.* (2003) who used diffuse reflectance measurement between 400 and 1800 nm regions of the spectrum on the apple cultivars Gala and Red Delicious. They compared them with TSS and firmness by the Magness and Taylor penetrometer and showed good correlations with principal component regression and Mahalanobis distance analysis.

Radiation

Both X-rays and γ-rays have been used to assess quality and maturity characteristics of fresh produce. A lettuce harvester was developed which used X-rays to determine which heads were sufficiently mature for harvesting (Lenker and Adrian 1971). Garrett and Talley (1970) used γ-rays for the same purpose. The basis of these tests depends on the rate of transmission of the rays through the lettuce, since this depends on the density of the head that increases as the lettuce matures. X-rays can also be used to detect internal disorders of crops such as hollow heart in potatoes Finney and Norris (1973), split pit in peaches (Bowers *et al.* 1988) and granulation in oranges (Johnson 1985). X-rays were used in prototype potato harvesters to differentiate between the tubers and extraneous matter such as clods of earth and stones (Whitney 1993). The equipment was mounted behind the chain lifter, but was found to be impractical because the height of fall of the tubers was too great. Butz *et al.* (2005) describe terahertz radiation (T-rays) that is in the far-infrared region. Unlike X-rays, T-rays are not harmful, so there are no exposure worries. They commented that they were not being used at that time on fruit and vegetable but non-invasive food applications were possible e.g. determination of the ripeness of tomatoes.

Physiological

For fruit, which pass through a distinct climacteric rise in respiration during ripening, it may be possible to sample the fruit, keep it at a relatively high temperature (for apples in Britain a temperature of about 20 °C would be appropriate) and measure its respiration rate. By doing this it may be possible to predict the number of days the fruit would have taken if left on the tree to commence the climacteric rise. Respiration rate is calculated by measuring their uptake of oxygen or the output from the fruit of such gases as carbon dioxide, ethylene or other organic volatile compounds associated with ripening. Recasens *et al.* (1989) measured the concentration of ethylene in the core of apples at different times during maturation and found that for many cultivars the commercial harvest date was 10–15 days after the initiation of the ethylene increase. However, there are problems of applying this method in practice. Testoni and Eccher Zerbini (1989) found high variability in the ethylene content between fruits and also poor correlation between internal ethylene and other maturity indices such as skin colour, firmness, TA and soluble solids. In previous studies on the respiration rate of apples it was found that for the cultivars studied, which were Cortland, Delicious, Golden Delicious and McIntosh, there was no definite point on the climacteric curve associated with harvest date (Blanpied 1960).