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Mealiness detection in agricultural crops: Destructive and Non-destructive tests. A review

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Abstract

Mealiness is known as an important internal quality attribute of fruits/vegetables which makes significant influence on consumer marketing decision. Mealiness phenomenon has been a topic of research interest over the past decades. In this review, the concept of mealiness is presented for potato, apple, and peach, followed by an in-depth discussion about application of destructive and non-destructive techniques in mealiness detection. The results suggest the potential use of electromagnetic-based techniques in evaluation of mealiness. Further investigations are in progress to find more appropriate techniques for cost and performance.

Keywords: Compression test; Non-invasive method; Optical techniques; Sensory evaluation; Texture attribute.

1- Introduction

It is obvious that quality of agricultural products plays an important role in human health. There are different definitions for quality. According to Abbott's expression, acceptability of a product for a specific usage can be defined as quality (Abbott 1999). Quality of agricultural products is evaluated in terms of external and internal characteristics such as… (Table 1). External characteristics have a significant effect on the consumer's decision to buy a particular product. Since external characteristics are readily perceived by sense of sight or touch, measurement of them has been studied considerably. Initially, fruits were classified by visual inspection by trained workers according to size, color, and defects. With the development of computers, human inspection has largely been substituted by new vision-based methods. At present, some sorting lines have been developed to separate fruits according to size, color, and external defects (Barreiro and others 2004). In addition, awareness of internal characteristics has been a topic of research interest in recent years, due to the obvious competitive advantages possible. Unlike external characteristics, information on internal characteristics cannot be obtained through human vision of the exterior. On this basis, studies for introduction of non-expensive methods with high accuracy and speed are still in progress.

Fruit/vegetable texture has high importance for consumers (Moshou and others 2003). Results of a survey in European countries showed that people considered texture as the most important attribute for some fruits/vegetables (Table 2), leading to the necessity of objective texture measurement. There are many publications in which texture attributes measured by instrumental tests. Shear (Harker and others 2002), compression (Shinya and others 2013), penetration (Rizzolo and others 2010), and tension (Harker and others 2002) tests are examples of those instrumental tests. In addition, many methods were developed to measure texture attributes of the fruits/vegetables non-destructively.

Texture is related to the cellular structure of the sample tissue (Barreiro and others 1998). Flesh firmness, crunchiness, crispiness, hardness, mealiness, and juiciness are some of the most common texture attributes (Zdunek and others 2010). Among texture attributes, mealiness is one of the most challenging as it cannot be expressed only by a single sensory attribute; a combination of sensory descriptors is necessary, for example a combination of juiciness and hardness (Barreiro and others 1998). Fruits/vegetables with a soft and lack of juiciness flesh during consumption are characterized as mealy (Moshou and others 2003). Mealiness development depends on cell wall ingredients, growing and storage conditions, variety, harvest date, and size of the sample. Mealiness occurs in some fruits and vegetables including, potato, tomato, apple, peach, and pea (Devaux and others 2005).

Many studies, ranging from sensory evaluation to spectroscopy-based techniques have been

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conducted to measure mealiness (Table 3), sometimes supported by mathematical modeling of cellular physiology (De Smedt and others 2002). Early studies were based on sensory evaluation in which a group of trained people score the level of mealiness. Later, different instrumental tests including puncher, shear, compression, and tensile tests were applied to find a relationship between them and mealiness. Since instrumental tests were time-consuming and destructive, non-destructive tests were developed. These methods can be divided into mechanical and electromagnetic techniques.

This paper covers an in-depth review on more publications in the field of mealiness detection since 1930s. Furthermore, this paper is intended to study mealiness in potato, apple, and peach because most of publications focused on them. Theory of mealiness development is discussed for each of them individually. Then destructive and non-destructive methods applied to detect mealiness are debated. At the end, results of each technique are summarized and some suggestions are given.

2- Mealiness phenomenon

Mealiness is an important texture attribute appearing in some fruits and vegetables. Cell separation instead of cell rupture is known as the most possible cause of mealiness. The mechanism in which cells are separated may be a little different for various crops. In the following, mealiness phenomenon is described for potato, apple, and peach samples.

2-1- Mealiness phenomenon in potato

The quality of cooked potatoes is assessed by texture which significantly affects on the consumer's purchase decision. Potato texture is often represented by mealiness, hardness, moisture, consistency, sloughing, and mouth feel characteristics (Woodmann and Warren 1972; Thybo and others 2000). However, consumers from different countries have different preferences about the cooked potatoes texture. They often prefer mealier potatoes for boiling and baking. Also mealy potatoes are considered more suitable for chipping and frying by industries (Greig and Smith 1950; Mccomber and others 1988). A cooked potato with a dry and flaky texture is considered as a mealy potato. A mealy potato crumbles easier than a non-mealy one (Burton 1948). Microscopic inspection showed that cell separation without breakage was the most likely cause of mealiness in potato (Karlsson and Eliasson 2003). Internal pressure of cell, cell wall constituents, and a combination of them have been reported as different possible causes of cell separation. In case of internal pressure of cells, when a potato is heated, starch grains within the cells are gelatinized and swell. The swelling process exerts an internal pressure on the cell walls and results in cell separation (Sterling 1955). Later in 1977, this result was proved by Sterling and Aldridge. They studied texture of two mealy and non-mealy potato varieties before and after baking. Microscopic images of the raw potatoes showed that starch grains were more numerous within the cells of the mealy potato compared to non-mealy one (Figure 1). Mealy baked potatoes showed the swelled cells that were separated and caused capillary space to be created (Figure 1). In case of cell wall constituents, cell separation is thought to be due to middle cell wall and lamellar constituents. Sterling and Bettelheim (1955) reported that a weak middle lamella allowed separation of cells. Dissolution of calcium-pectic gel in middle lamella has a significant role in its weakness and so results in the separation of cells (Jarvis and Duncan 1992). In 1992, Jarvis and others reported that both starch gelatinization and pectin degradation caused separation of cells. Important role of both pectic materials and starches on potato texture had been already pointed out by Reeve (1977).

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2-2- Mealiness phenomenon in apple

Texture has a significant role at marketability of apple (Jaeger and others 1998). Consumers often prefer a crispy and juicy apple. Apples gradually lose their firmness, crispiness, and juiciness during cool storage (Johnston and others 2002). This type of apple is characterized as mealy (Gómez and others 1998). Since eating a mealy apple produces a dry sensation (like starch) in the mouth, mealiness in apple is considered as a negative quality characteristic by consumers and so reduces the commercial value (Andani and others 2001). The process of mealiness development is related to changes of the strength of the cell walls and the middle lamella (Harker and Hallett 1992). In fresh apples, the middle lamella is strong enough to provide adhesion between neighboring cells. Apart from high adhesion, the cell walls are very fragile. Combining the fragile cells and a strong middle lamella will cause the cell walls to break (Figure 2-a), releasing cellular liquid content and resulting in a fine sensory sensation during chewing (Harker and Hallett 1992). During storage the middle lamella loses its strength and a softening phenomenon occurs (Billy and others 2008). With diminishing cell adhesion, applying a load on the apple tissue (e.g. chewing process) causes separation of cells instead of cell rupture (Figure 2-b) (Reeve 1970; Haard and Salunkhe 1975). In this case, individual cells preserve their contents and so consumer perceives it as a non-juicy fruit. It was reported that chemical changes in pectin compositions, as major components of the middle lamella, had a significant role in decreasing adhesion force between the cells (Yoshioka and others 1992; Grant Reid 1997).

Different factors such as the cultivar, harvesting date, storage condition (including air composition, temperature, and relative humidity) and fruit size can affect mealiness development (Costa and others 2012; Galvez-Lopez and others 2012). Intensity of mealiness can vary among different apple varieties (Lapsley and others 1992). Nara and others (2001), for example, stored eight apple varieties (Fuji, Iwai, Golden delicious, Jonagold, Tsugaru, Starking delicious, Natsumidori, and Akane) at 20^{o} C for a certain time. After 8 weeks, the lowest and the highest development of mealiness were observed for Golden and Starking delicious, respectively. Effect of harvesting date on mealiness advancement has been investigated from years ago. Fisher (1943) noticed that mature apples became much mealier than immature ones. Similar results were reported later (Harker and Hallett 1992; Barreiro and others 1998). Since apples are stored for a long time, undoubtedly storage conditions can have an important role in controlling mealiness. For this aim, several studies have been carried out to consider effect of storage conditions. Studies showed that under low oxygen (ULO) conditions, apples became mealy slower than normal air conditions (De Belie and others 2000; Rizzolo and others 2010). Moreover, temperature was defined as an effective parameter of storage condition. For inducing mealiness, it is enough to store apples under a high relative humidity (95%) and a high temperature (20^{o} C) for a few weeks (Barreiro and others 1998; FAIR 1998). During long storage, water loss results in softening and so mealiness of apples (Hatfield and Knee 1988). It was showed that relative humidity had a significant effect on weight loss and firmness. Apples in the higher relative humidity (95%) preserved their firmness and weight better than those in the low RH (25%). In addition to cultivar, harvesting date, and storage condition, fruit size has been introduced as an effective feature in mealiness. Small apples in size were less prone to mealiness than large ones (Barreiro and others 2000; De Smedt 2000).

2-3- Mealiness phenomenon in peach

Chilling injury is a physiological disorder which develops in some fruits such as peaches, apricot, and plum. Mealy texture, flesh browning, and failing to ripe properly during cold storage are symptoms of chilling injury (Lurie and Crisosto 2005). Crisosto and others (1999) reported that in most cases the mealy phenomenon commenced prior to flesh browning. Also it was noticed that simultaneous development of both mealy and flesh browning was rare. In addition, there were some peaches in which only mealiness occurred. On this basis, focusing on mealiness detection instead of flesh browning was proposed.

Mealiness in peach, also called wooliness, is considered as an unfavorable sensory attribute (Campos-Vargas and others 2006). Peaches are gradually softened during cold storage. After a long period of storage, abnormal softening is occurred and juicy flesh is turned to a dry and mealy texture. Mechanism in which mealiness is occurred has been well known by researchers (Brummell and others 2004; Lurie and others 2003). It is due to changes in pectin metabolism. Altering balance of polygalacturonase (PG) and pectinesterase (PE) activities was introduced as one of the main causes. Under cold conditions, activity of PG is reduced while significant changes do not occur in PE activity. It leads to impaired solubilisation of pectin and results in the build up of insoluble low-methoxy pectic compounds. Insoluble compounds in the apoplast, such as gel-forming pectic compounds, trap free water and result in a dry mealy texture (Zhou and others 1999; Brummell and others 2004; Lurie and others 2003). A larger amount of insoluble pectic material with heavy molecules was observed in mealy peaches rather than in fresh ones (Lurie and others 1994). Another theory was that mealiness in peach might be due to decreasing intercellular adhesion and so cells separation instead of rupturing, like apple and potato (Brummell and other 2004).

Mealiness intensity is related to different factors including genetic background, cultivars, maturation stage, size, and seasonal conditions (Crisosto and others 1999; Lurie and Crisosto 2005; Campos-Vargas and others 2006). The peaches early harvested were more susceptible to mealiness (Ortiz and others 2000; Girardi et al., 2005), although other researchers introduced the mature fruits mealier than immature ones (Guelfat-Reich and Ben Arie 1966; Salunkhe and others 1968). Like other fruits, role of storing conditions in preserving quality of peach is very important. A delay in development of mealiness and flesh browning was obtained for low value of O_2 and high CO_2 (Girardi et al., 2005).

3- Mealiness detection approaches

3-1- Destructive tests

3-1-1- Relationship between texture attributes and physical, chemical, and sensory measurements

Sensory test is a way in which characteristics of agricultural crops are described by the senses of touch, smell, taste, sight or hearing. For this aim, people are trained well and they score the samples according to the specific attributes (Andani, 2000). In addition to sensory test, different attributes of fruits/vegetables can be determined by chemical and physical measurements. Summary of these methods applied to mealiness detection in potato, apple, and peach is brought in following.

a- Potato

Numerous studies have been carried out to associate physical (specific gravity, starch granule size, and cell size) and chemical (starch content, protein, dry matter, nitrogen, etc) properties with mealiness in potato.

Specific gravity has been introduced as a useful property in mealiness detection. Many publications have reported a good correlation between specific gravity and mealiness (Heinze and others 1955; Smith 1955; Bettelheim and Sterling 1955). A study was conducted by Unrau and Nylund (1957 a) to detect mealy potato from non-mealy by specific gravity. For this aim, three potato varieties Waseca, Cobbler, and Red Pontiac were used. Potato tubers of each variety were categorized within two different specific gravities (1.080 and 1.100). The potatoes were then baked and evaluated for mealiness by a test panel consisting of seven assessors. Test panel members gave scores 1-10 to the boiled potatoes according to their mealiness. The obtained results for the samples within each individual variety showed that differ in specific gravity leaded to differ in mealiness. In some cases, the samples belong to different varieties had identical specific gravities but they differed in mealiness. This means that application of specific gravity as a practical method for mealiness detection is not absolutely reliable (Cunningitam and other 1965). Similarly results were reported by other researchers (Haddock and Blood 1939; Nylund and Poivan 1953).

Larger starch grains were observed for raw mealy potato than non-mealy ones (Thygesen and others 2001; Mccomber and others 1994). However, Unrau and Nylund (1957b) reported no association exists between starch granule size and mealiness. Beside the starch granule size, larger cells with more irregularly shape were observed for raw mealy potatoes (Mccomber and others 1994).

The positive correlation of starch content with mealiness in potato has been observed by Barmore (1937), with correlation coefficient of r= 0.56. To understand the most effective properties for describing mealiness, a study was carried out by Thygesen and others (2001). In that study, eleven properties (starch content, dry matter, size of starch grains, nitrogen, citric acid, phytic acid, Ca, Mg, Na, K, and pectin methyl-esterase activity) were considered for different potato varieties. An expert sensory panel of 10 assessors analyzed the boiled potatoes and described potato texture by mealiness. There was a significant positive relationship at level 5% between chemical variables (dry matter content and citric acid) and mealiness. Since starch content includes about 60-80% dry matter content, it could correlate with mealiness well. The good correlation of dry matter and mealiness is reported by several researchers (Freeman and others 1992; Mccomber and others 1994).

Negative associations were found between mealiness and nitrogen with some low correlation coefficients (Barmore 1937, Thygesen and others 2001). For example, a correlation coefficient -0.34 was obtained by Barmore (1937).

As mentioned above, several physical and chemical properties in addition to sensory tests have been used to describe texture attributes of potato. As a conclusion, dry matter content and starch content can be introduced as the most reliable chemical properties for describing texture attributes of potato, especially mealiness.

b- Apple

Sensory analysis has been used for describing apple texture by many investigators. Barreiro and others (1998) investigated mealiness in three apple varieties (Jonagold, Cox’s Orange Pippin, and Boskoop) through sensory attributes: juiciness, hardness, crispiness, juiciness during chewing, toughness, density of flesh, fibrous, granular, floury, pulpy, and slimy were defined as texture attributes. A trained sensory panel scored the samples and it was noticed that a combination of texture attributes was needed for describing mealiness. Crispness, floury, juiciness, and hardness were introduced as the best combination of texture attributes in mealiness detection. Just two years earlier, in 1996, it was reported that hardness and juiciness were more important attributes for consumers (Daillant-Spinnler and others 1996). Another work was carried out by Harker and others in 2002. Panel test members were asked from to score apple samples for different texture attributes. Consumers could distinguish differences in apple samples using crispness, crunchiness, and juiciness. Since these attributes are related to mealiness, it can be concluded that mealy apples may be detected by sensory tests.

Observation of the cell structure by microscope has also been used to detect mealiness. In a study by De Smedt and others (1998), three apple cultivars (Jonagold, Cox's Orange Pippin, and Boskoop) were stored under 20° C and 95% RH to the moment they became mealy. Apple samples were applied to tensile test and their microscopic images were then obtained. Images showed that the number of intact cells (i.e. the cells that did not break during tensile test) were higher in mealy apples than non-mealy ones. Similar results were reported by Tu and others (2000) and Tu and others (1996) too. In addition, morphological features of the cells (e.g. area, perimeter, and roundness) were considered. Results showed that morphological features could be used to categorize Cox's Orange Pippin and Boskoop apples into the categories fresh and mealy. The cells of mealy apple were more rounded (Figure 3). More circular cells in mealy apples than non-mealy ones were also observed by Hatfield and Knee (1988). Additionally, they reported a lower amount of intercellular spaces in fresh than mealy apples. This result was also found by other researchers (Vincent 1989; Harker and Hallett 1992).

Some attempts were carried out to associate SSC with mealiness. Reports showed a decrease in SSC when apples became mealier (Marigheto and others 2006, Marigheto and others 2008, Rizzolo and others 2010). In addition, a relationship between titratable acidity (TA) and mealiness was investigated for Red delicious apples (Rizzolo and others 2010). A significant negative correlation (r= -0.7) was observed.

As a conclusion, a combination of sensory attributes including juiciness, hardness, and crispiness may be more useful in detection of mealy apples.

c- Peach

Detection of mealy peaches was investigated through a panel test (Crisosto and Labavitch 2002). Judges scored the samples by the sense of taste and sight. In a visual way, the fruit was cut in half and its flesh was inspected for mealiness symptom. In this way, the flesh was squeezed by the hand and it was scored according to amount of juiciness. In taste manner, judges scored the samples for intensity of the feeling of graininess. One week before appearing mealiness symptom, it was possible to detect mealy peaches by the sense of taste.

In another study, mealy peaches (O'Henry and Summer Lady cultivars) were detected through visual symptom (Obenland and others 2003). Released juiciness after hand squeezing and also granular appearance of flesh was considered as mealiness indicator. Moreover, free juiciness (amount of juiciness extracted during consumption) was also measured using the technique proposed by Crisosto and Labavitch (2002), (refer to section 3-1-2-peach). It was found that visually mealiness detection was possible when free juiciness decreased to 30% and 46% for cultivars of O'Henry and Summer Lady, respectively. Hence, the visual detection of mealy peaches was introduced as an undesirable technique. On the other hand, relationship between Expansin protein and mealiness was studied. A decline in Expansin protein was noticed when peaches became mealy.

Mealiness, graininess, and off-flavor were considered as sensory attributes of peaches (cvs. Venus and BigTop) perceived by a panel test (Cantín and others 2010). A positive relationship was found between mealiness and graininess (r= 0.9). Moreover, off-flavor showed high positive correlations with mealiness (r= 0.63) and graininess (r= 0.68).

Only a few numbers of samples can be evaluated by a sensory panel. In addition, sensory-based methods are subjective and time-consuming (Huang and Lu, 2010). For this reason, instrumental tests have been preferred. Different instrumental tests such as puncher, shear, compression, tensile tests, and also recording sounds generated during chewing are presented as follows.

3-1-2- Instrumental tests

a- Potato

Various instrumental techniques have been applied to describe potato mealiness. It could reasonably be assumed that a mealy boiled potato would be cut easier than a non-mealy one. Rathsack (1935) investigated the association between starch content and rate of cutting by a fine wire under a specific weight, reporting a positive correlation coefficient 0.53. This indicates that mealier potatoes had less resistance to shear than non-mealy ones. Similar results were noted by Unrau and Nylund (1957a). They used a food mixer to mash baked potatoes and the amount of required electrical energy was measured. The authors found a high negative correlation (r= -0.92) between mealiness and consumed electrical energy, indicating that mealy potatoes required less energy to cut. In addition, shear test has been used by other investigators to describe mealiness in potato (Mccomber and others 1987; Watson and Jarvis 1995). The puncture test is an alternative method used by researchers to measure firmness of potato (Barmore 1937; Huang and others 1990). In addition to shear and punching tests, compression test was used to measure mealiness. It was reported that a better description of texture quality was achieved through compression test (Diehl and Hamann 1979; Wium and others 1997; Nielsen and Martens 1997). Following these research findings, Thybo and Martens 1999 examined texture properties of potato using the compression test as applied to seven different potato varieties. Before any test, potatoes were boiled within 20-25 min. Nine sensory attributes of the boiled potato (Reflection from surface, hardness, firmness, springiness, adhesiveness, graininess, mealiness, moistness, and chewiness) were then measured by ten trained assessors. Cylindrical samples of the potato with diameter of 12 mm and height of 10 mm were cut and used in uniaxial compression test. Force-displacement parameters (stress, strain, and modulus of deformability) and several variables from the compression profile named TPA (fracturability, hardness, cohesiveness, adhesiveness, springiness, gumminess, and chewiness) were measured as described by Bourne (1978). Results showed that force-displacement parameters were better in description of the mechanical sensory attributes in comparison with TPA parameters. When a partial least square regression (PLSR) model was developed using stress and strain at fracture, modulus of deformability and dry matter, a relatively good correlation (r= 0.76) was found between measured and predicted mealiness.

In summary, the compression test is more suitable in detection of mealy potato compared to the other destructive tests.

b- Apple

In order to measure adhesion between neighboring cells of apple during storage, tensile test was applied on H-shaped section of samples (Harker and Hallett 1992). The sample was stretched at the rate of 2 mm/min until it ruptured. The obtained data showed a decrease of the tensile strength of fruit tissue during storage because of reduction in cell adhesion. On this basis, in 1996 a similar tensile test was used to investigate mealiness in apple during storage (Tu and De Baerdemaeker 1996). Ring-shaped samples were prepared and mounted on two half ring-shaped cylinders (Figure 4). The cylinders were subjected to an axial load at 50mm/min until rupturing. Results showed that force value at rupture point (maximum force) was less in mealy apples than that of fresh ones. Reduction of tensile rupture force during storage and under different RH conditions (30%, 65%, and 95% RH) was reported by Tu and others (2000) later. A more decrease of tensile rupture force was observed for 30% RH storage compared to 65% and 95% RH.

Different instrumental tests (including puncture, tensile, twist, Kramer shear tests, and the recording of chewing sounds) were investigated for explaining texture attributes of apple measured by a test panel (Harker and others in 2002). It was reported that the best description of crispness, crunchiness, hardness, juiciness, ease of breakdown, and mealiness was obtained for puncture test. Puncher force value 50 N was determined as a threshold for recognition of mealy apples cultivar of 'Royal Gala'.

Another study was conducted by Barreiro and others (1998) to correlate sensory attributes of apple with features obtained from a confined compression test. Confined compression is a test in which samples are confined by a ring during compression. For this aim, cylindrical samples of 1.7 cm height and diameter were prepared. The sample was confined in a disk which had a hole about the size of the sample. Filter paper was placed under the disk to collect release juiciness during compression. The sample was compressed by 2.5 mm at 20 mm/min using a probe of 15.3 mm (Figure 5). The extracted features of the confined compression test are presented in Table 4. FDl, F2, Areal, Area2, GRAD, and juiciness area were introduced as the most effective parameters for describing sensory attributes. Combination of these effective parameters could be successfully correlated with floury (r^2= 0.67), free juiciness at the first bit (r^2= 0.83), juiciness during chewing (r^2= 0.74), and crispness (r^2= 0.67) attributes. These were in agreement with the result found by Paoletti and others 1993. They reported a high correlation (r= -0.744) between mealiness and instrumental juiciness.

The possibility of predicting the sensory attributes of three apple varieties (Golden delicious, Braeburn, and Fuji) was examined using puncher and compression tests (Mehinagic and others 2004). The puncher test was done by an 11 mm probe in diameter which penetrated in the unpeeled flesh to 10 mm under speed of 50 mm/min. Data were recorded during penetration and force/displacement curve was acquired (Figure 6). Several parameters of force/displacement curve were defined to correlate with sensory attributes (Table 5). Beside the penetration test, a double compression process was applied on the samples (Figure 7). The sample was deformed to 7 mm at 50 mm/min. The studied parameters of force/time curve of the double compression test are presented in Table 5. All extracted parameters of penetration and compression curves were negatively in correlation with mealiness attribute. Correlation coefficients between the penetration parameters and mealiness ranged from -0.62 to -0.77. Better correlation was observed for the compression parameters. The highest correlation coefficients with mealiness were obtained for H_2 (r= -0.86), H_1 (r= -0.84), and gard1 (r= -0.82), respectively. Good correlation coefficients 0.91, 0.90, and 0.87 were reported between juiciness and compression parameters H_1, H_2, and Grad1 too. Additionally, a positive correlation was found between instrumental parameters, crunchiness, chewiness, and touch resistance. These are in agreement with the results reported by Harker and others (2002). After determining effective parameters, several models were developed to predict sensory attributes. The developed model for predicting mealiness consisted of H_2 and Grad1 that could present good results (r^2= 0.86).

As said earlier, mealiness is related to amount of free juiciness and softness. Since crispiness

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may be a good indication of flesh softness, some attempts have been carried out to measure crispness of apple through the sound generated during chewing (Harker and others 1997; De Belie and others 1999; Roudaut and others 2002; Ioannides and others 2007).

De Belie and others (2000) investigated the relationship between crispness of Cox's Orange Pippin apple variety with chewing sound). The chewing sounds were recorded by a microphone placed in the near of mouth. Fast Fourier transformation was applied on the recorded signals. Analyzing data by principal component analysis (PCA) introduced the chewing sound as a successful technique to separate apples based on their crispness. Although, it was previously reported that recording of chewing sound not only had not any benefit over other tests but it was a difficult test (Harker and others 2002).

In the recent years, chewing act was replaced by new developed instruments. In this mode, the common apparatus used for measuring mechanical properties of the tissue have been equipped to acoustic systems. So the sound produced during mechanical tests (for example penetration test) is recorded by a microphone. An instance of the instrument which simultaneously measures firmness and acoustic data is shown in Figure 8. Texture changes of different apple cultivars during shelf-life were investigated with this instrument (Zdunek and others 2010). Firmness parameter was measured through penetration test. Simultaneous with penetration test, sounds of flesh rupture were recorded by acoustic system in the range of 1–16 kHz. Acoustic signal peaks higher than a specific value was counted and sum of them (C_{AE}) was considered as acoustic parameter. In addition to instrumental tests, sensory attribute of mealiness was measured through trained panel test. Firmness and C_{AE} showed a decreasing trend during shelf life. Firmness and C_{AE} were correlated negatively to mealiness. Better correlation coefficient ($r= -0.39$) was resulted for C_{AE} than firmness parameter. Moreover, prediction of mealiness was done by developing calibration models (based on C_{AE} data) that explained 0.61% of variance. This result may be enhanced if prediction of mealiness is carried out by combining C_{AE} data and free juiciness measured separately.

In another study, simultaneous measuring acoustic and mechanical data was conducted to assess apple texture (Costa and others 2011). Compression test was applied on cylindrical samples and generated sound during compression was recorded by a microphone at 5 cm distance of sample. Twelve mechanical parameters were extracted from force-deformation curves and through acoustic-deformation curves, four acoustic features were obtained. In addition to mechanical and acoustic data, three sensory attributes of firmness, crispness, and juiciness were acquired. Development of PLS models based on mechanical and acoustic data showed good results for predicting firmness and crispness. It is suggested to develop calibration models for prediction of mealiness using these parameters in addition to free juiciness.

In summary, mealy apple detection through the compression test is preferred. The reason for this is that both information about free juiciness and flesh firmness can be obtained simultaneously and so better results will be achieved.

c- Peach

Instrumental techniques applied to peach fruits are the same as those used for potato and apple with the exception of free juiciness measurement.

Samples of the Maycrest peach variety at different ripeness were stored under cold conditions for 1 month (Ortiz and others 2000). Different instrumental tests were applied to categorise peaches into four classes, including crispy, non-crispy-high juiciness, non-crispy-intermediate juiciness, and non-crispy-low juiciness. Penetration test was applied on samples and the maximum force value during penetration was defined as firmness. Fruit samples of 1.4 cm diameter and 2 cm length were prepared for the shear test. Moreover, the sample was deformed at a rate of 20 mm/min until it was sheared. The maximum force was defined as shear crispness. Beside penetration and shear tests, compression test was applied on cylindrical samples (1.4 cm in diameter and length). In confined case, the sample was limited to a disk with the same size and it was compressed as size as 2 mm at a rate of 20 mm/min using a probe. Maximum force, hardness, degree of permanent deformation, and juiciness area were registered as compression parameters. In another case, the similar cylindrical samples were placed between two flat plates and they were pressed until rupture occurred. Rupture force was considered as compression crispness. Based on the results, wooly peaches were introduced as low hardness, non-crispy, and non-juicy fruits. Crispy peaches had shear crispness higher than 40 N and juiciness value above 2 cm^2.

Since sensation of lack of juiciness plays a negative role in consumer selection, most of researches have focused on measuring free juiciness. Centrifuging homogenized fruit was an early quantitative method for mealiness assessment that was introduced by Lill and Van der Mespel (1988) and Von Mollendorff and De Villiers (1988). In this method, fruit flesh was first homogenized and then centrifuged for a certain time. Finally, liquid phase was separated and expressed as percentage of total flesh. Difficult procedure and poor separation of liquid phase were its main obstacles (Crisosto and Labavitch, 2002).

To enhance the process of free juiciness measurement, Crisosto and Labavitch (2002) developed a new device (Figure 9). Peach flesh was subjected to different pressing forces during 1-10 min and subsequently the collected juiciness was centrifuged to remove solid particles. Ratio of juiciness weight to initial weight of the sample tissue was computed. Fruits were also subjected to a panel test to evaluate the sensory perception of mealiness. According to the results, free juiciness measured by the new developed device (Figure 9) was able to make a high correlation with mealiness perceived through panel test (r^2= 0.91). On the other hand, a comparison was made between this way and the method developed by Von Mollendorff and De Villiers (1988). Low correlation (r^2= 0.39) was observed between mealiness and free juiciness measured through Von Mollendorff and De Villiers's method. On this basis, quantitative method developed by Crisosto and Labavitch (2002) was proposed as a reliable way to perceive mealy peaches.

Recently an alternative way to measure free juiciness, named the paper absorption method (PAM) was introduced (Infante and others 2009). In this method, cylindrical samples of three different peach cultivars were prepared. The samples were weighed and covered with two sheets of paper. Weight of the each paper was measured previously. The enclosed sample was passed between two rollers and it was squeezed. Finally, the paper sheet which was in contact with flesh was weighed again and it was expressed as percentage of total initial flesh mass (mass/mass). Also a comparison between the PAM and Lill and Van der Mespel's method (1988) was performed. Moreover, free juiciness was also measured by a trained panel test. Results showed that the PAM could describe free juiciness with higher determination coefficient (r^2= 0.74) than that proposed by Lill and Van der Mespel (1988) (r^2= 0.64). In addition, the PAM process was done faster than that of Lill and Van der Mespel (1988).

Destructive tests are preferred as standard methods in mealiness detection. The best ones for different samples are summarized as follows. Measurement of chemical features including dry matter or starch content is the best way to identify mealy potatoes. For detection of mealy apples, the confined compression test has been introduced as the most practical technique. Free

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juiciness measurement by squeezing/pressing peach flesh is more suitable way in detection of wooliness. In addition, shear or compression test must be used to describe peach flesh for its crispness. Time-consuming and being destructive are the main disadvantages of destructive test that limit its application. For this reasons, studies are in progress at the moment to find more suitable techniques in aspects of cost, time, on-line potential, and being non-destructive. Nevertheless, using of destructive test as standard methods is inevitable.

3-2- Non-destructive tests

3-2-1- Mechanics-based techniques

In this section, three techniques including ultrasonic, acoustic, and force impulse response are discussed for their principles and applications.

a- Ultrasonic technique principles

Ultrasound was introduced in food processing in the 1970s to egg-albumin quality testing (Mizrach 2008). In this technology, an ultrasonic wave, produced using a transducer, is sent into the sample flesh and its back propagation is recorded. To generate the ultrasonic wave a short electrical pulse is sent to a transducer containing piezoelectric crystals (e.g. ceramic) and converted into a mechanical wave through the piezoelectric effect. The produced energy is transmitted to the flesh and it is received in another point of the sample by a transducer named receiver. The receiver re-converts the ultrasound signal into electrical energy and finally it is saved in a computer as function of time. A schematic of an ultrasonic setup developed by Mizrach (2000) is shown in Figure 10. As can be seen, the four main components of an ultrasonic system are a wave generator, transmitter, receiver, and computer.

Obtained data are computed by attenuation coefficient (α) and velocity (C_p) parameters as follows (Equations 1 and 2), (Mizrach 2008):

$$C_p = \frac{l}{t} \tag{1}$$

where l and t are the distance between tips of two transducers and transmit time, respectively.

$$A = A_0 e^{-\alpha l} \tag{2}$$

where A and A_0, respectively, are the ultrasonic signal amplitudes at the beginning and at the end of the propagation path of the ultrasonic wave.

b- Ultrasonic technique applications

Attenuation and velocity are influenced by texture and physiochemical attributes of fruits (Kuttruff 1991). There are some reports about existence of good relationship between changes in the fruit tissue and the attenuation (Mizrach and others 1996; Mizrach and others 1997). For this reason, the possibility of apple mealiness detection using ultrasonic technique was investigated (Mizrach and other 2003). They developed an ultrasonic system to classify apples into three fresh, mid-mealiness, and mealiness levels. Ultrasonic attenuation was measured for two apple varieties Jonagold and Cox. Jonagold apple variety could be distinguished into three mealiness levels; however, ultrasonic technique did not show good results for Cox variety.

Another study was conducted by Bechar and others (2005) to evaluate the performance of ultrasonic technology in mealiness detection, Jonagold and Cox were two apple varieties used in the study. Three mealiness levels were obtained under the FAIR protocol. According to this protocol, fresh apples are those stored under 95% RH and 3^{o} C for 26 days. If apples are stored for 26 days under the same relative humidity but higher temperature (20^{o} C), apples are considered as mealy (over-ripe). Ripe apples (mid-mealiness) are achieved when apple is kept at high relative humidity (95%) and low temperature (3^{o} C) for 16 days and then it is followed by a high temperature (20^{o} C) for 10 days. The ultrasonic setup is shown in Figure 11. The distance and angle between transducer tips was 2 mm and 120^{o}. Since contact force between transmitter and fruit surface is important, transmitter was equipped to a strain-gage. Ultrasonic data were obtained for both green and red parts of each apple. The experiment was done under several loads and the ratio of received energy to mechanical load (Slope) was considered as ultrasonic data. Acceptable results were only observed for Cox variety. Although detection of fresh Cox variety from the ripe one (mid-mealiness) was not possible, a linear discriminate analysis using the ultrasonic data (Slope) collected on the green and the red sides of the fruit could classify Cox variety into mealy and non-mealy groups with accuracy over 94%.

c- Acoustic impulse response (AIR) technique principles

The acoustic impulse response is an inexpensive and interesting sonic-based technique. This technique is affected less by the wave attenuation in comparison with ultrasonic one (Benedito and others 2006). It consists of a probe, microphone, signal conditioner, and a computer (Figure 12). The probe is hit on the sample surface and the response signal (the audible range) is recorded by a microphone. The fast Fourier transform is often applied on the data and suitable parameters are extracted for analyzing (García-Ramos and others 2005).

d- Acoustic impulse response (AIR) technique applications

Apart from monitoring firmness changes of fruits (especially apple, pear, and peach) through acoustic methods, some studies have been carried out to describe sensory attributes of apple using the AIR technique. Numerous sensory attributes (useful in mealinsee description) of different apple cultivars (Jonagold, Cox's Orange Pippin, and Boskoop) were determined by a trained panel (Barreiro and others 1998). To obtain acoustic data, each apple was hit by a rod and the produced sounds within the frequency range of 200-1600 Hz were recorded using a microphone. Measurements were taken at three different points on apple equator and mean value of them was considered. Two parameters including frequency resonance and stiffness (Equation 3) were computed from acoustic data.

$$stiffness = f^2 \times M^{2/3} \tag{3}$$

where *f* and *M* are frequency resonance and apple mass, respectively.

Results showed a high correlation over 0.8 between acoustic parameters (frequency resonance and stiffness) and juiciness. In addition, some models based on acoustic parameters were developed to predict crispy, juiciness, and floury sensory attributes. When juiciness at first bite and during chewing was defined as a linear function of the frequency resonance, the developed model explained over 80% of the data. The developed models for crispness and floury were based on stiffness. The r^2 values of 0.63 and 0.5 were obtained for crispness and floury, respectively. A combination of acoustic data and destructive parameters (confined compression test) could increase performance of models for juiciness during chewing and crispness. Also De Smedt (2000) reported a significant correlation between stiffness parameter and sensory attribute of juiciness. Statistical models using destructive (the confined compression test) and non-destructive data (AIR) were able to predict juiciness (r= 0.85) and crispiness (r= 0.71) well. These results are encouraging because the free juiciness and crispiness play a significant role in detection of mealy apples.

e- Impact force response

In this technique, a mass is impinged on the fruit and interaction between them (for example impact force and impact duration) is analyzed (Figure 12). Most of studies carried out with this technique are related to texture properties of fruit, especially firmness (Chen and others 1993; Steinmetz and others 1996; Jarėn and Garcỉa-Pardo 2002). According to its fine performance, some researchers suggested this technique to be used in on-line fruit's sorting machines (Jarėn and Garcỉa-Pardo 2002).

Mechanical impact method was used for detection of mealiness in several apple varieties such as Golden delicious, Granny smith, Starking, and Top red apples (Arana and others 2004). Apples were stored at 4^{o} C for 75 days and during storage time six tests were done within each 15 days. Apples were classified in two mealy and fresh classes based on sensory test. For non-destructive test, a mass of 52 g was freely fall on the apple from heights of 2, 5, and 8 cm. Maximum impact force and deformation, permanent deformation of fruit, impact duration, and absorbed energy were obtained from impact process. In addition, center, width, and depth of the bruise region were considered. Good correlation with mealiness was found for maximum impact force, maximum deformation, permanent deformation of fruit, and impact duration. The best correlation coefficient was obtained for maximum impact force that negatively related to mealiness (0.6< r< 0.8). Higher correlation coefficients corresponded to mealier varieties (Starking and Top red apples). A positive relationship was observed between mealiness and other parameters. Classification algorithms were developed by discriminate analysis and overall classification accuracy of 77% was obtained. The highest classification accuracy (80%) was achieved for Golden delicious.

Ortiz and others (2001) studied the possibility of detecting crispy peaches from non-crispy-soft ones using the impact response technique. For this purpose, each peach was collided by a 50 g steel rod dropped from a 4 cm height. Several parameters including maximum impact force and deformation, duration of impact time, absorbed energy, maximum energy, and permanent deformation were measured during impact. Peaches were submitted to several destructive tests and the measured parameters were used as standard. Forward stepwise discriminate analysis was carried out to select most effective impact response parameters. Maximum impact force, maximum deformation, impact time duration, absorbed energy, and permanent deformation were introduced as best features, respectively. Correlation coefficients of 0.81, 0.75, and 0.64 were obtained for maximum impact force with firmness, shear crispness, and hardness, respectively. Also maximum deformation correlated significantly with firmness (r= -0.71), hardness (r= -0.53), and shear crispness (r= -0.66). The developed algorithm was able to classify crispy and soft peaches with overall accuracy of 80.83%. Successful classification of peaches into crispy and non-crispy classes may be a good indication for detection of wooly peaches too.

3-2-2- Electromagnetic-based techniques

This section contains five techniques including Near-infrared spectroscopy (NIR), Nuclear magnetic resonance/ Magnetic resonance imaging (NMR/ MRI), Time resonance spectroscopy (TRS), hyperspectral backscattering imaging, and fluorescence. Each technique is considered for principles and applications individually.

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a- Near Infrared Spectroscopy (NIR) Principles

The discovery of near-infrared (NIR) region date goes back to 1880 and is ascribed to Herschel, however prior to Second World War, the NIR region was not considered useful for spectroscopy (Roggo and others 2007). NIR spectra comprise of overtones (related to NIR region) and combinations of the fundamental mid-infrared (MIR) bands. The frequencies of these overtones and combinations of molecular vibrations are overlapped in the NIR. Severe overlapping between NIR bands was the main reason of its lack of attention, because it would be difficult to interpret the spectra (Roggo and others 2007). In the recent years due to the computer progresses and development of chemometrics approaches, NIR spectroscopy has been increasingly applied for determining chemical and physical properties of agro-food products (Blanco and Villarroya 2002; Roggo and others 2007). Measurement of grain moisture is known as the first use of NIR spectroscopy in agricultural applications (Norris 1964). Because of NIR spectroscopy sensitivity to the C-H, N-H, and O-H chemical bonds, until now a lot of studies have been reported regarding the applications of NIR spectroscopy in a wide range of agricultural products. NIR, as a spectroscopy method, covers a finite range of the electromagnetic spectrum from 780 to 2500 nm. When NIR radiation interacts with an object, the reflected or transmitted radiation is measured, resulting in NIR spectra. Finally, multivariate calibration techniques are employed to extract the desired chemical information (Huang and others 2008).

b- Near Infrared Spectroscopy (NIR) measurement setup

NIR spectra are obtained using the three most prevalent configurations as shown in Figure 13. In reflectance mode (Figure, 13-a), detector and light source are in a same side and are mounted under a specific angle. In this case, the detector receives the light reflected by internal contents (scattered light). In transmittance mode (Figure, 13-b), the sample is placed between light source and detector. As can be seen from Figure, 13-b, after light passes thorough the sample, it is received by detector. Like reflectance configurations, detector and light source can also be in the same side but parallel to each other. This design is known as interactance mode (Figure, 13-c). In this mode, a light barrier is placed between source and detector to avoid regular reflection (Nicolaï and others 2007).

c- Near Infrared Spectroscopy (NIR) Applications

NIR was used to describe sensory texture attributes of steam-cooked potatoes (Boueriu and others 1998). PLSR models showed high correlation coefficients ranging from 0.89-0.94 between NIR data and sensory attributes such as mealy, waxy, firm, and moist.

In another study, prediction of sensory mealiness attribute of potato was done based on NIR spectroscopy technique (Thybo and others 2000). Samples of raw and cooked potato were prepared and their NIR spectra in the wavelength range 400-2498 nm were obtained while the angle of the light source and detector was 45^o. Measuring NIR spectra of each sample was done in ten repetitions and their mean was considered as the final NIR spectrum of the sample. Results showed that mealy potatoes had a lower absorption than non-mealy ones in vision region 425-500 nm. Also lower absorptions were observed for the cooked potatoes with high dry matter in the water region (the wavelengths 970, 1450, and 1940 nm related to the second overtone, first overtone, and fundamental stretch of O-H, respectively). On the other side, the obtained results of PLSR presented a good correlation (r= 0.83 and r= 0.73 for cooked and raw potato respectively) between NIR spectra data and mealiness.

Several years ago, some relationships had been found between spectroscopy data (at 670-

710 nm) and apple sensory attributes including juiciness, toughness, and crispness (Watada et al., 1985). In 1999, it was reported that NIR spectroscopy might be useful for detection of mealy apples non-destructively (Nicolaï et al., 1999). Prediction of sensory attributes of nineteen French apple cultivars by visible/NIR spectroscopy was carried out (Mehinagic and others 2003). Touch resistance, roughness, crunchiness, chewiness, juiciness, and mealiness were considered as texture attributes. After scoring the apple samples by the panel test, visible/NIR spectra of 380 intact apples were acquired. For this aim, a visible/NIR spectrometer covering wavelengths ranging from 400 to 2100 nm was used. Spectra were obtained on two opposite sides of apple at interactance mode. Only roughness, crunchiness, and mealiness could correlated with visible/NIR spectra well. Good correlations (r> 0.8) between roughness and visible/NIR spectra occurred at absorbance bands 1886 and 2050 nm. These wavelengths most likely corresponded to starch and proteins, respectively (Osborne et al., 1993). For mealiness, an acceptable negative correlation was found at wavelengths 680-710 nm (related to chlorophyll absorbance) and 980 nm (absorbance band of starch). Also crunchiness positively correlated with the same wavelengths. After determination of absorbance bands corresponding to roughness, crunchiness, and mealiness, it was decided to develop prediction models based on PLS. Correlation coefficients for roughness, crunchiness, and mealiness were 0.84, 0.49, and 0.41, respectively.

To investigate the relationship between sensory texture data of apples and visible/NIR spectra another study was conducted by Mehinagic and others (2004). Study was carried out on Golden Delicious, Braeburn, and Fuji cultivars. The apples were stored under 3° C for different periods (3, 20, and 30 weeks). Similar to previous studies, sensory attributes of apples were scored by a test panel and visible/NIR data were collected. When spectroscopy data were analyzed, some relationships were observed between them and texture properties (touch resistance, crunchiness, mealiness, juiciness, and chewiness). The 720 (r≈ 0.35), 1440 (r≈ 0.27) known as sucrose peak, and 2338 nm (r≈ 0.12) known as carbohydrate peak were three wavelengths positively correlated with mealiness and a negative correlation was found at the 1940 nm (r≈ 0.17) known as water peak (combination of O–H stretch and bending). Contrary to mealiness, negative relationships were found between crunchiness, chewiness, and touch resistance and absorbance bands of 720, 1440, and 2338 nm. Some positive correlation was found for juiciness in the 630–700 nm range (r≈ 0.35) and 1940 nm (r≈ 0.25). Also it could negatively relate to 970 (r≈ 0.25) and 1450 (r≈ 0.3) nm (water peaks). Since successful prediction models were not developed when only visible/NIR spectroscopy data had been used by Mehinagic and others (2003), combination of visible/NIR spectroscopy and destructive tests including puncher and compression tests (see more details about the destructive tests in section 3-1-2-apple) were investigated. As can be seen from Table 7, that combination was resulted in models with high performances.

Classification of non-crispy peaches into three classes based on amount of extractable juiciness was carried out by NIR technique (Ortiz and others 2001). NIR spectra were acquired for each peach in wavelength range of 900-1400 nm (bandwidth of 10 nm). For this aim, a NIR spectrometer equipped to a 12 V/ 100 W light source was used. Light was reached to the fruit surface through passing from a 4 mm optical fiber. After collecting the NIR spectrum, its first and second derivative was computed. In addition to NIR spectroscopy, destructive tests such as penetration, confined compression, and shear rupture test were applied on peaches to identify soft fruits. Instrumental test parameters were the same as that described by Ortiz and others (2000). Free juiciness was measured during compression test by inserting filter paper beneath sample. Although low coefficients of correlation (0.41≤ r ≤0.56) were found between NIR spectra and the free juiciness, discriminate analysis could make acceptable classification accuracies. The best classification accuracy was 78.57% which was obtained for high-juiciness group. The groups with medium and low free juiciness were classified with 73.85 and 60% accuracies, respectively.

In the same study by Ortiz and others (2001), possibility of mealy peach detection was also investigated. The soft fruits with low juiciness were defined as wooly (mealy) peaches. At first, crispy peaches was detected from soft peaches using impact response method and then NIR technique was employed to separate the soft peaches into high, medium, and low juiciness classes (Figure 14). Discriminate analysis showed that classification of peaches into wooly and non-wooly classes was done with accuracy 80%.

d- Nuclear Magnetic Resonance (NMR)/ Magnetic Resonance Imaging (MRI) Principles

NMR is based on the absorption of electromagnetic radiation in the radio-frequency region (60-800 MHz for hydrogen nuclei), (Kotwaliwale and others 2010). Hydrogen and carbon are two most familiar nuclei that absorb radiation in NMR (Pavia and others 2009; Katti and others 2011). Atomic nuclei spin about their axis and this property is assigned by a spin quantum number (I) (Pavia and others 2009; Katti and others 2011). Spin quantum number is non-zero for all nuclei except those have an even mass and atomic number (Pavia and others 2009). Only those with a non-zero spin quantum number can give rise to an NMR spectrum. Since each nucleus is a charged particle, its spin makes a magnetic field. So in addition to the spin momentum, nucleus has a magnetic moment. When an external magnetic is applied, magnetic nucleus align itself with the field and precession phenomenon is appeared (Figure 15-a). This phenomenon is similar to the precession of child's spinning top (Figure 15-b). In this case, nucleus begins to spin about its own axis with a specific angular frequency, which is called Larmor frequency (Pavia and others 2009). Absorption will occur if only frequency of the electric field component of the arriving radiation just matches the Larmor frequency. In this case, transformation of energy is done and thus causing a spin change. This condition is called resonance (Pavia and others 2009). Magnetic resonance imaging (MRI) is similar to NMR in the principle; just MRI output is as 2- or 3-dimentional images.

e- Measurement of NMR/ MRI data procedure

A magnet generates a constant and powerful magnetic field covering the sample. The magnetic field can have the strength from 0.1 to 4 Tesla (Katti and others 2011). In addition to the magnet, there is a radio frequency (RF) source. RF source generates a short pulse. The pulse can contain a range of frequencies (Pavia and others 2009) or only a specific frequency. For food processing, a NMR setup specified to hydrogen nuclei (^1H) is commonly used because water is the chief ingredient of foods (Butz and others 2005). In this case, the RF pulse contains only one frequency matching Larmor frequency of hydrogen nuclei. When the RF source is turned on, a short duration pulse is radiated, resulting in the excitation of the magnetic nuclei (Pavia and others 2009). After the RF source is switched off, nuclei lose their energy and electromagnetic radiation is emitted. This emission is called a free-induction decay (FID) signal (Pavia and others 2009). The rate of energy loss is characterized by two relaxation times (longitudinal relaxation, T_1 and transverse relaxation, T_2). T_1 and T_2 depend on the texture properties. T_2 (more popular in NMR) can be measured directly from FID. Carr–Purcel–Meiboom–Gill (CPMG) is another most popular method for measuring T_2 as introduced by Carr and Purcell (1954) and Meiboom and Gill (1958). In this method, a series of 90^o (A pulse causing a 90^o rotation of net magnetization vector) and 180^o (a pulse causing a 180^o rotation of net magnetization vector) pulses (called spin-echo sequence) are consequently applied and data acquisition is done within a certain time called time echo (TE).

f- Nuclear Magnetic Resonance (NMR)/ Magnetic Resonance Imaging (MRI) Applications

Sensory attributes of potato were predicted using the NMR technique (Thybo and others 2000). Mealiness was one of the nine texture properties measured by a test panel. After scoring mealiness by the test panel members, transverse relaxation time (T_2) of the raw and the cooked samples were measured. For this aim, a low field ^{1}H NMR spectrometer operating at a frequency of 23.2 MHz was used. T_2 relaxation was obtained for both free induction decay (FID) signal and CPMG pulse sequence. CPMG relaxation curve of two mealy and non-mealy potatoes is shown in Figure 16. A faster relaxation time (T_2) was observed for the mealy potato (Figure 16). Finally, PLSR was used to correlate mealiness with CPMG and FID data. It was observed that prediction of mealiness in the raw samples was done better than that of the cooked potatoes. In addition, PLSR results of the raw samples represented a higher correlation for CPMG (r= 0.9) data than FID (r= 0.7).

As previously mentioned (see section 3-1-1-potato), chemical features (such as starch content and dry mater) are known to be the most effective features in predicting sensory attributes of potato (Thygesen and others 2001). For this reason, they attempted to predict chemical features and sensory attributes by NMR technique (Thygesen and others 2001). CPMG relaxation curves of raw samples were acquired by a low field ^{1}H NMR (23.2 MHz). CPMG data were analyzed by partial least square (PLS) and multiple linear regression (MLR) methods. The best prediction obtained for dry matter, starch content, and size of starch grains ranging from r= 0.81 to r= 0.89. Prediction of contents of citric acid, phytic acid, magnesium, and sodium was done with some success, however, no correlation was found between CPMG data and calcium, nitrogen, and pectin methyl-esterase activity. Analyzing GPMG data by PLS showed a high correlation coefficient (about 0.9) with mealiness. Based on the results, they introduced NMR as a reliable method in predicting sensory attributes of the raw potato.

The latest report about predicting texture attributes of potato by NMR comes back to 2003 (Povlsen and others 2003). In that study, six texture properties (hardness, cohesiveness, adhesiveness, mealiness, graininess, and moistness) of four potato varieties were correlated to NMR data. CPMG sequence (time between 90^o and 180^o pulse was 1000 μs) was used to obtain T_2 curve. PLS, the bi-exponential fitting, the distribution analysis and SLICING (a new method purposed by the authors) were used to model NMR data. The highest (r= 0.83) and the lowest (r= 0.48) correlation coefficients between mealiness and NMR data were obtained by the bi-exponential fitting and the distribution analysis, respectively.

The Possibility of mealiness detection in Top Red apples was examined by MRI technique (Barreiro and others 1999). The apples were stored under controlled and non-controlled atmosphere conditions within 6 months. Images 64 × 64 pixels were acquired from the apples with TE of 8 and 9.5 ms (20 epochs were acquired). Five parameters including minimum, maximum, and average value of T_2 maps, histogram, and pixel numbers of images were studied. After image acquisition, destructive tests (penetration and compression) were applied on apples. Firmness, hardness, and juice area (cm^2) were registered as destructive tests. Apples with firmness less than 16 N and juice area below 4 cm^2 were considered as mealy. Minimum of T_2 for mealy apples was significantly lower than that of fresh ones and no significant difference was observed for maximum and average of T_2 between fresh and mealy apples. Also the number of pixels and firmness were negatively correlated. Correlation coefficients -0.71 and -0.76 were obtained for the images acquired below 30 ms and 35 ms, respectively. In these images, normal histogram was observed for non-mealy apples while histogram of mealy apples was more skew. Later, these results were confirmed by Barreiro and others (2000).

In 2002, some correlations were found between destructive tests and MRI data (Barreiro and others 2002). The juiciness and hardness as two most important indices of mealiness could be successfully described by MRI. A high negative correlation coefficient (r= -0.79) was found between juiciness and standard deviation of T_2 maps. Also minimum value of T_2 maps and hardness showed correlation coefficient of 0.84.

Replacement of the common NMR setups by a faster and non-expensive one was examined by Marigheto and others (2008). It was attempted to associate the internal sub-cellular physiological changes of the red delicious apples including vacuole, cytoplasm and extra-cellular compartment, and cell wall with mealiness. The apples were stored under conditions of 85% RH and room temperature for several weeks. NMR spectra were acquired using three different spectrometers operating at proton frequencies of 23.4 (DRX23), 100 (DRX100), and 300 (DRX300) MHz. Analysis of T_2 showed that detection of mealiness was only applicable at high field strength (e.g. frequency of 300 MHz). Since the NMR setup operated at high frequency was not suitable for online operations, two-dimensional NMR at low field was explored. Using DRX23 spectrometer, T_1-T_2 spectra were obtained with CPMG 90–180°. Mealy apples showed higher T_1 and T_2 values in comparison with fresh ones. This result contrasted with the results obtained by Barreiro and others (2002) who found a decrease in T_2 peak with developing mealiness. On the other hand, a considerably higher T_1 value was observed for the cell wall component of mealy apples.

Detection of wooly peaches using the MRI technique was examined by Barreiro and others (2000). Maycrest peaches were stored under two different cool conditions (1^o C and 5^o C) for 3 weeks. MRI images 64 × 64 pixels were obtained using spin echo sequence. One slice and 20 echoes were acquired with TE= 9.5 ms and repetition time equal to 3000 ms. Different features were extracted from T_2 maps and T_2 histograms. After MRI images acquisition, peach samples were submitted to several destructive tests including penetration, confined compression, and shear rupture tests. Analyses of destructive data considered peaches as wooly which had shear resistance (crispness) less than 30 N, harness less than 14 N/mm and juiciness area less than 3.5 cm^2. When T_2 maps of wooly and non-wooly peaches were compared, it was found that the number of pixels below 60 ms was more for wooly peaches. Also, a flat histogram was observed for wooly peaches. For these reasons, the authors suggested MRI as technique could be used to recognize mealy peaches.

g- Time Resolved Spectroscopy (TRS) Principles

Interaction of a light beam with a fruit results in different phenomena as follows. A fraction of the incident light is reflected by the fruit surface in regular or specular reflectance. The remainder of the light passes through the skin and penetrates to the fruit flesh. The penetrated light may be absorbed by the tissue or transmitted through the entire fruit or reflected back by the tissue components (Figure 17). Some of the light reflected back by the tissue is called scattering or body reflectance (Lu 2008; Mollazade and others 2012). Absorption and scattering phenomena are described by absorption (μ_a) and scattering (μ_s) coefficients. These coefficients are known as the most important optical properties of fruits because they carry information about different properties of fruits (Lu 2008; Mollazade and others 2012). To measure the optical properties of biological tissues, three methods named time resolved (Patterson and others 1989), steady-state spatially resolved (Groenhuis and others 1983; Kienle and others 1996), and frequency domain (Patterson and others 1991; Chance and others 1998) have been introduced.

Usually in TRS, a tunable laser is used as the light source (Valero and others 2004; Valero and others 2005; Lu 2008). The sample is irritated by a short pulse. The light beam penetrates the sample and after traveling in a banana shaped path finds its way out of the sample (Figure 18). An optical fiber is located at a distance r from the incident point (Figure 18) which collects and transmits the backscattered photons to a detector (Valero and others 2004; Valero and others 2005). The detector counts single photons within a short time (approximately 10^{-9}- 10^{-12} s) (Tuchin 2000) and thus the TR curve is obtained for a specific object (Figure 19). For determining the optical properties from the TR cure, it is necessary to express diffusion process by an equation. For this aim, the Boltzmann equation (also known as diffusion theory) has been used (Equation4) (Tuchin 2000; Lu 2009).

$$\frac{n}{c}\frac{\partial}{\partial t}\Phi(\rho,t) - D\nabla^2\Phi(\rho,t) + \mu_a\Phi(\rho,t) = S(\rho,t) \qquad (4)$$

where

t time,

ρ distance from the incident point,

c speed of light in vacuum,

n index of reflection,

$S(\rho, t)$ photon source,

μ_a absorption coefficient

$D= [3(\mu_a + \mu'_s)]^{-1}$ diffusion coefficient,

$\mu'_s= (1-g) \times \mu_s$ reduced scattering coefficient,

μ_s scattering coefficient,

g anisotropy factor.

The diffusion theory (Equation 4) was solved by Cubeddu and others 1994 for the TRS as follows:

$$R(\rho,t) = (4\pi\frac{Dc}{n})^{\frac{-3}{2}} z_0 t^{\frac{-5}{2}} \exp(-\mu_a\frac{ct}{n}) \times \exp(-\frac{\rho^2 + z_0^2}{4Dct/n}) \qquad (5)$$

where z_0 is penetration depth and R is diffuse reflectance.

Finally optical properties can be approximated by fitting the Equation (5) on the TR curve (Valero and others 2005), (Figure 19).

h- Time Resolved Spectroscopy (TRS) Applications

The Relationship between optical properties of apple and mealiness was explored (Valero and others 2005) using TRS. Optical properties of two apple varieties (Cox and Golden delicious) were measured by TRS technique. Light was transmitted into the fruit flesh and the reflected light was registered by an optic fiber placed at 20 mm distance away from light source (Figure 20). Diode Lasers 672, 750, and 818 nm were used as light sources. In addition a tunable laser was used to produce wavelengths from 900 to 1000 nm at steps of 10 nm. TRS curves were obtained for each wavelength and then absorption and transport scattering

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coefficients were computed by fitting the TRS curves on Equation (5). To measure mechanical properties, cylindrical apple samples of 1.7 cm height and diameter were subjected to a confined compression test. Hardness and juiciness area were defined for the samples deformed 2.5 mm at 20 mm/min. Hardness values of 20 N/mm and juiciness area of 4 cm^2 were considered as threshold values. Using these threshold values the samples were classified into three groups as presented in Table 7. The correlations between mechanical and optical properties were then tested. Since no strong correlations were found ($r< 0.4$), classification algorithms based on discriminant analysis were developed. First, fifteen TRS variables were used; most of them were absorption coefficients at wavelengths 670, 818, 900, 930, 940, 960, and 980 nm. Discriminant analysis showed overall classification accuracy of 80%, 51%, and 47% for group 1 (mealy and non-mealy), group 2 (fresh, mid-mealy, and mealy) and group 3 (fresh, soft, dry, and mealy), respectively. Improving classification accuracy was studied through selection of most effective features. Absorption coefficients derived from 670 nm and also 960-980 nm were selected as powerful TRS features. The classification model based on these features improved classification accuracy in group 1 by 8%.

Another study was conducted to describe texture characteristics of apple by optical properties in the visible region (Rizzolo and others 2010). The optical properties of Jonagored apples were measured using TRS with laser diode light sources at wavelengths 630, 670, 750, and 780 nm. Absorption and reduced scattering coefficients of the four wavelengths were obtained from TRS curves. After optical measurement, sensory attributes including firm, crispy, mealy, and juicy were scored by a trained panel test. The fruits were classified into three groups (low, medium, and high intensity of the sensory attributes) according to sensory parameters. Correlation of sensory attributes and optical properties was possible only for reduced scattering coefficient. The correlation coefficients were less than -0.61 for firm, -0.64 for crispy, 0.61 for mealiness, and -0.49 for juiciness. The highest correlation coefficients were obtained for 780 and 730 nm respectively. In terms of classification, discriminant analysis functions were built using selected absorption and scattering coefficients. The highest overall classification accuracy was found when apples were classified for mealiness in comparison with other sensory attributes (71.9%). Apples with low mealy intensity were correctly detected over 80% while classification accuracy of 47% was resulted for high mealy apples. Mid-mealiness apples were classified with accuracy of 72.4%. A poor result was obtained for classifying the apples based on their juiciness (57.3%).

j- Hyperspectral backscattering Imaging Technique Principles

In steady-state spatially resolved method, a continuous-electromagnetic wave beam perpendicularly interacts on the sample and the backscattered reflectance is detected at different distances (r) from the incident point (Figure 21). There are two common configurations for detecting the backscattered reflectance (Lu 2008). In the first configuration, several optical fibers are used and the backscattered reflectance is detected by them at different points of r (Lin and others 1997; Mourant and others 1997; Dam and others 2001). This configuration is called steady-state spatially resolved spectroscopy. Making a good contact between the optical fibers and the sample is introduced as the most serious problem of spatially resolved spectroscopy (Lu 2008). The second configuration is an imaging based technique (Wang and Jacques, 1995). Instead of optical fibers, an imaging device is located above the sample (without any contact with the sample) to capture the backscattered reflectance. The captured image can be a monochromatic or hyperspectral image (Lu 2008).

After obtaining the backscattered reflectance curve of the sample, it is possible to estimate optical properties such as absorption and scattering coefficients. To achieve this aim, the backscattering process must be expressed as an analytical equation. Under the assumption of inexistence of photon source in the medium, the diffusion theory (Equation 4) was solved for the steady-state case as follows (Farrell and others, 1994):

$$R_f(r) = \frac{a'}{4\pi}\left[\frac{1}{\mu_t'}\left(\mu_{eff}+\frac{1}{r_1}\right)\frac{exp(-\mu_{eff}r_1)}{r_1^2} + \left(\frac{1}{\mu_t'}+\frac{4A}{3\mu_t'}\right)\left(\mu_{eff}+\frac{1}{r_2}\right)\frac{exp(-\mu_{eff}r_2)}{r_2^2}\right] \tag{6}$$

where

r distance from the incident point,

$a' = \frac{\mu_s'}{(\mu_a+\mu_s')}$,

$\mu_s' = \mu_s(1-g)$ the reduced scattering coefficient,

$\mu_{eff} = \frac{3\mu_a}{(\mu_a+\mu_s')^{1/2}}$ the effective attenuation coefficient,

$\mu_t' = \mu_a + \mu_s'$ the total interaction coefficient,

$r_1 = \left[\left(\frac{1}{\mu_t'}\right)^2 + r^2\right]^{1/2}$,

$r_2 = \left[\left(\frac{1}{\mu_t'}+\frac{4A}{3\mu_t'}\right)^2 + r^2\right]^{1/2}$,

$A = \frac{(1+r_d)}{(1-r_d)}$,

$r_d \approx -1.44n_r^{-2} + 0.710n_r^{-1} + 0.668 + 0.0636n_r$,

$n_r = \frac{n_s}{n_{air}}$

Now, the optical properties can be determined by fitting Equation (6) to the backscattered reflectance curve.

k- Hyperspectral backscattering imaging setup

A hyperspectral image has three dimensions like a cube (Lu 2008). Two axes (x and y axes) represent spatial information and the third axis (λ) describes spectral information (Figure 22). As can be observed from Figure 22, each pixel of the hyperspectral image represents a spectrum including numerous wavelengths in a specified region of electromagnetic spectrum (Lu 2008).

There are four modes to make a three-dimensional image cube. These modes are point scan, line scan, area scan, and single shot (Mollazade 2013). The line scan is the most common mode. A hyperspectral backscattering imaging system in line scan mode consists of a source light, optical fibers, an imaging spectrograph, a detector and a computer (Figure 23).

A continuous wave beam emitted by a tungsten lamp is transported, typically through an optical fiber to the sample. At a specific distance of incident point, a line-scan system is located that scans one line of the sample and acquires the backscattered reflectance. The backscattered reflectance is passed through a spectrograph (a prism-grating-prism) and thus it is dispersed into different wavelengths. By projecting the dispersed light on a CCD detector, a two dimensional image is created; one axis includes spectral information and spatial information is described by the other axis. For creating a three dimensional image it is enough to move sample perpendicularly to the scanning direction (Lu 2008).

l- Hyperspectral Backscattering Imaging Technique Applications

Apple mealiness detection was investigated using the hyperspectral backscattering imaging technique (Huang and Lu 2010). Red delicious apples were prepared and kept under conditions of controlled atmosphere (2% O_2 and 3% CO_2 at 0^o C), and 4^o C for about 4 months. In addition, another group of the apples was stored under high temperature (20^o C) and high relative humidity 95% to induce mealiness. The apples were removed from storage and their images were acquired. A light beam of 1 mm diameter was impinged on fruit under the angle 15^o. A hyperspectral backscattering imaging setup was equipped to a line-scan spectrograph covering the wavelengths 400-1000 nm. Ten scans were obtained, and average of them was considered as final image (Figure 24). For each image, wavelengths of 600-1000 nm were studied at many different points from the incident point of beam to distance of 20 mm. After image acquisition, mechanical properties of apples (Juiciness and hardness) were determined using confined compression test. Juiciness area (J) 5 cm^2 and hardness value (H) of 40 kN/m were defined as threshold values. On this basis, apples were categorized into two groups as represented in Table 8. Spectral curves showed two absorbance peaks at 670 and 970 nm corresponding to chlorophyll and water, respectively. Computing reflectance intensity of the images showed higher values for non-mealy apples and this difference was more remarkable at 600-730 nm. For this reason, it was attempted to correlate reflectance value with hardness and juiciness. Models developed by PLSR could predict hardness ($r\leq 0.76$) better than juiciness ($r\leq 0.54$). In addition, the possibility of detecting mealy apples investigated. Different classification accuracies were found using PLSR; higher classification accuracy was obtained for two-class (mealy and fresh) models and it was decreased as the number of classes increased (e.g. classification into fresh, dry, soft, and mealy). The apples were classified in two-class, and four-class with accuracies of 74.6-86.7%, and less than 61%, respectively.

To enhance ability of hyperspectral backscattering imaging technique for mealiness detection, another study was carried out by Huang and others (2012). The imaging setup was the same as that used by Huang and Lu (2010). Hyperspectral backscattering images were taken in the range of 600-1000 nm. After acquiring the images, cylindrical samples of apple were taken for compression testing. Hardness and juiciness were defined from compression test as follow (Equation 7 and 8):

$$S = \frac{A_p}{l_p} aE \qquad (7)$$

where S is the hardness measured by confined compression, A_p is the cross section of the probe used for the test, l_p is the displacement of the probe, a is a constant related to the Poisson's ratio of the material and E is the elasticity modulus.

$$J = c(W_a + BW_s) \qquad (8)$$

where J is the juiciness measured as the spot on a filter paper, c is a constant, W_a is the apoplast containing water, W_s is the symplast containing water, and B is broken cell index.

The 40 kN/m and 5 cm^2 were defined as threshold values. Those apples with a hardness value less than 40 kN/m and juiciness area below 5 cm^2 were considered as mealy. Three different algorithms including Locally linear embedding (LLE), the mean-LLE, and the mean reflectance were used to characterize the images. Finally classification of apples into mealy and non-mealy groups (only two groups) was carried out using partial least squares discriminant analysis (PLSDA) and support vector machine (SVM). The overall classification accuracy by coupling PLSR and LLE algorithm was 80.4% and classification accuracy 76.2% and 73.0% were made for the mean-LLE algorithm and the mean reflectance, respectively. Overall classification accuracy was improved by using SVM. When coupling of LLE algorithm and SVM was used, classification accuracy was promoted to 82.5%. An enhancement of 3.2% and 5.3% was also occurred for the mean-LLE algorithm and the mean reflectance, respectively.

m- Fluorescence technique principle

When a molecule is excited by a specific electromagnetic wave, it elevates to the higher energy state and absorption phenomenon is occurred. After a certain period of time, the absorbed energy is lost by vibrational relaxation producing heat or reemitting energy (Trivi 2009). The mechanism in which excited molecule loses its energy through emitting light is called fluorescence (Trivi 2009). The fluorescence event lasts for a short time, usually less than 10 s (Butz and others 2005). Commonly, ultraviolet or visible light is used as radiation source and it reemits at a lower energy value (Butz and others 2005). Measurement of chlorophyll fluorescence has been of significant interest for agricultural applications (Butz and others 2005). For the first time in 1997, determination of apple firmness was investigated through chlorophyll fluorescence (Song and others 1997). On this basis, further studies were carried out.

n- Fluorescence technique applications

Fluorescence measurement of chlorophyll was applied in inspecting apples for mealiness (Moshou and others 2003). Jonagold and Cox varieties were stored under the conditions proposed by FAIR protocol to obtain three levels of mealiness (low, medium, and high). Each apple was excited at a peak wavelength of 680 nm and fluorescence data were registered within 1 s. Fluorescence measurement was followed by destructive tests including penetration and compression. Maximum force as firmness index from penetration test, hardness, and juiciness area from compression test were also obtained. With increasing mealiness, a decreasing trend for fluorescence values was observed. Higher fluorescence values were recorded for the Cox variety. This means that Cox variety was more resistance to mealiness. Three different classifiers including quadratic discriminant, ANN, and Self organizing map (SOM) were applied to categorize apples into three classes of non-mealy, mid-mealy, and mealy. The best performance was observed using SOM method for two varieties. Overall classification of 75.83%, 78.33%, and 90% were obtained for Jonagold variety using quadratic discriminate, ANN, and SOM, respectively. Classification of Cox variety was done with lower accuracy.

In another similar work, Moshou and others (2005) introduced the most effective fluorescence features and their relation to mealiness and destructive parameters. Apple varieties under study were Jonagold and Cox. Each sample is illuminated by a 650 nm LED (light emitting diodes). Good correlation coefficients ranging from 0.74 to 0.89 were found between mealiness and fluorescence parameters including slope of fluorescence curve, the yield, the normalized fluorescence, and maximum of fluorescence. In destructive test, firmness was introduced as the best parameter correlated negatively with mealiness (r= -0.85).

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4- Summary and future perspectives

In this study, the concept of mealiness and the ways used to detect it in potato, apple, and peach were comprehensively reviewed. A comparison between different methods applied to mealiness detection is presented in Table 9. Also a summary of results and some suggestions are presented as follows:

- Fruits/vegetables with a soft and lack of juiciness sensation in the mouth are known as mealy. Lack of juiciness is due to separation of cells without rupture. In peaches, it may be also due to the gel structure retaining free juiciness and so makes a dry sensation in the mouth.
- According to the kind of samples, mealiness can be considered as a positive or negative sensory attribute. Mealiness in apple and peach fruits is undesirable phenomenon and results in a rejection by consumers while mealier potatoes have a high consumer acceptance.
- Mealiness can be influenced by several parameters such as variety, maturation, physical and chemical properties, and storage conditions. Different samples show dissimilar behaviors during long storage. Apple and peach tend to be mealier while mealiness in potato decreases during storage.
- Encouraging results were reported for detection of mealiness through sensory panel testing. It was found that more than one sensory property was needed for description of mealiness. Several obstacles including: being time-consuming, subjective nature of process, need of expert people, and also the destructive aspect of sensory evaluation limit its application (Huang and Lu 2010).
- Observation of chemical changes in mealy samples has been studied extensively. The dry matter/starch content of potato is a feature which has shown a good relation with mealiness. The authors of this review suggest finding appropriate wavelengths related to starch content in potato through NIR or hyperspectral backscattering imaging technique, and the possibility of starch prediction by these techniques should be investigated further. If prediction of starch content is done well, it should be possible to grade mealy potato in online operations.
- It was attempted to correlate mechanical features of fruits/vegetable with mealiness attributes. For this aim, different instrumental tests were applied. Among these methods, the compression instrumental test showed the best performance for describing mealiness in apple and potato. The hardness and juiciness parameters measured from the compression test have been used by most researchers to describe mealiness. Simultaneous and easy measurement of free juiciness during compression test is more prominent advantage of this method compared to other tests. Combination of compression and shear tests was proposed for peach fruits. Moreover, free juiciness should be measured for peaches individually. Juiciness, shear crispiness, and hardness were introduced as the most effective mechanical descriptors of wooliness. A disadvantage of instrumental measurement is its destructive aspect; nevertheless it must be used as a standard method.
- Crispiness was introduced as one of the most effective descriptors of mealiness. It was expected to make a good correlation between crispiness and the sound produced during chewing. But poor relationships were obtained in most cases. This may be due to: 1- chewing speed and force applied on samples might be different from one person to another, 2- attenuation of sounds produced in the mouth and 3- high rate of noise to signal. With introduction of a new apparatus (discussed in section 3-1-2- apple), an

enhancement was observed in results. This new device was more reliable and fast in measuring the chewing sound but it was destructive too. In addition, It must be mentioned that direct prediction of mealiness through recorded sound (either chewing or instrumental tests) were not completely successful.

- Mechanics-based nondestructive tests made an acceptable accuracy in mealiness classification. When they were used in combination with other instrumental or optic-based techniques, better results were achieved. These techniques are rapid, inexpensive and on-line potential but their performance is influenced by the wave attenuation and sample shape/mass (Wang and others 2009; Benedito and others 2006; García-Ramos and others 2005).
- Significant correlation was found between NMR/MRI technique and texture attributes although prediction of free juiciness was not successful. Better results were achieved when classification of mealy samples was pursued. Although ability of NMR/MRI in mealiness detection has been proved, it is an expensive and time-consuming technique (Kotwaliwale and others 2010).
- Except potato, poor results were obtained by NIR technique in description of mealiness both prediction and classification. Rapid measurement, simpler equipments, and on-line potential are some of its advantages. Extensive calibration is one of the serious problems in working with NIR instruments (Manley and others 2008).
- Detection of mealy fruits from non-mealy ones by the TRS technique was possible with acceptable accuracy. However by increasing the number of groups, classification accuracy reduced greatly. Expensive equipments, need to good contact between sensors and fruit surface, and also long time to acquire TRS data are instances of drawbacks of TRS technique (Mollazade and others 2012; Lu 2008).
- Like TRS, classification of apples only into mealy and fresh groups was done well by hyperspectral backscattering imaging technique. Better performance is expected if hyperspectral images are explored for more valuable features through image processing techniques. There is no need to make direct contact between fruits and sensors in this technique. Hyperspectral backscattering imaging technique suffers from some disadvantages such as expensive instruments and time-consuming image acquisition process (Jha 2010).
- Fluorescence could detect mealy apples from non-mealy ones with good accuracy. Since this technique acts based on chlorophyll fluorescence, it is most probable that detection of mealy fruits was done according to firmness not based on free juiciness. To investigate this possibility, it is better to examine detection of soft-juicy fruits from soft-dry ones. Possibility of photochemical changes (usually in ultraviolet region) and dependence on environmental factors are main disadvantages of fluorescence technique (Karoui and Dufour 2008).
- Conducting a comprehensive study is suggested to find more appropriate wavelengths for description of mealiness attribute. Then possibility of mealiness detection is investigated using a technique named laser light backscattering imaging. Laser light backscattering is a non-expensive, fast, and imaging-based technique. Find more information about this technique in the paper written by Mollazade and others (2012).

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Table 1- Components of quality factors of fruits and vegetables (Noh and others 2001).

	Quality factor	Measurement/characteristic
External quality factors	Size	Weight, volume, dimension
	Shape	Diameter/depth ratio
	Color	Uniformity, intensity
	Defect	Bruise, stab, spot
Internal quality factors	Flavor	Sweetness, sourness, astringency, aroma
	Texture	Firmness, crispiness, juiciness, mealiness
	Nutrition	Carbohydrates, proteins, vitamins, functional property
	Defect	Internal cavity, water core, frost damage, rotten

Table 2- Most relevant quality attributes (or defects) for several fruit/vegetable species as stated through consumers survey in a European Project (FAIR CT 95 0302, Mealiness in fruits), (Barreiro and others 2004).

Species	Most relevant quality attribute	Second	Third
Apple	Firmness/texture	Bruises	Taste (sugar and acidity)
Pear	Firmness	Taste (sugar and acidity)	Bruises
Peach	Firmness	Taste (sugar and acidity)	Bruises
Apricot	Firmness	Sugar	Color
Tomato	Color	Firmness	Taste (sugar and acidity)
Melon	Sugar	Color	-
Citrus	Rots-molds	Blemishes/Bruises	Taste (sugar and acidity)

Table 3- A summary of different methods applied to mealiness detection in fruits.

Measurement method	Principle	Technique being used	Sample	Reference
Destructive	Sensory, physical and chemical attributes	-	Apple	Barreiro and others (1998)
			Potato	Thygesen and others (2001)
	Acoustic	Recording chewing sound	Apple	De Belie and others (2000)
		Recording the sound produced during mechanical test	Apple	Zdunek and others (2010)
	Instruments	Penetration	Potato	Huang and others (1990)
			Apple	Mehinagic and others (2004)
			Peach	Ortiz and others (2000)
		Compression	Potato	Thybo and Martens (1999)
			Apple	Mehinagic and others (2004)
			Peach	Ortiz and others (2000)
		Shear	Potato	Lujan and Smith (1964)
			Peach	Ortiz and others (2000)
		Tensile	Apple	Tu and De Baerdemaeker (1996)
Non-destructive	Mechanics	Ultrasonic	Apple	Bechar and others (2005)
		Acoustic impulse response	Apple	Barreiro and others(1998)
		Force impulse response	Apple	Arana and others (2004)
			Peach	Ortiz and others (2001)
	Electromagnetic	NMR/ MRI	Apple	Marigheto and others (2008)
			Potato	Thybo and others (2000)
			Peach	Barreiro and others (2000)
		NIR	Apple	Mehinagic and others (2003 and 2004)
			Potato	Thybo and others (2000)
			Peach	Ortiz and others (2001)
		Hyperspectral backscattering	Apple	Huang and others (2012)
		TRS	Apple	Valero and others (2005)
		Fluorescence	Apple	Moshou and others (2005)

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Table 4- The studied parameters of the compression curve (Barreiro and others 1998)

Definition	Index
First peak with 0.5N threshold	Fl
Deformation for F1	D1
Hardness (force-deformation slope for F1 and D1)	FDl
Force for 2.5mm deformation	F2
Elastic deformation	ELAS
Permanent deformation	PERM
Area below the force-deformation loading curve	AREA l
Area below the force-deformation unloading curve	AREA2
F2/ elastic deformation	GRAD
Juice area	JUIC

Table 5- The studied parameters of the puncher and compression curves (Mehinagic and others 2004)

Puncher test		Compression test	
Definition	Index	Definition	Index
Total puncture force	F_s	Hardness associated with the first compression	H_1
Flesh rupture breakdown force	F_f	Hardness associated with the second compression	H_2
Slope of the force-deformation curve	Grad	Work associated with H_1	WH_1
Deformation associated with F_s	D	Work associated with H_2	WH_2
Work associated with F_s	W_s	Slope of the first compression	$Grad_1$
Work associated with F_f	W_f	Slope of the second compression	$Grad_2$
Flesh limit compression force	FLC		

Table 6- Stepwise multilinear regression between sensory and instrumental data, (all abbreviations are defined in **Table 6**, (Mehinagic and others 2004).

Sensory attribute (Y)	Regression equation	R^2-adjusted
Crunchiness	Y= f (W_f, $A_{698\ nm}$,FLC)	0.84
Chewiness	Y= f (H_2, $A_{698\ nm}$)	0.86
Touch resistance	Y= f (Grad)	0.84
Mealiness	Y= f (H_2, Grad1)	0.86
Juiciness	Y= f (H_2, Grad1, $A_{2396\ nm}$)	0.96
Fondant	Y= f (W_f)	0.75

Table 7- Notation of fruit categorizations according to the destructive instrumental mealiness state: “firm” sample when hardness> 20 n/mm; “juicy” sample if juiciness area> 4 cm^2 (Valero and others 2005).

	Two classes		Three classes		Four classes	
	Juicy	Non-juicy	Juicy	Non-juicy	Juicy	Non-juicy
Firm	Nonmealy	Nonmealy	Fresh	Nonmealy	Fresh	Dry
Not firm	Nonmealy	Mealy	Nonmealy	Mealy	Soft	Mealy

Table 8- Classification of apple mealiness according to the destructive instrumental measurements of hardness and juiciness (Huang and Lu 2010).

	Two classes		Four classes	
	J (≥5 cm^2)	J (<5 cm^2)	J (≥5 cm^2)	J (<5 cm^2)
H (≥40 kN/m)	Non-mealy	Non-mealy	Fresh	Dry
H(<40 kN/m)	Non-mealy	Mealy	Soft	Mealy

where H is hardness and J is juiciness area.

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Table 9- Comparison between different techniques applied to mealiness detection in potato, apple, and peach.

Technique	Performance	Advantages	Disadvantages	References
Sensory testing	Excellent	Being used as a standard method	Subjective, time-consuming, destructive	Huang and Lu 2010
Instrumental destructive test	Excellent	Being used as a standard method, objective	Time-consuming, destructive	Huang and Lu 2010
Mechanics-based technique	Sounds good but need to more special investigations	Non-destructive, rapid, cheap instruments	The wave attenuation, dependence on sample mass/shape	Wang and others 2009; Benedito and others 2006; García-Ramos and others 2005
NMR/MRI	Very good	Precise, non-destructive	Long time required for imaging and analyzing, expensive for equipments and maintain	Kotwaliwale and others 2010
NIR	Only good for potato samples	Rapid, non-destructive, on-line potential	Need to extensive calibration and validation	Manley and others 2008
Hyperspectral backscattering imaging	Good	Non-destructive, multi-constituent Information	Expensive in instrumentation, time-consuming	Jha 2010
TRS	Good	Non-destructive, determination of absorption and scattering coefficients	Expensive in instrumentations, time consuming, need to a good contact between sensors and the object	Mollazade and others 2012; Lu 2008
Fluorescence	Sounds good but need to more investigations	Non-destructive	Dependence on environmental factors	Karoui and Dufour 2008

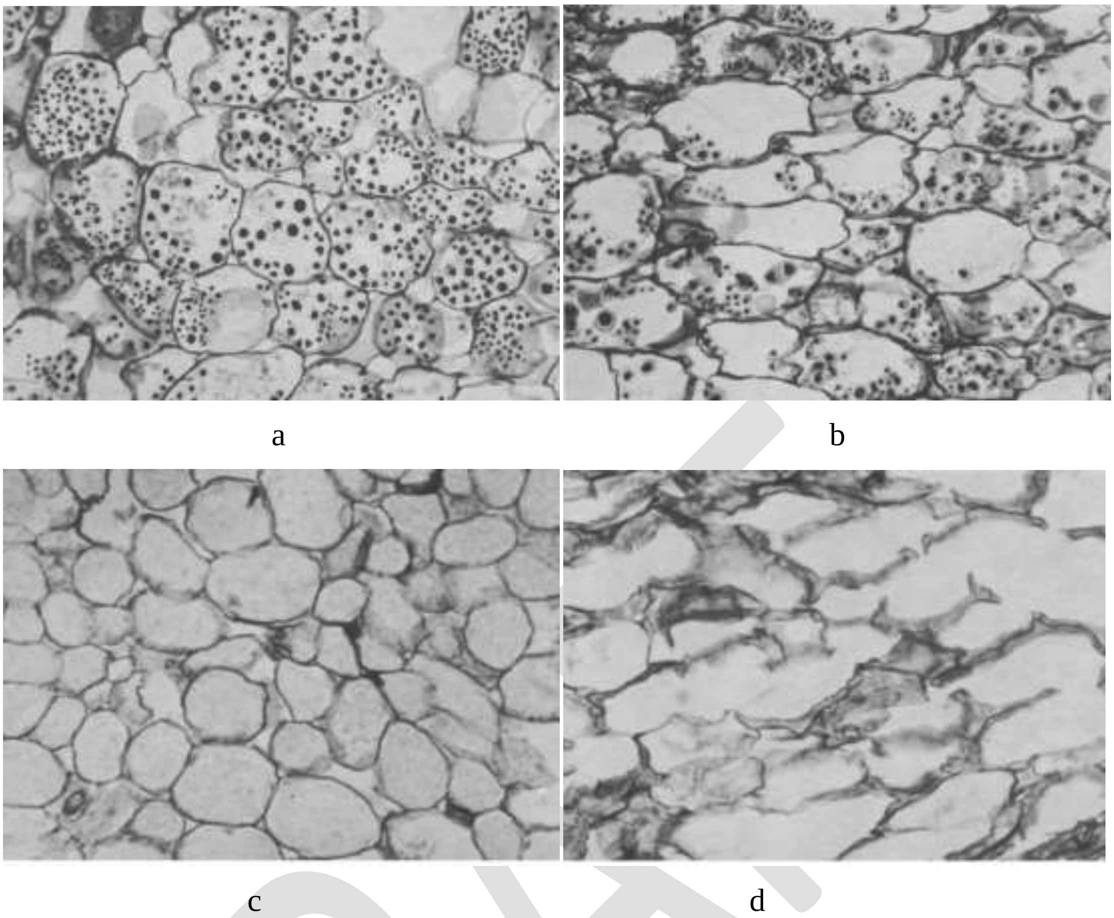

Figure 1- a) Longitudinal section of raw mealy potato (var. Jersey) showing many starch grains, **b)** longitudinal section of raw non-mealy potato (var. Velvet) with less starch grains, **c)** longitudinal section of baked mealy potato (var. Jersey). Starch is gelatinized; many intercellular spaces are present and cells are rounded, **d)** longitudinal section of baked non-mealy potato (var. Velvet). Cell walls are shrunken and disintegrated and many large, irregular cavities have been created (Sterling and Aldridge 1977).

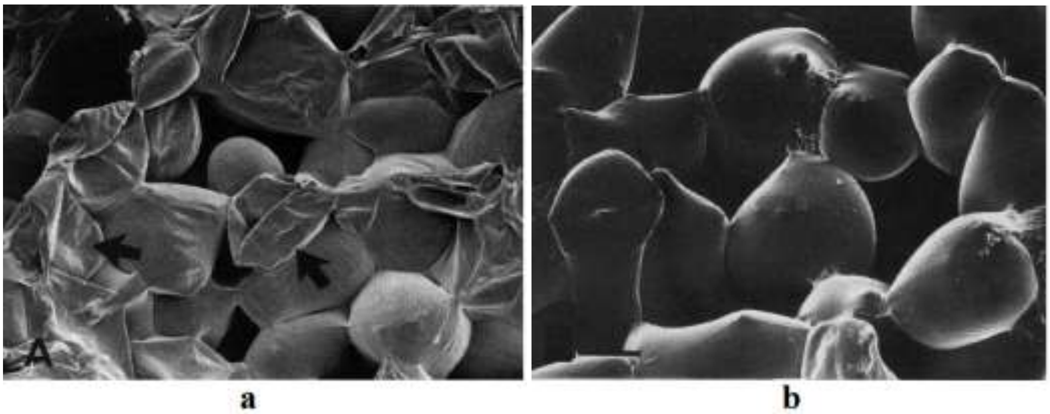

Figure 2- Fracture surfaces of plugs of apple cortical tissue following tensile tests as observed using low-temperature scanning electron microscopy. Apples were stored for 16 weeks at 0C before application of tensile tests; **a)** Cells at the fracture surface from non-mealy tissue showing collapsed cells (arrowed) that have apparently been ruptured and lost contents during the fracture process, **b)** cells show no collapse but do show some distortions (Harker and Hallett 1992).

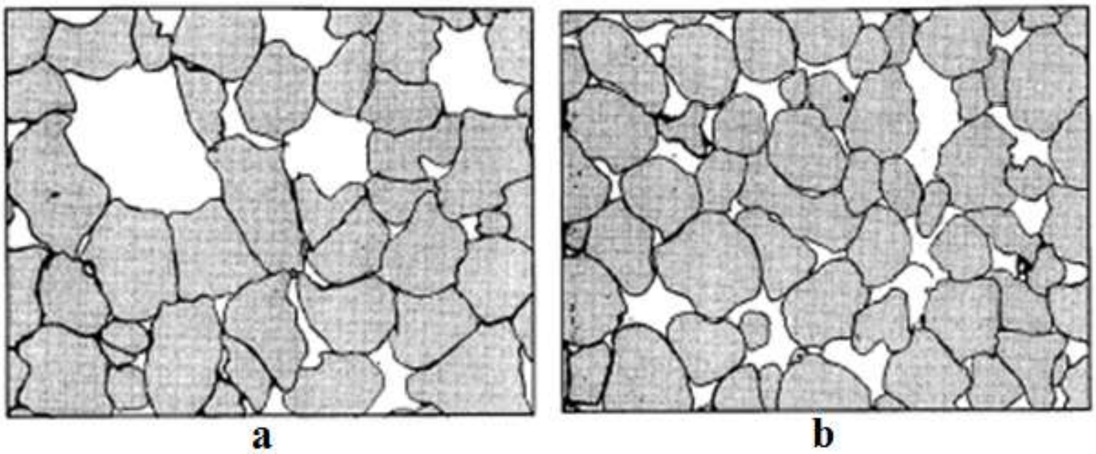

Figure 3- Segmented light microscopic image of **a)** fresh and **b)** mealy ‘Boskoop’ apple (De Smedt and others 1998). As can be seen, more rounded cells are observable in mealy apple than non-mealy one.

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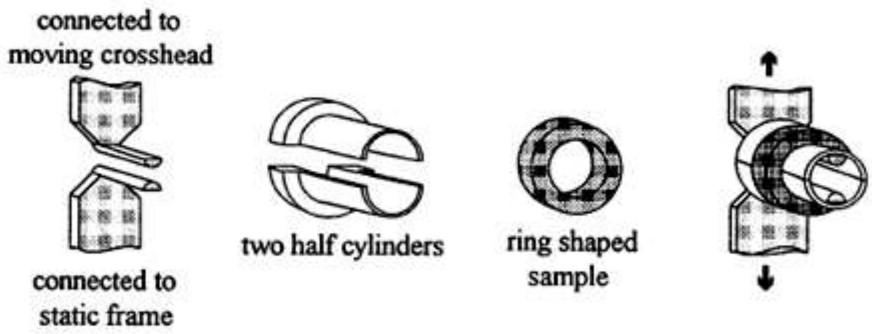

Figure 4- The device for apple tensile measurement (outer diameter of the ring: 17 mm, inner diameter of the ring 10 mm, thickness of the ring: 5 mm (De Smedt and others 1998).

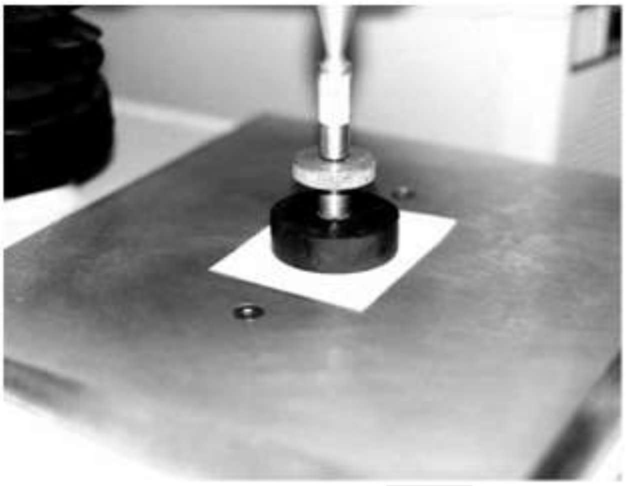

Figure 5- A confined compression test device Barreiro and others (1998).

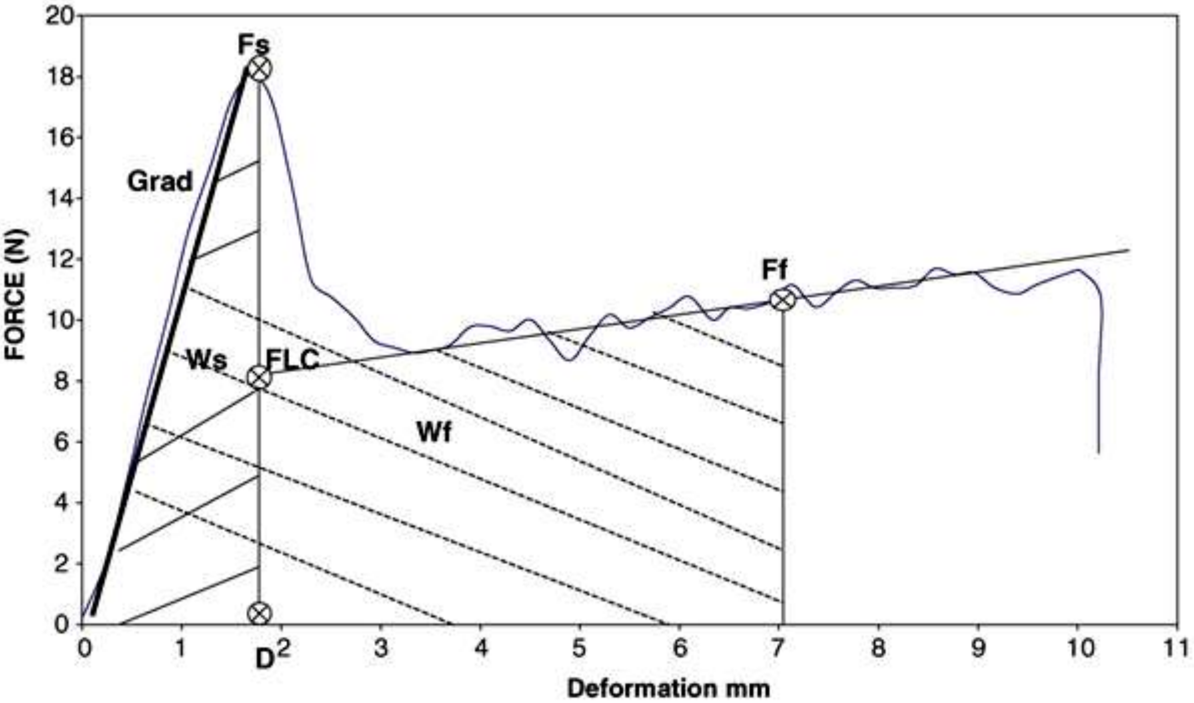

Figure 6-Force/deformation curve obtained during a penetration test on unpeeled apple (cylindrical probe with a 4mm diameter convex tip; penetration speed of 50 mm/min; depth of 10 mm), (Mehinagic and others 2004).

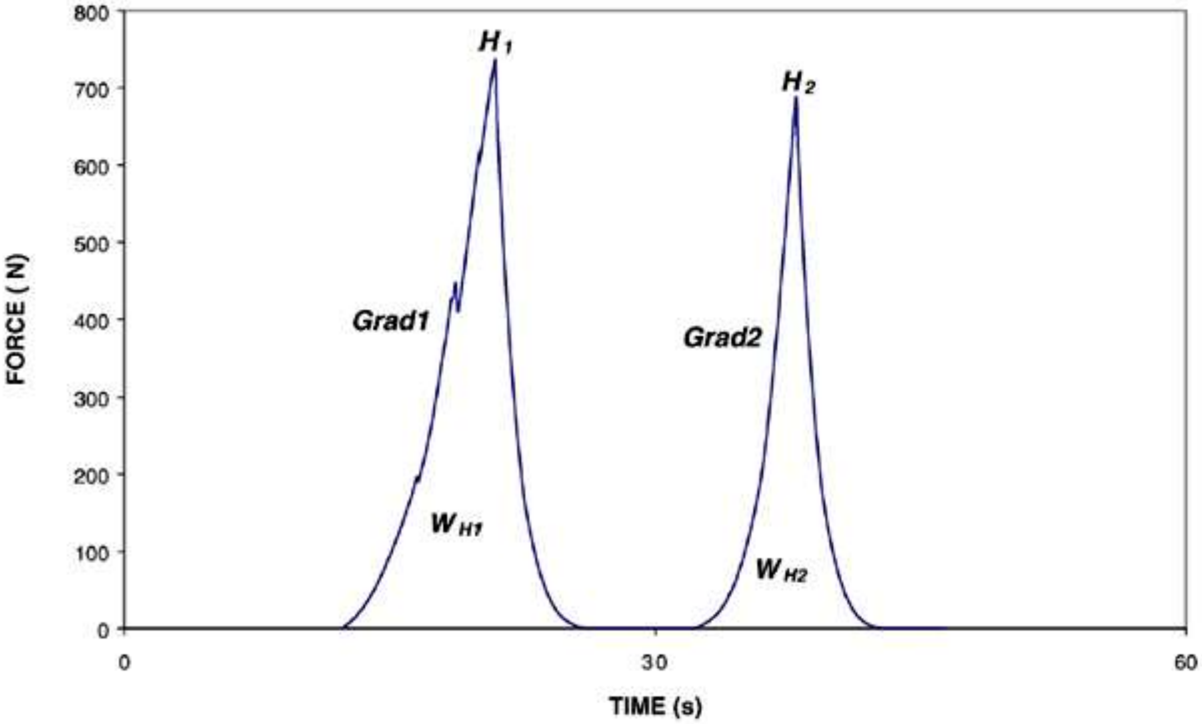

Figure 7- Force/time curve obtained by double compression on unpeeled apples, (2 parallel plates; 50 mm/min; 7 mm deformation) (Mehinagic and others 2004).

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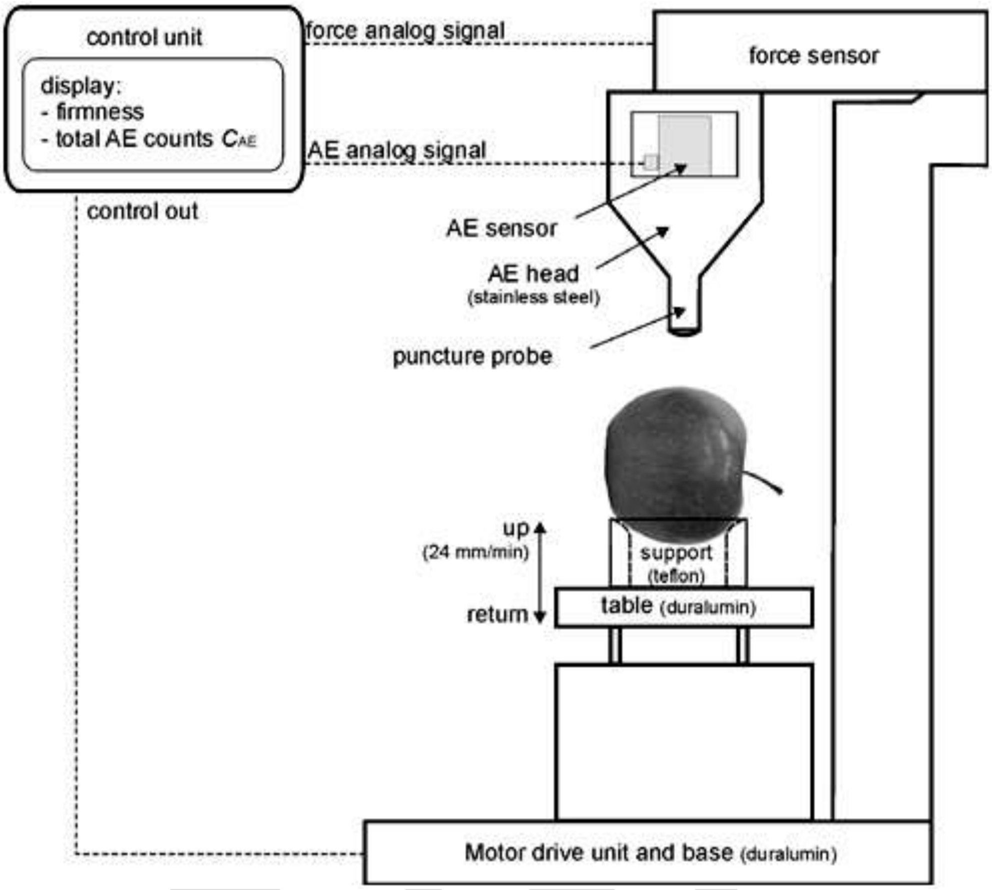

Figure 8- A schematic view of the contact acoustic emission detector (CAED) used for instrumental texture evaluation of apples (Zdunek and others 2010).

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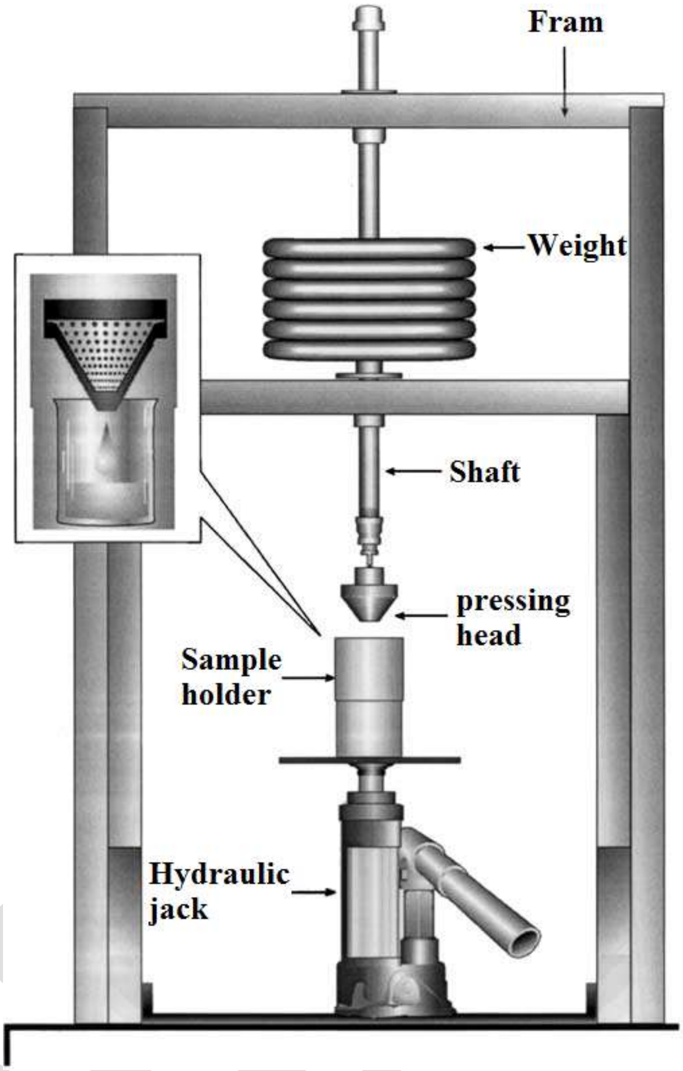

Figure 9- Scheme of the pressing apparatus (Infante and others 2009).

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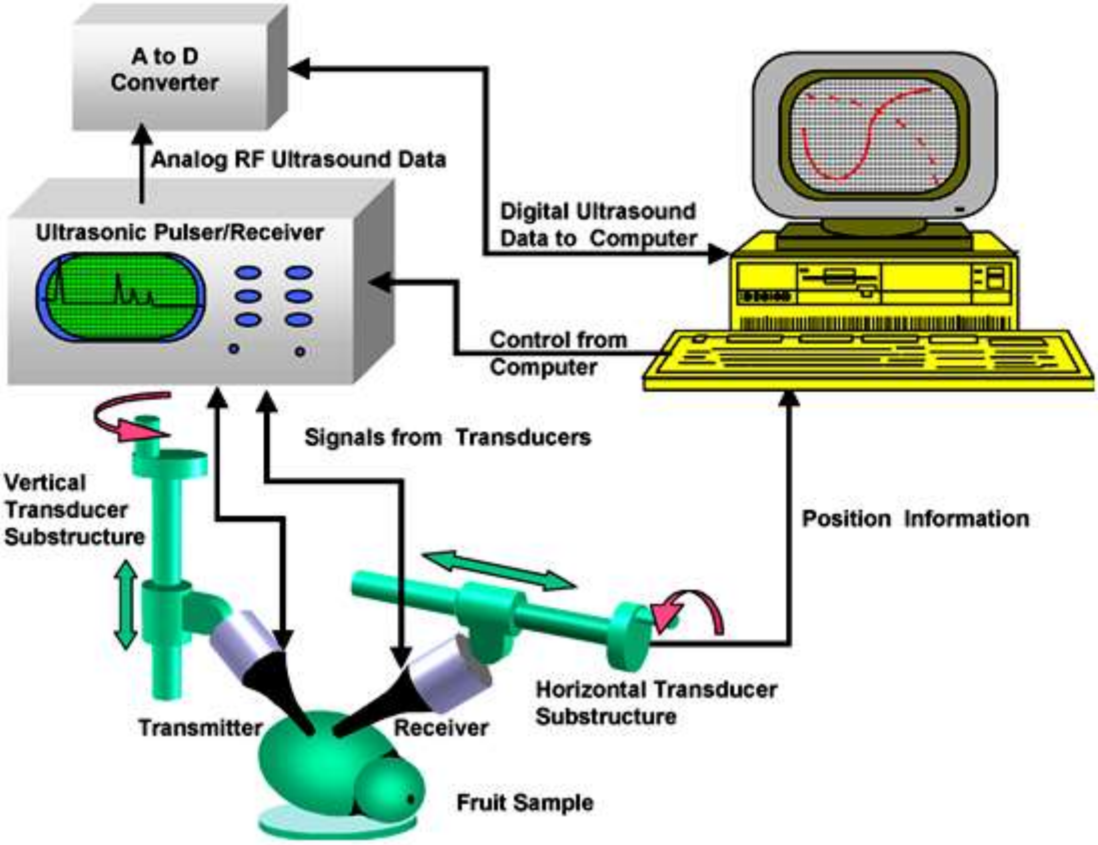

Figure 10- Schematic diagram for continuous-touch ultrasonic system (Mizrach 2000).

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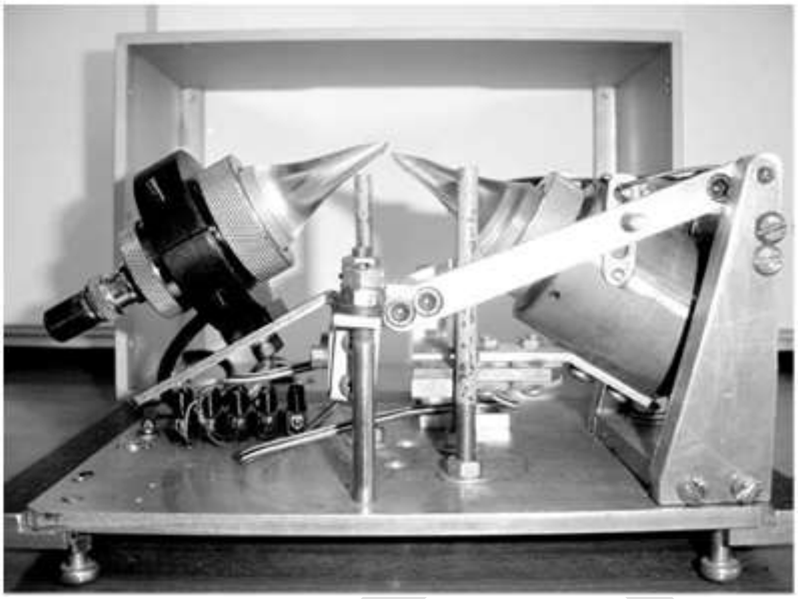

Figure 11- Ultrasonic setup used by Bechar and others (2005).

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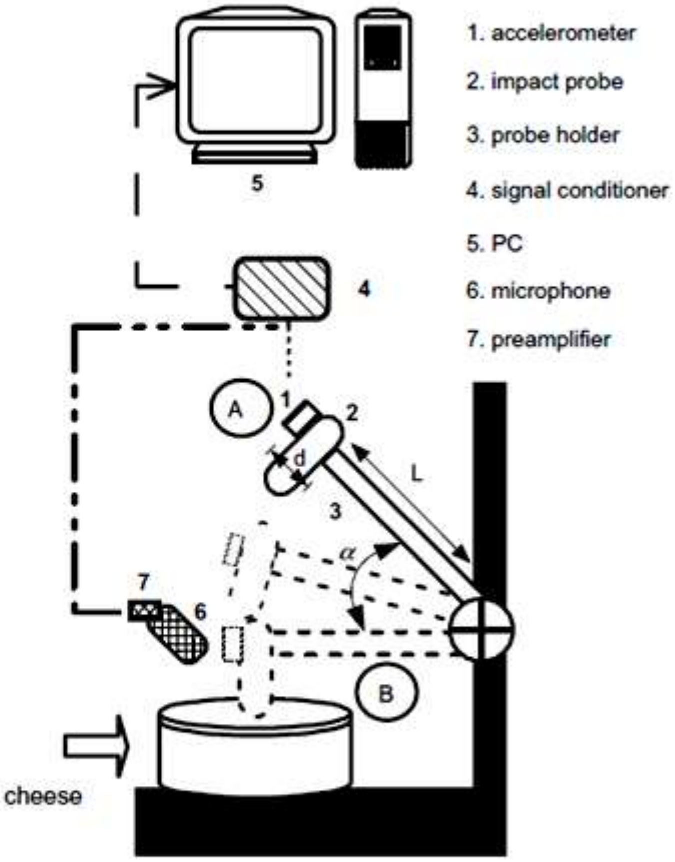

Figure 12- Schematic diagram of the impact and acoustic response system for cheese texture assessment (Conde and others 2007).

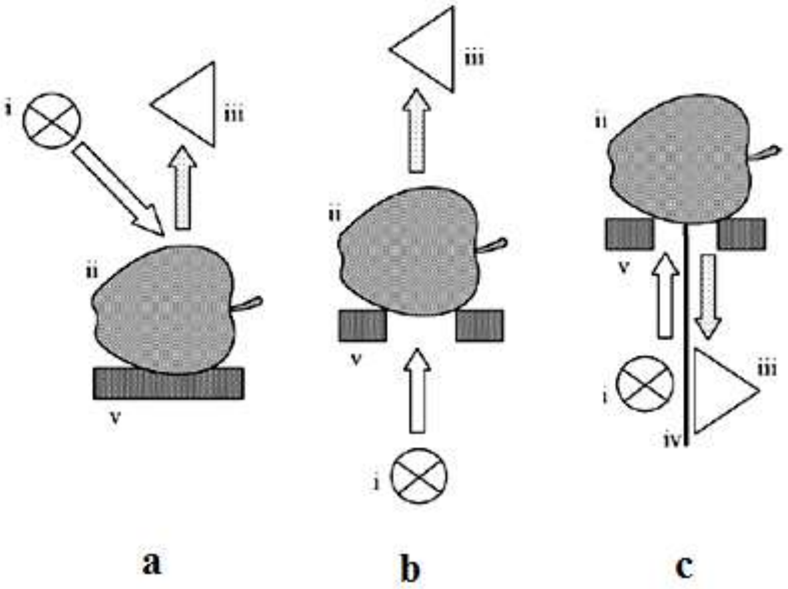

Figure 13- NIR spectroscopy configuration: a) reflectance mode, b) transmittance mode and c) interactance mode, with (i) the light source, (ii) sample, (iii) monochromator/detector, (iv) light barrier and (v) support (Nicolaï and others 2007).

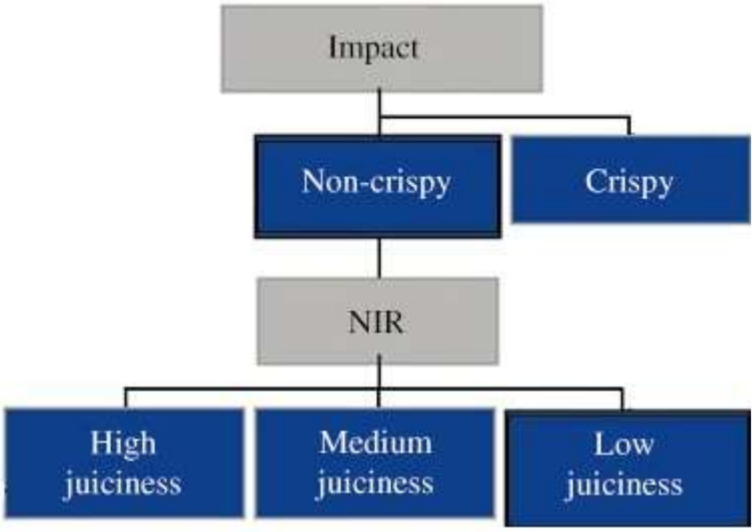

Figure 14-Two-step classification pattern for the non-destructive procedure (Ortiz and others 2001).

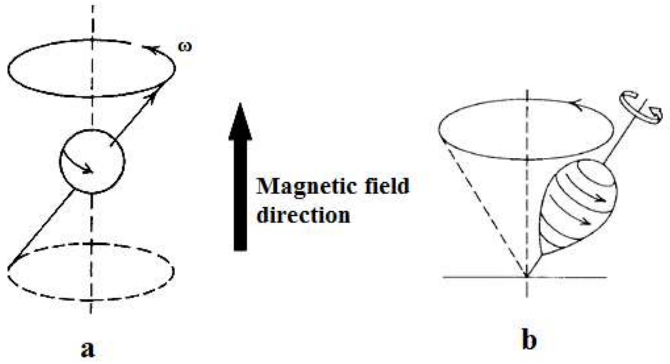

Figure 15- Precession phenomenon: **a)** the precession of a spinning nucleus resulting from the influence of an applied magnetic field, **b)** precession of child's spinning top (Pavia and others 2009).

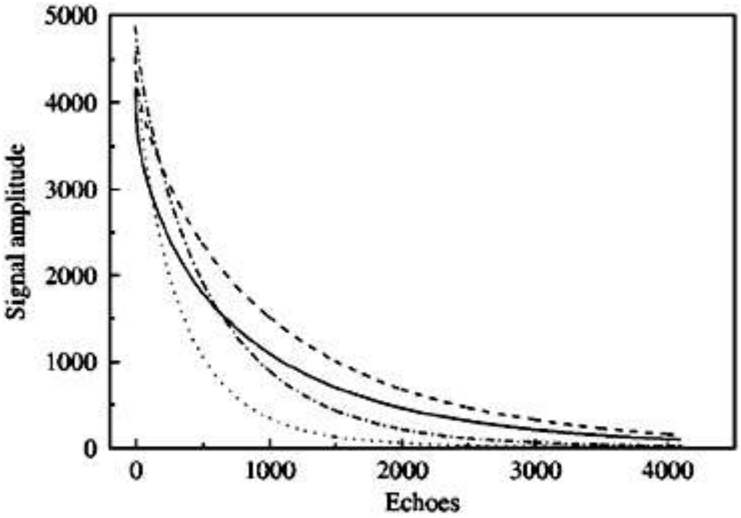

Figure 16- CPMG relaxation curves of two potato samples (Oleva and Sawa) in raw and cooked stage, (——) Oleva raw, (– – –) Sawa raw, (······) Oleva cooked, very mealy and (-·-·-) Sawa cooked, very firm springy (Thybo and others 2000).

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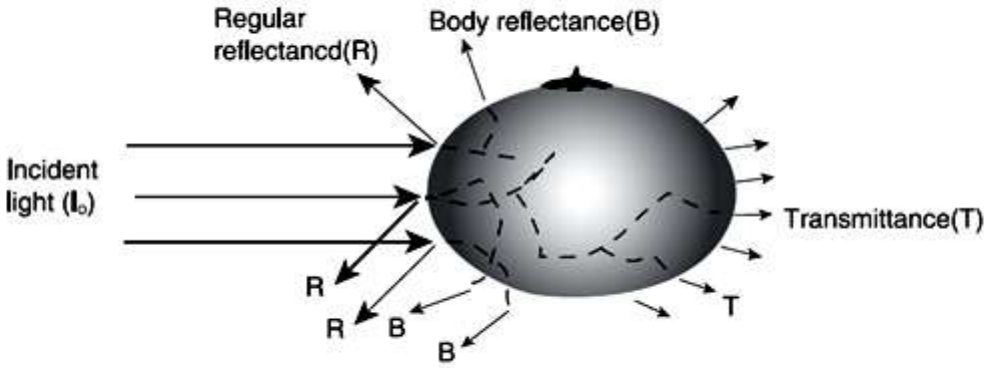

Figure 17- Distribution of incident lights on a biological sample (Chen 1976).

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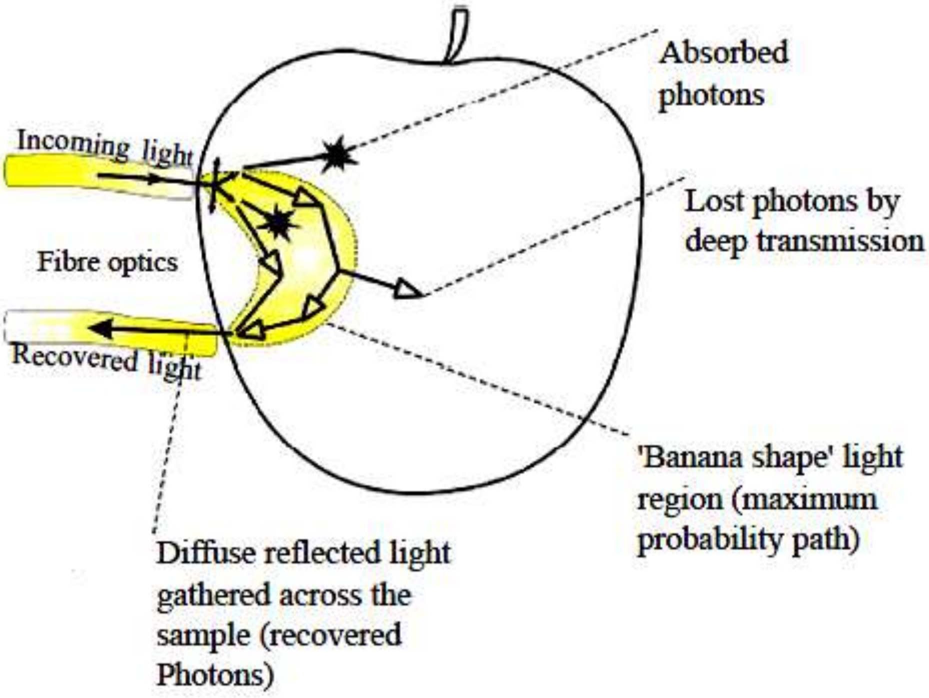

Figure 18- Schematic of TRS measurement and light paths in the sample (Valero and others 2004).

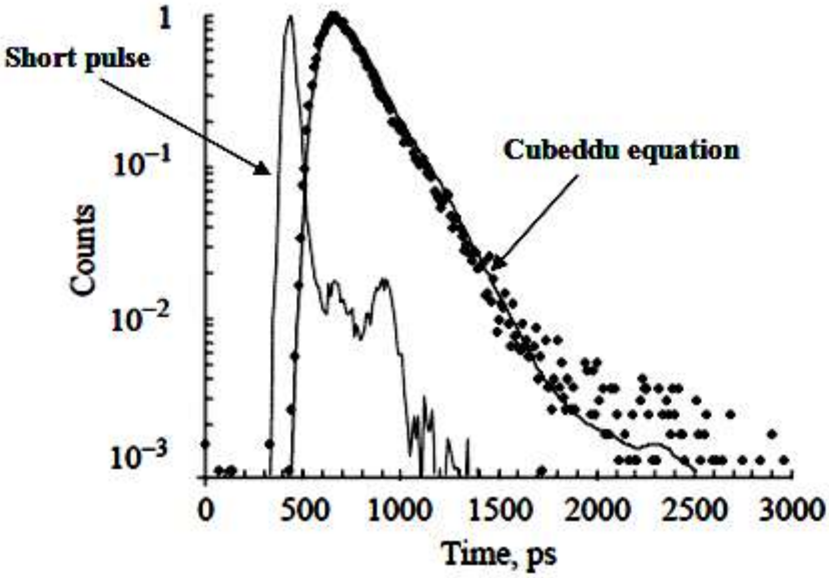

Figure 19- Determination of the absorption and scattering coefficients by fitting the Cubeddu equation (Levenberg-Marquard algorithm) on TRS data, TRS data (•) (Valero and others 2005).

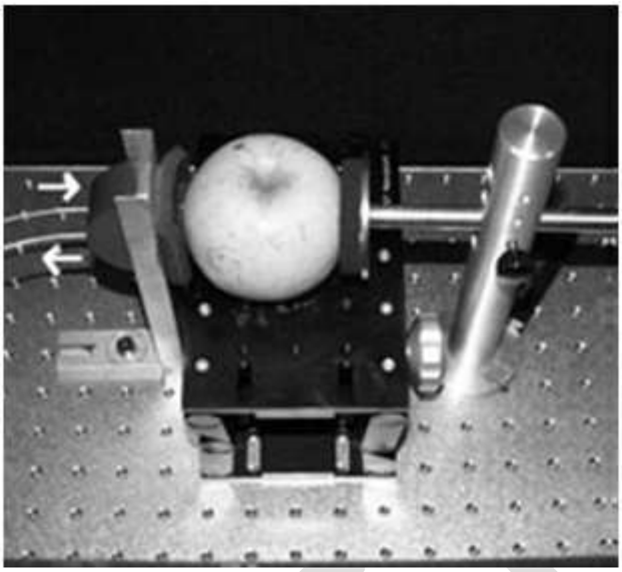

Figure 20- Scheme of the sample presentation for TRS measurements. Fruit holder with incoming fiber and out coming fiber (white arrows in photo) in contact with fruit skin (Valero and others 2005).

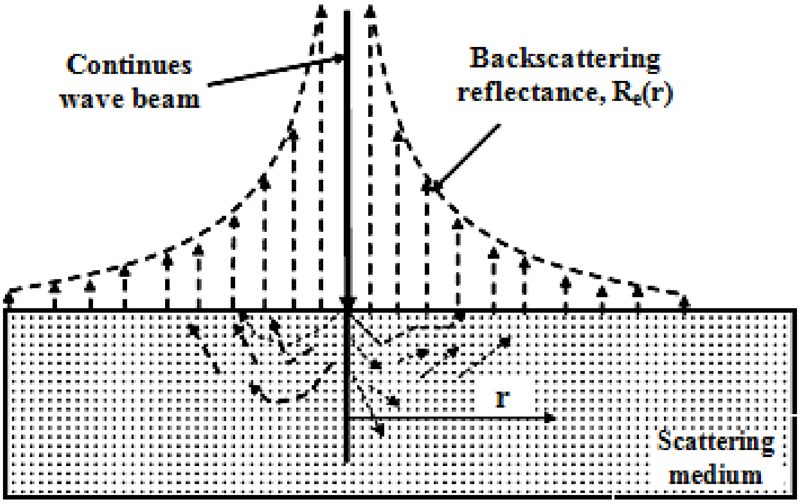

Figure 21- Principle of measuring the optical properties of a scattering medium using steady-state spatially resolved spectroscopic or imaging technique. (Lu 2008).

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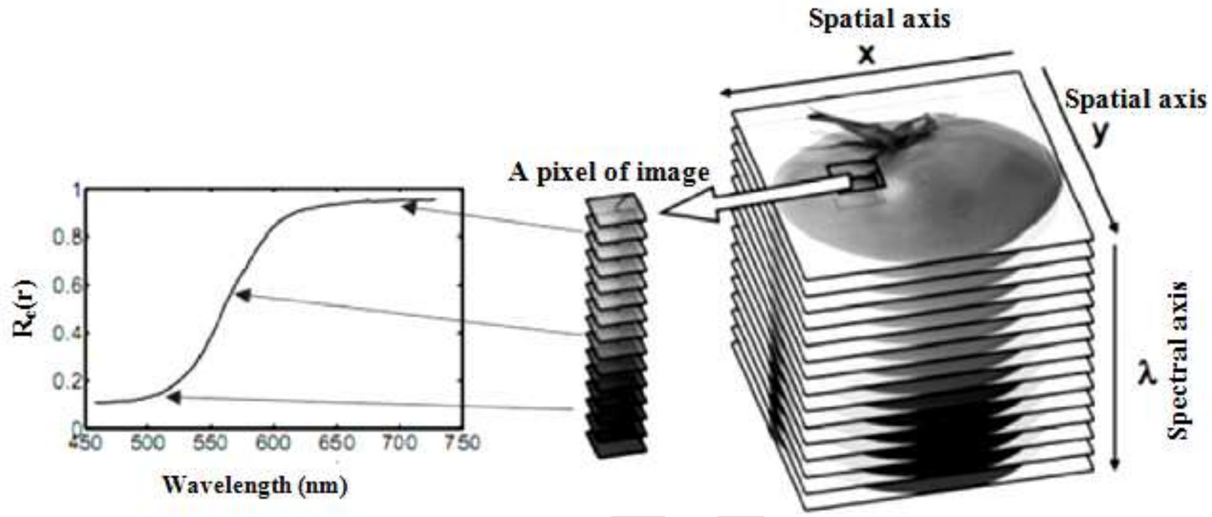

Figure 22- A sample of hyperspectral image (Ploder 2004).

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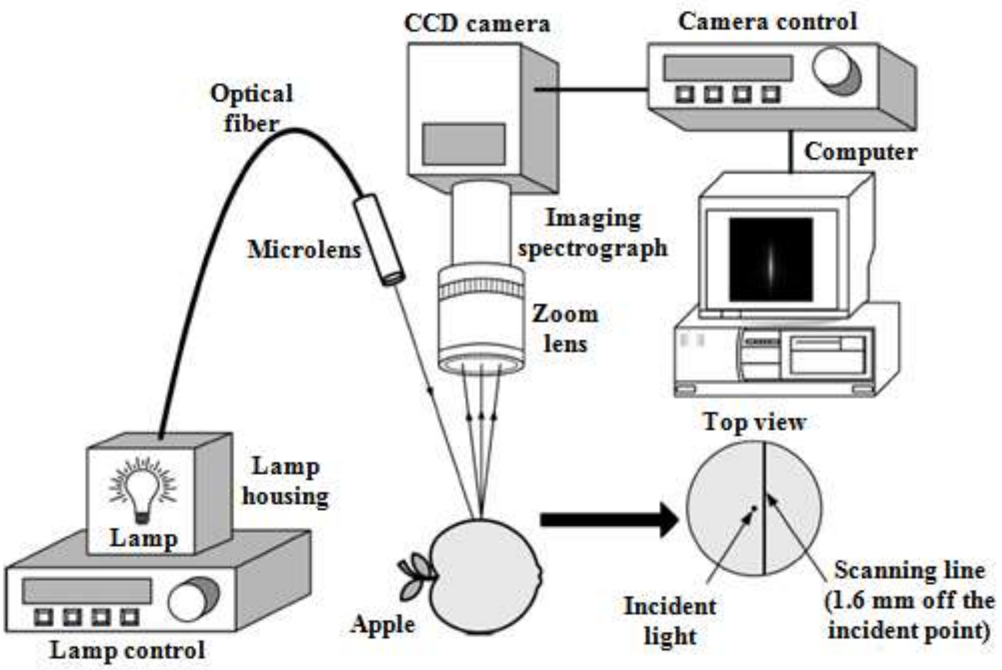

Figure 23- Hyperspectral imaging setup in line scan mode (Lu and others 2006).

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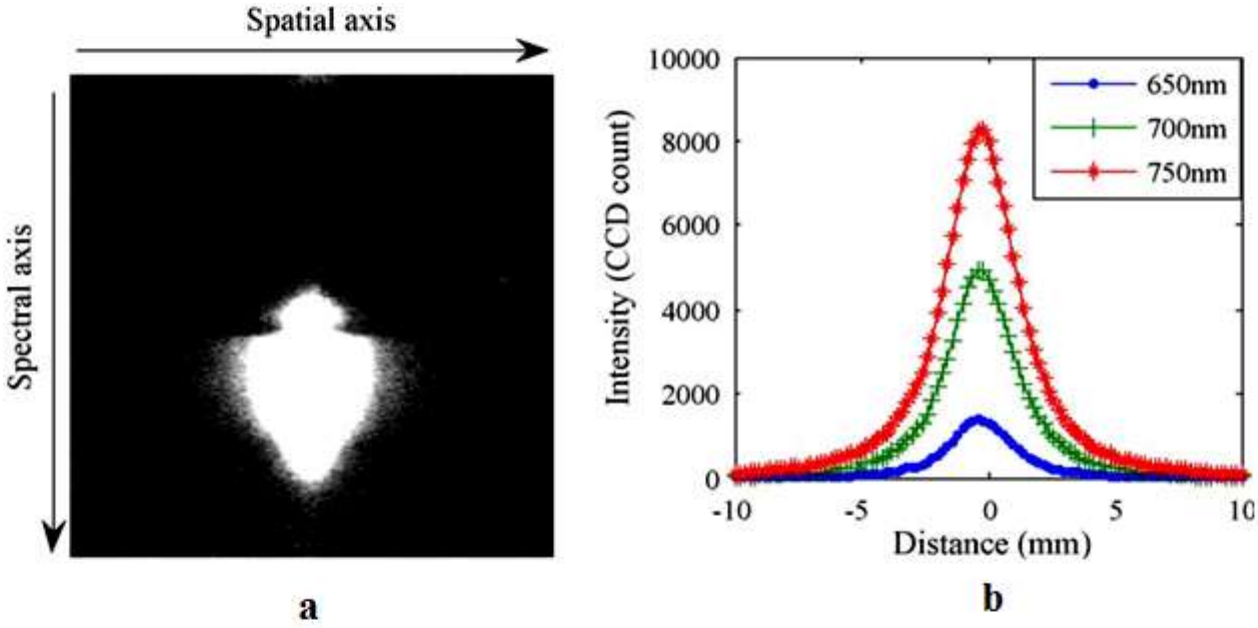

Figure 24- a) Hyperspectral scattering image of an apple, and **b)** raw spatial scattering profiles at three wavelengths (Huang and Lu 2010).